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Research Paper

FarmLCA: A novel approach to assess agroecological innovations in Life Cycle Assessment

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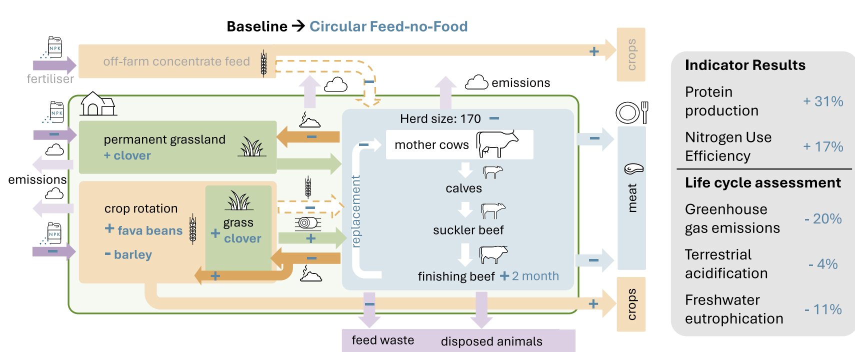
HIGHLIGHTS

- FarmLCA assesses trade-offs and synergies of agroecological innovations.
- It models crop-livestock interactions, on-farm and upstream environmental impacts.
- Feed-no-food scenarios of a Scottish mixed beef farm were assessed with FarmLCA.
- Circular farms avoiding food as feed produce more protein and reduce environmental impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Agroecological innovations are seen as solutions to reduce environmental impacts of agriculture but can potentially lead to trade-offs with food production. Appropriate tools are needed to better understand synergies and trade-offs among environmental issues, resource efficiency and food production.
Objective: This study presents the FarmLCA tool, which models farms as interconnected crop-livestock systems and assesses environmental impacts from farms and farm-inputs. A mixed beef farm serves as case study to assess synergies and trade-offs of avoiding human edible feed in beef production.
Methods: FarmLCA allows the calculation of cradle-to-farm gate life cycle assessments (LCA). Emissions of environmentally harmful substances from crops and livestock are modelled based on the farm management. Upstream impacts from imported inputs (including fertilizer or feed) are accounted for with life cycle inventory data. Yields and nutrient requirements are checked for plausibility, based on management handbooks, while manure availability and composition are calculated based on livestock production. Environmental impacts, nutrient use efficiency and food production for a typical mixed beef farm in Scotland were calculated (*baseline*) and compared to alternative farm management scenarios: a *Feed-no-Food* scenario, avoiding concentrate feeds resulting in a smaller herd size and a *circular Feed-no-Food* scenario, additionally optimizing productivity and synergies between crop and livestock (e.g. more legumes in crop rotation, reduced replacement rate and feed waste).

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Results and conclusions: In the *Feed-no-Food* scenario, the beef production was reduced by 25 %, but more calories and protein were produced overall due to cereal and legumes now being available for direct human consumption. However, slower growth of livestock led to increased environmental impact of beef, whilst reduced livestock numbers required more mineral fertilizer for crop production to replace on-farm manure. In the *circular Feed-no-Food* scenario, beef and overall calorie production were slightly reduced compared to the baseline, but 1.5 more high quality protein (expressed by the Digestible Indispensable Amino Acid Score, DIAAS), were produced. Environmental impacts of beef were reduced and nitrogen self-sufficiency improved due to increased legume share in the rotation.

Significance: Existing LCA approaches often fail to capture the complex dynamics of integrated crop-livestock systems and agroecological practices. FarmLCA addresses this by modelling both on-farm processes and upstream inputs, enabling a consistent assessment of environmental impacts, nutrient use efficiency, and food production. It offers a more holistic and systemic view of the consequences of agroecological innovations and enables the identification of synergies and trade-offs between environmental protection, resource efficiency, and food production.

Guest Editor: Paul Crosson.

1. Introduction

Agriculture is a main contributor to humanity exceeding the planetary boundaries (Campbell et al., 2017), particularly for the global climate and biodiversity crises. Over the past decades, livestock production drastically increased around the globe and is responsible for a large share of these environmental impacts (FAO, 2006; Herrero et al., 2016). About half of all agricultural land is used for feed production and a third of the cereals produced globally are fed to livestock (Mottet et al., 2017). Importing feeds and fertilizer strongly contributes to a disruption of global and regional nitrogen and phosphorous cycles and to the environmental problems associated with this (Billen et al., 2021).

Considering these challenges, there is growing recognition that incremental efficiency gains may not be sufficient to address the environmental impacts of livestock systems (Van Zanten et al., 2018). This has led to increasing interest in transforming agriculture through more circular and ecologically integrated approaches (Wezel et al., 2020). Agroecological innovations are seen as solutions to achieve more sustainable food systems and achieving the Sustainable Development Goals (Bicksler et al., 2023). Principles of agroecology include both elements within the food system and at the agroecosystem level. Within the food system this may include a dietary transition to more plant based diets and avoiding feed and food competition, e.g. Storyline 4 “Local-agroecological-food-systems” (Röös et al., 2022). For the latter, the main principles encompass recycling of nutrients and biomass, reduction of purchased inputs and increased self-sufficiency, enhancing soil, animal health and biodiversity, using synergies between elements of the agroecosystem (i.e. livestock, crops, trees, soil and water) as well as economic diversification (Wezel et al., 2020). Recent studies showed that dairy farms with lower concentrate inputs improved net protein contribution to the food system (Wild et al., 2025), whilst improved efficiency and use of grassland can reduce competition for crop land (Ineichen et al., 2023). However, agroecological farming systems can also create trade-offs because they are often more land demanding due to lower productivity which can sometimes result in higher environmental impacts per unit of food produced (Boschiero et al., 2023; Mathis et al., 2022; Seufert and Ramankutty, 2017). To support decision-makers such as farmers, advisors, policy makers, retailers or consumers in identifying sustainable solutions for food production, farm level holistic and dynamic tools are needed (Prost et al., 2023) to capture the complexity, synergies, trade-offs and feedback mechanisms within agroecosystems.

Life Cycle Assessment (LCA) is a common methodology to assess environmental impacts of food production. Typically, the emissions of environmentally relevant substances to different environmental compartments (air, soil, water) occurring on-farm during crop and livestock production are quantified, as well as environmental impacts related to production and transport of inputs (e.g. fertilizer, chemicals, machinery, feed). However, LCA has been criticised as not being able to capture the benefits of agroecological systems, such as organic systems and favouring high-input and intensive systems (van der Werf et al., 2020). To calculate agricultural LCAs, specific tools are available with different scope, which often are well suitable to assess conventional agriculture or a single sector, but differ in the extent to which they account for the complexity and interconnectedness of more complex agroecological farms.

While some tools were specifically developed to compile agricultural life cycle inventory (LCI) data and to calculate on-farm emissions (e.g. MEANS-InOut (Auberger et al., 2018)), others allow to additionally assess environmental impacts (e.g. Swiss Agricultural Life Cycle Assessment (SALCA) (Nemecek et al., 2024), including indicators for biodiversity and soil quality). To assess impacts of livestock farms, $SIMS_{DAIRY}$ (Del Prado et al., 2011) or Sustell™ (dsm-firmenich, 2025) can be applied, whilst others including Crop.LCA (Goglio et al., 2018b), focus solely on LCA of crop production. Tools like Agrecalc (2025) and Cool Farm Tool (Hillier et al., 2011) allow the calculation of farm carbon footprints, the latter also assesses water use and biodiversity (Crowther et al., 2024). The online platform HESTIA provides open-source models for calculating emission, gap-filling missing data and impact assessment and allows data sharing in a harmonized way (HESTIA, 2024).

These tools and models are generally well-suited for assessing the environmental impacts of specialized and conventional agricultural systems in Europe, but may not adequately reflect the complex interactions and internal feedbacks of mixed and agroecological systems, where crop and livestock components are interlinked. For example, a change in crop fertilization may influence the availability of livestock feed, which in turn affects the quantity and composition of manure applied to fields and such interdependencies are central to agroecological farm design yet remain largely unaccounted for in existing assessments.

To address this gap, a novel tool called FarmLCA was developed that combines a flexible farm system model with LCA. This Excel tool allows the calculation of “standard” agricultural LCAs, but additionally also allows assessment of a farm as a system, modelling crops and livestock as interconnected dependant units. The tool includes the compilation of agricultural life cycle inventories (LCI), linking background data from ecoinvent (Wernet et al., 2016) or Agribalyse (Colomb et al., 2015), together with emission modelling from fields (including changes in soil organic carbon) and livestock. It also comprises multiple allocation methodologies, calculating environmental impacts though Life Cycle Impact Assessment (LCIA), as well as displaying results using different functional units (e.g. mass, area, livestock cohort, farm enterprise), and contribution analysis as process groups (e.g. tillage, fertilization, harvesting, field emissions). Furthermore, allocation of impacts between co-products is improved by allocation of both inputs and emissions to specific products from the same plot, such as pasture used for grazing, silage and hay production.

In the first part of this article, we present the overall structure of the FarmLCA model, implemented emission models, procedures to fill data gaps, conduct plausibility tests and propose indicators to assess nutrient circularity of farms in addition to LCA impact categories. Then, we illustrate the usefulness and limitations of the model by applying it to a typical mixed conventional farm in Scotland, producing arable crops and beef. Two potential future scenarios are modelled for this farm showing the consequences of avoiding both external feed and on-farm produced human edible feeds (Feed-no-Food) as well as an additional optimization of the farm to further reduce mineral fertilizer inputs and increasing yields (circular Feed-no-Food). Finally, a sensitivity analysis is conducted to show the effect of uncertain parameters on the environmental performance of the scenarios.

2. FarmLCA model

2.1. Model structure

The FarmLCA tool is fully programmed in MS Excel and consists of five main components (Fig. 1). First, data on crop and livestock production and on farm management can be specified into a user interface. The tool provides standard data to prevent data gaps as well as plausibility checks to avoid implausible data. Second, a farm system model quantifies the bio-physical flows of nutrients between the crop and livestock system as well as the agricultural products produced on the farm. Third, a set of sub-models quantify emissions from fields, livestock and manure management. Fourth, the life cycle inventory is compiled by collating external inputs and emissions emitted from fields or livestock to the outputs (plant or livestock products) and defining allocation procedures for co-products. Finally, a full cradle-to-farm gate life cycle impact assessment is calculated for all the products produced per farm for a range of impact categories (Fig. 2), and a contribution analysis can be displayed for different functional units, for example per kg, per hectare, or per farm. In addition, indicators for nutrient circularity and food production can be calculated at farm scale. Optionally, data on costs or farm operations and prices of sold products can be indicated, to calculate economic gross-margins (see Weiner et al., 2024). In the following, each step is explained in more detail.

2.2. Data entry, data gap filling and plausibility testing

2.2.1. Plant production

In a first step, the different types of land use of a farm (e.g. different crops in a rotation, permanent crops or grassland) are entered in separate columns. General production parameters, such as country, climate, soil data, field sizes, production system (organic/conventional) as well as the main crop(s) produced need to be specified. A staggered drop-down system is implemented that allows selection of standard life cycle inventory datasets from ecoinvent (Wernet et al., 2016) or Agribalyse (Colomb et al., 2015), which can be specified for each plot or by each crop or forage type, best fitting the respective crop or grassland in terms of production intensity and region. After selecting an inventory for the main crop, standard values per hectare are displayed in each column for all crop management such as tillage, sowing/planting, fertilization, grazing, pesticide usage, irrigation, harvest, yields, off-farm material and energy inputs as well as off-farm transports, waste or use of natural resources. For all these parameters, the inventory values can be replaced with farm-specific values, as available. When primary farm data are not available, locally relevant management books for values such as crop yields should be used as these strongly affect the impacts per kg due to for example, climate and soil characteristics.

As agroecological farmland is often multifunctional, the model allows the entry of two different land uses per land use type (such as the main crop production and a cover crop with for example livestock grazing or mechanical harvesting). Furthermore, for each land use type up to four different products can be specified that result from a field (such as wheat grains, straw and fodder from cover crops). For each plot, the share of crops harvested and sold needs to be indicated, to determine crop residues left on field, as well as crop output and available feed for on-farm use (e.g. by livestock). In addition, if feed or bedding is used on-farm, this must be specified for each plot.

Finally, a potential change in land management in the past 20 years can be specified, which is relevant to soil carbon calculations.

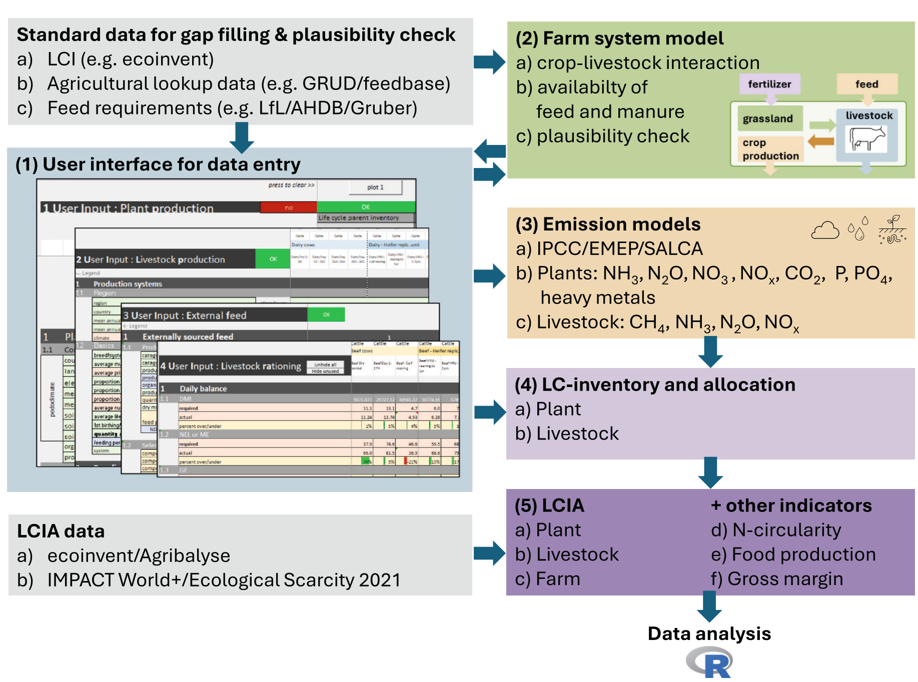

Fig. 1. Structure of the FarmLCA model.

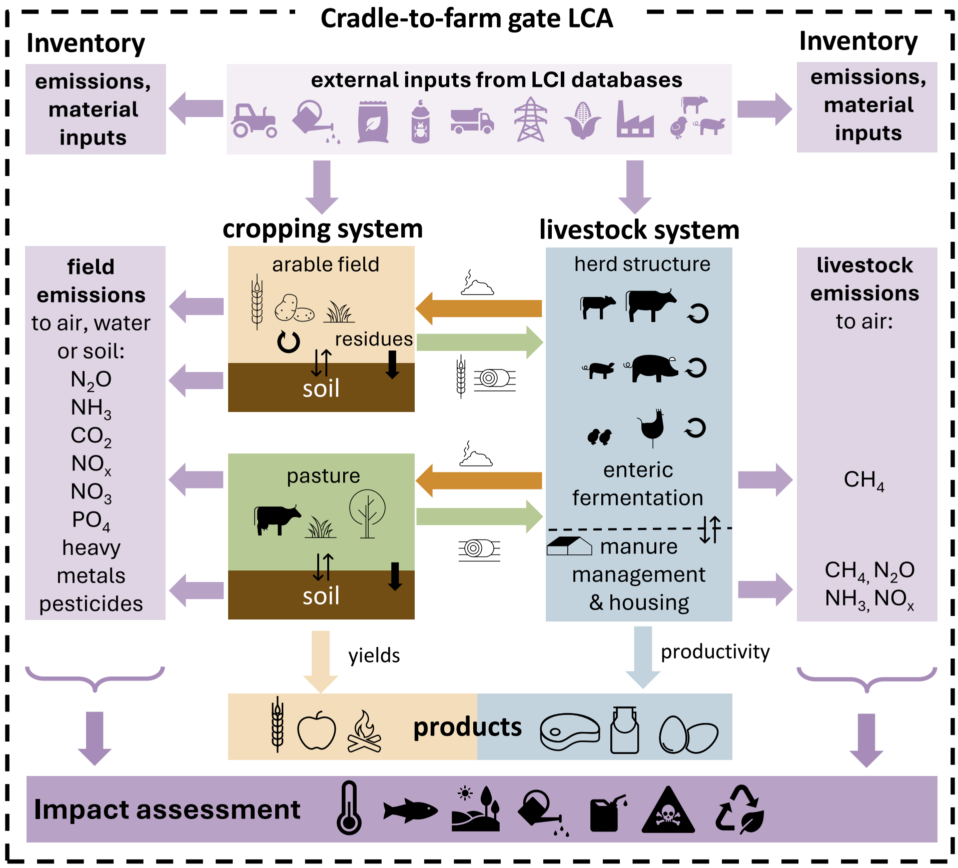

Fig. 2. System boundaries of FarmLCA model, included processes and emission models.

Management aspects, including tillage, inputs and residue management can be specified.

For fertilization, the total amounts of macronutrients (N, P, K) applied per field from all sources, such as organic fertilizer from on-farm livestock as well as imported mineral and bio-based fertilizers and manure are calculated. These values are compared with yield adjusted crop nutrient requirements from management recommendations in GRUD („Grundlagen für die Düngung“, Richner et al., 2017) and ecoinvent (Wernet et al., 2016) and over- or under-fertilization is visualized in colours as part of the plausibility checks. This allows cross-checking of data and correction where necessary.

2.2.2. Livestock production

For farms with livestock production, FarmLCA allows the modelling of a wide range of livestock species including dairy and beef cows, beef finishing, pigs, sheep, horses, alpacas, laying hens and broilers. Each herd or flock is specified and split into different livestock categories to reflect their nutritional requirements (e.g., the lactation phase of dairy cows or the multiple production phases of pigs from piglet to finishing). For each livestock category, the breed type, number of livestock, mortality rate, age of first birth, liveweight, traded livestock, days of feeding, bedding, housing and manure management, as well as produced output (meat liveweight, milk, wool, eggs, etc.) needs to be indicated. Based on this data, the daily feed requirement regarding dry matter, metabolizable and gross energy, crude protein and other parameters are calculated for each livestock category. Equations and reference values are derived per livestock type from the following sources: dairy cows (Gruber et al., 2004); beef and heifers (Lfl, 2024), pigs (AHDB, 2025), sheep (AHDB, 2024), alpaca/horses (IPCC, 2019), laying hens (Leinonen et al., 2012b) and broilers (Leinonen et al., 2012a).

If a farm purchases external concentrate feed, the tool allows to flexibly specify different concentrate feed mixtures. Based on a comprehensive list of feed ingredients compiled from available data from ecoinvent or Agribalyse, the respective inventories can be selected for each component of the concentrate feed mixture. The nutrient composition of the feed mixture is also calculated based on the typical nutrient composition of the different feed ingredients (based on data from Feedbase, 2025).

Finally, for each livestock category, the rationing of each feed type is specified per animal per day. This includes the rationing from on-farm concentrate feed, roughage and grazing, but also from off-farm feed mixtures. The FarmLCA tool thereby calculates the amount of on-farm feed still available (or wasted), as well as a comparison between supplied feed and required feed for each livestock category. This supports in checking the plausibility of data provided by farmers or compiled from statistical data and correcting it to ensure a balanced supply and demand. This is particularly relevant when modelling impacts of potential management changes of farm systems to ensure plausibility. In addition to feeding, the amount and sources of bedding should be indicated. Bedding produced on the farm as well as purchased bedding can be added.

The housing system is specified for each livestock category, as well as the time spent in housing, open yards or grazing. In addition, the type of solid and liquid manure storage system, the amount of manure directly applied, stored or used for biogas as well as the storage duration can be indicated. This is then used to calculate emissions from manure storage and housing as well as to quantify manure availability.

2.3. Farm system model: Crop–grassland–livestock interactions

FarmLCA allows the modelling of interactions of crops, grassland and livestock. For each animal species, the amount and N and P content of liquid and solid manure is calculated based on the actual feed livestock receive and the nutrient retention in livestock, using Tier 2 equations from IPCC (Gavrilova et al., 2019), thus manure nutrient content reacts to diet composition and animal productivity. In addition, the type of housing and the time spent grazing are used to calculate the amounts of manure collected in the housing system based on GRUD (Richner and Sinaj, 2017). The amount and type of manure applied can be indicated for each single field of crops or grassland. Thus, the model can capture changing nutrient availabilities from manure, if the feeding or herd size is changed. A change in the crop land use, on the other hand, affects the availability of feed and bedding for livestock. In both cases, users receive instant feedback on the respective changes. This allows ex-ante assessments of systemic changes in farm management and supports the quality checking of data balancing of supply and demand for fertilizer and feed.

Grazing livestock can be modelled on temporary and permanent grassland, but also on crops or residues (such as winter cereal grazing) or in agroforestry systems, such as between fruit trees. The type of forage, including the legume proportion can be specified as well as the feed intake during grazing on different types of land, which is determined based on estimated total feed intake minus concentrate and conserved feeds. Plausibility tests for energy and protein intake are also conducted, since the feed intake through grazing is often uncertain. With reference to current trends in grazing management, it is possible to indicate the utilisation rate of forage, such that practices like mob grazing or deliberate underutilisation with the aim of increased residues can be modelled. Furthermore, feed quality such as crude protein level can be adapted, allowing for differentiation between for example, young versus mature grass. The nutrients excreted on this land whilst grazing are automatically calculated based on the time spent grazing on specific plots.

2.4. Modelling direct emissions of on-farm activities

Direct emissions from both crop and livestock activities are estimated through the implemented emission models in the FarmLCA tool (Table 1 and Fig. 2). The main GHG emissions related to fertilization (mineral and organic, including pasture deposition), manure storage, housing and enteric fermentation are estimated using the most recent methods from IPCC (2019). Where possible, Tier 2 methods are used to improve accuracy, but Tier 1 (including disaggregated values e.g. for N_2O) are used in case of limited data availability (e.g. unknown site-specific values). Other agricultural emissions are estimated using specific models such as EMEP/EEA (2023) for ammonia or SALCA (Nemecek et al., 2024; Oberholzer et al., 2006) for phosphorus and heavy metals. For pesticides, no specific emission models have been implemented so far, but could be modelled separately with PestLCI (Birkved and Hauschild, 2006) and UseTox (Rosenbaum et al., 2008). Further details are provided in the Supporting Information (SI) section 1.1–1.2.

For **soil organic carbon** (SOC) changes and its potential impact on climate change, no full consensus exists so far on how impacts should be assessed (Joensuu et al., 2021), but recommendations on how to model SOC in agricultural LCAs were made recently (Pelaracci et al., 2025). In FarmLCA, the IPCC (2019) Tier 2 steady state method based upon the Century model (Parton et al., 1988), is implemented and results are reported separately from other GHG emissions, as recommended by the European Commission-Joint Research Center (2010), considering both a 20 and 100 year time frame (see also SI section 1.1.4).

2.5. Life cycle inventory and impact assessment

The FarmLCA tool generates the life cycle inventory (LCI) data for each plot or livestock category by combining the farm-specific input values with default inventory values from ecoinvent and Agribalyse on crop management (e.g. tillage, seeding, fertilizer, pesticides, irrigation) and livestock management (e.g. feed, housing; Fig. 2).

Table 1
Overview on implemented emission models for plant and livestock production.

Emission	Process	Methods
Plant production		
Carbon Dioxide (CO_2), to air	Plant absorption	ecoinvent 3.8 (Wernet et al., 2016)
	Lime	IPCC (2006) Tier 1
	Urea	IPCC (2006) Tier 1
Dinitrogen oxide (N_2O), to air	Field emissions	IPCC (2019) Tier 1 (disaggregated factors)
Ammonia (NH_3), to air	Mineral and organic fertilizers (including pasture deposited manure)	EMEP/EEA (2023) Tier 2, IPCC (2019) Tier 1
Nitrate (NO_3), to groundwater	Leaching: crops/ grassland	SQCB (Faist Emmenegger et al., 2009) IPCC (2019) Tier 2, expanded with drainage factor of % of area drained
to surface water	Leaching: crops/ grassland	
Nitric oxide (NO_x) to air	Field emissions	EMEP/EEA (2023) Tier 1, IPCC (2019) Tier 1
Phosphate (PO_4), to groundwater	Leaching: PO_4	SALCA-P (Nemecek et al., 2024)
to surface water	Runoff: PO_4	SALCA-P (Nemecek et al., 2024)
	Runoff: P	SALCA-P (Nemecek et al., 2024)
Trace metals (Cd, Cu, Cr, Hg, Ni, Pb, Zn) to ground water	Leaching	SALCA-SM (Nemecek et al., 2024)
to surface water	Erosion	SALCA-SM (Nemecek et al., 2024)
to soil	Emissions	SALCA-SM (Nemecek et al., 2024)
Optional: Soil organic carbon (SOC), to air	Tillage land (crops and temporary forages)	IPCC (2019) Tier 2, steady state
	Permanent grassland	IPCC (2019) Tier 2, steady state (Bolinder et al., 2007)
Livestock production		
Methane (CH_4), to air	Cattle, enteric	IPCC (2019) Tier 2
	Sheep or other ruminant, enteric	Belanche et al. (2023), IPCC (2019) Tier 1
	Pig, poultry	Jørgensen et al. (2011), FEON (2023)
	Manure storage	IPCC (2019) Tier 2
Dinitrogen oxide (N_2O), to air	Manure storage/ housing	IPCC (2019) Tier 2
Nitric oxide (NO_x), to air	Manure storage	IPCC (2019) Tier 2
Ammonia (NH_3), to air	Manure storage/ housing	EMEP/EEA (2023)

For fields or animal species producing multiple co-products (such as wheat and straw or milk and meat), different options for impact allocation are implemented. For crops, the default is economic allocation, but the user can alternatively select mass allocation, based on either dry or fresh-matter. For livestock products, economic, biophysical (IDF, 2015 for dairy) or mass allocation can be selected.

Results can finally be displayed for typical functional units, such as per ha, per livestock category, per kg product or for the full farm. In addition, results can also be assessed per 100 g protein, per kcal or 100 g Digestible Indispensable Amino Acid Score (DIAAS), which reflects the protein quality of produced products (McAuliffe et al., 2023b).

For life cycle impact assessment, the most recent version of the FarmLCA tool (v4.1) calculates impacts with both Impact World+ methodology v1.3 (Bulle et al., 2019) and Ecological Scarcity 2021 method (BAFU, 2021). Impacts for on-farm emissions are estimated based on values modelled by the tool (see Section 2.4), whilst for other processes, (for example ploughing, fertilizer or external feed inputs), pre-calculated impacts are imported into the tool as well as the characterization factors for all relevant substances. Therefore, impacts per unit of input are according to the original inventory assumptions including soil organic carbon. The collated impacts are first calculated per field (ha) and livestock category. In a next step, LCIA results are calculated for multiple plant or livestock products, using different functional units and allocation methods (see above).

2.6. Indicators for nitrogen circularity and self-sufficiency

To quantify and compare the degree of circularity and self-sufficiency of agroecological farms, FarmLCA calculates additional indicators for nitrogen. First, the **nitrogen use efficiency** (NUE, Eq. 1) for the whole farm is calculated based on the total N output of the farm in relation to the required N inputs (EU Nitrogen Expert Panel, 2016).

$$NUE = \left(N\_output_{farm} / N\_input_{farm}\right)^{*} 100 \quad (1)$$

With:

NUE: nitrogen use efficiency (%)

$$\text{N-output}_{farm} = \{crops\} + \{straw\} + \{trees/branches\ (net)\} + \{livestock\ (net)\} + \{livestock\ products\ (milk, egg, wool)\} \quad (2)$$

$$\text{N-input}_{farm} = \{mineral\ fertilizers\} + \{biological\ nitrogen\ fixation\} + \{atmospheric\ N\ deposition\} + \{compost\ and\ bio\text{-}based\ fertilizer\} + \{seed\ and\ planting\ material\} + \{manure\ (net)\} + \{irrigation\ water\} + \{feed\ and\ fodder\ (net)\} + \{bedding\ material\} \quad (3)$$

In addition, two indicators on **N-self-sufficiency** (Eq. 4) of plant as well as livestock production were developed, which quantify the share of N inputs needed for plant or livestock production that is produced on-farm. Here, only inputs controllable by the farmer are accounted for, thus atmospheric N deposition and N in irrigation water are not considered as inputs.

$$\text{N-self-sufficiency}_i = \text{N-inputs}_{(on\text{-}farm,i)} / \left(\text{N-inputs}_{(on\text{-}farm,i)} + \text{N-inputs}_{(off\text{-}farm,i)}\right)^{*}100 \quad (4)$$

i: type of agricultural product (plants or livestock products).

$$\text{N-inputs}_{,\ on\text{-}farm,plants} = \{biological\ nitrogen\ fixation\} + \{on\text{-}farm\ produced\ compost\} + \{on\text{-}farm\ produced\ manure\} + \{on\text{-}farm\ produced\ seed\ or\ planting\ material\} \quad (5)$$

$$\text{N-inputs}_{,\ off\text{-}farm,plants} = \{mineral\ fertilizers\} + \{purchased\ bio\text{-}based\ fertilizer/compost\} + \{purchased\ manure\} + \{purchased\ seed\ and\ planting\ material\} \quad (6)$$

$$\text{N-inputs}_{,\ on\text{-}farm,livestock} = \{on\text{-}farm\ produced\ feed\ and\ fodder\} + \{on\text{-}farm\ produced\ bedding\ material\} \quad (7)$$

$$\text{N-inputs}_{,\ off\text{-}farm,livestock} = \{purchased\ feed\ and\ fodder\} + \{purchased\ bedding\ material\} \quad (8)$$

2.7. Indicators for food production

To show the change in food produced on the farm after a management change, the total energy (kcal) and proteins (kg proteins and kg proteins corrected for their quality by DIAAS) can be calculated for all sold human edible outputs (livestock products and crops), enabling multiple products to be compared on the same basis, e.g. calories or protein. For the meat, a conversion from live weight to human edible meat was undertaken based on carcass yield (Coyne et al., 2019; Mosnier et al., 2021) and percent of human edible meat in carcass, including typical losses until retail (Caldeira et al., 2019). Typical losses from farm gate to retail were also considered for crops (Caldeira et al., 2019; Gatto et al., 2023). For both plant and livestock products, typical nutritional composition of foods were taken from Public Health England (2021). For the different products, average DIAAS (for persons older than 3 years) were calculated based on Adhikari et al. (2022), Herreman et al. (2020) and Ertl et al. (2016). A more detailed description of implementation for the case study can be found in SI Table S1–S3.

3. Case study description

3.1. Goal and scope

A cradle-to-farm gate LCA was performed on a typical Scottish mixed beef farm, with the aim to show the environmental consequences of avoiding human edible feed in the cattle ration. The functional unit was 1 kg liveweight produced per herd (finished beef and slaughtered beef cows). Thus, no allocation was performed between the finished beef and the slaughtered cows. In addition, the environmental impacts of the main cereals produced on farm (wheat and oats) were calculated per kg crop, using economic allocation between grain and straw. To allow for a more holistic assessment that combines crop and livestock impacts, results are also presented as impacts per hectare functional unit.

3.2. Baseline

For the baseline, a typical mixed beef farm in Scotland was assumed, with typical data for livestock and plant production derived from the Scottish Farm Management Handbook (FMHB, SAC Consulting, 2023). If data was missing, it was supplemented with data from mixed Scottish beef farms recorded within the MIXED project (Moakes, S. and Oggiano, P., 2025), with default data from ecoinvent, Agribalyse or based on expert knowledge. An overview of input data and sources is provided in the SI Tables S4–S6.

For the livestock herd (180 animals in total), the following livestock categories were considered: beef cows (calving 6 times before being culled), spring-born calves (0–6 months), overwintering suckler beef (6–12 months), finishing beef (male: 12–18 months; female: 12–20 month), as well as replacements units of beef cows. Livestock were assumed to be fed with concentrate feed produced off-farm (97.5 % soybean meal, 2.5 % mineral supplement) and on-farm produced winter barley, grass silage (from temporary and permanent grassland), and direct grazing on temporary and permanent grassland (Fig. 3A). The farm had a total size of 512 ha, including 115 ha permanent grassland and 397 ha under crop rotation. The assumed 6-year crop rotation consisted of wheat-oat-wheat-barley-grass-grass, where the wheat (*Triticum aestivum*), oat (*Avena sativa*) and a proportion of the barley (*Hordeum vulgare*) were sold, while the grass (mainly *Lolium perenne*) and remaining barley were used as feed and the cereal straw used as bedding. The available liquid and solid manures were assumed to be applied on temporary grassland only, while fertilization via direct excretion during grazing was directly allocated to permanent and temporary grassland. In addition, both types of grassland received mineral fertilizer to fulfil crop nutrient requirements. The on-farm produced crops were fully fertilized with mineral fertilizer, while standard inventory data was used for the off-farm produced concentrate feeds. Typical feed waste of 19 % was assumed, similar to assumptions within Agribalyse (Koch and Salou, 2016).

3.3. Feed-no-food scenarios

Two different feed-no-food scenarios were introduced to the baseline farm. In a first scenario "**Feed-no-Food**" (FnF); (see Fig. 3B), no external concentrate feed was imported and the on-farm produced barley was also not fed to the cattle but sold for human consumption. The farmland area, crop rotation and grassland management were assumed to be

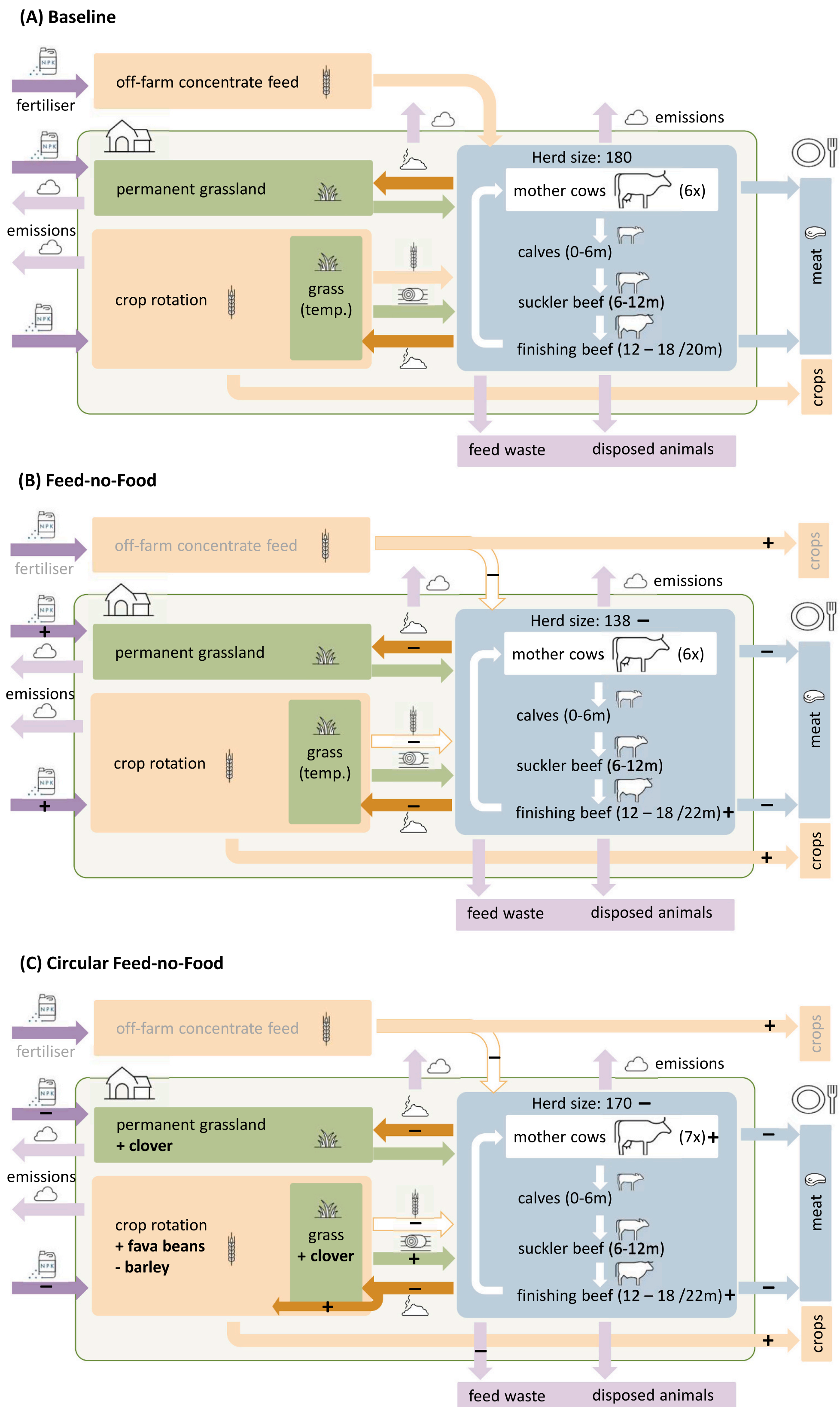

Fig. 3. Farm system model of (A) baseline; (B) feed-no-food scenario; (C) circular feed-no-food scenario. System elements in grey font were not analysed here. Elements marked with plus or minus sign were adapted compared to the baseline (changes in resulting emissions are not illustrated).

unchanged, and no external fodder was bought. It was assumed that the lower overall feed quality and quantity resulted in a two month slower growth of finishing beef (Doyle et al., 2023; FMHB, SAC Consulting, 2023), and therefore a smaller overall herd size (total 138 animals), leading to reduced manure production and meat output.

In a second step, a "**circular Feed-no-Food scenario" (cFnF)** was introduced (Fig. 3C), still assuming the same land area, but including additional management changes for plant and livestock production to optimize productivity and better use synergies within the farm (i.e. increase circularity). For plant production, the crop rotation, permanent grassland and fertilization were adapted. The crop rotation was adapted to wheat-oat-fava beans-wheat-grass clover-grass clover, as legumes including fava bean (Aschi et al., 2017; FAS, 2024) and grass clover leys (Berdeni et al., 2021) reduce dependency on mineral N and have been shown to induce positive soil changes that enhance cereal productivity within a rotation. In doing so, the barley was replaced by fava beans (*Vicia faba* for human consumption) which in combination with the grass clover (e.g. *Lolium perenne* and *Trifolium pratense*), reduced the required amounts of N-fertilizer (mineral and organic), due to N-fixation by legumes (average N-fertilizer use reduction of 45 %). Also, the permanent grassland was improved by inter-sowing grass clover on 25 % of the area which reduced required manure and mineral fertilizer inputs (average N-fertilizer use reduction of 58 %). Hence, more manure was available to be applied to the arable fields, which further reduced mineral fertilizer inputs (see SI Table S5). Adding legumes to temporary grassland has shown to also increase the total biomass yield, thus we assumed an average of 25 % more available biomass (Barneze et al., 2020; Lüscher et al., 2014).

For the livestock production, the productive lifespan of beef cows was increased by one year and cows were culled after 7 calvings (instead of 6 in the baseline), reducing the required replacement units. Feed waste was also assumed to be reduced by 4 % through more careful management (from overall 19 % based on typical Agribalyse values, to 15 % feed wasted), as waste reduction is a typical approach farms take when improving efficiency. Due to the improved grassland management, more feed (25 % yield increase in temporary forage with legume inclusion, (Lüscher et al., 2014)) and better quality (crude protein assumed to be +20 % for temporary and + 25 % for permanent grass with legumes (Feedbase, 2025)), was assumed to be available, supporting higher livestock numbers (total herd size of 170) and meat output on the farm compared to the simple feed-no-food scenario.

To understand, how much the assessment of changes in soil organic carbon (SOC) would affect results of all three scenarios, SOC changes of the crop rotation (including temporary grasslands) and permanent grasslands were modelled separately, using different time horizons (20 and 100 years) as recommended by e.g. Goglio et al. (2015) and Joensuu et al. (2021). First, the SOC of the baseline system was calculated. This data was then used as a starting value to assess how a management change (FnF or circular FnF) could change the carbon stored in soils.

For the indicator on food production, we assumed that under both feed-no-food scenarios, human edible concentrate feed (imported soybeans, on-farm produced wheat, oat, barley, fava beans) would still be produced but directly consumed by humans.

3.4. Life cycle impact assessment (LCIA)

Impacts were assessed with Impact world+ v1.3 midpoint indicators (Bulle et al., 2019). The following impact categories were selected: Climate change, short term (referred to as Climate change); P-Eutrophication (Freshwater eutrophication); N-Eutrophication (Marine eutrophication); Acidification (Terrestrial acidification); Fossil and nuclear energy use (Energy use); Mineral resources use (Material use); Water scarcity; and Land occupation, biodiversity (Land occupation), which accounts for both the area used as well as the potential biodiversity impacts of different types of land use (Bulle et al., 2019). Each scenario was compiled and assessed in a separate FarmLCA Excel file and results were further analysed and processed in R software (R Core Team, 2025).

3.5. Sensitivity analysis

In the FarmLCA tool, assumptions on crop yields and livestock productivity are entered based on primary data, literature or expert opinion, which can have a strong impact on LCA results per kg crop or meat. Therefore, sensitivity analyses were conducted on the circular FnF scenario, to reflect the uncertainty in the assumed changes in productivity of grassland (10 % lower or higher yields) and animal growth (+/− 1 month of required fattening period before slaughter). These values are expert-derived realistic ranges. The area of each crop was assumed to be constant and the herd size that can be sustained with the on-farm feed was adapted based on feed availability estimation within the model.

4. Case study results

4.1. Food production

The baseline system produced the highest meat output (101 t LW y^{-1}), the FnF and circular FnF showed a 24 % and 6 % lower meat production, respectively. In terms of on-farm crop production (fresh matter, FM), 11 % more crops were produced in the FnF scenario compared to the baseline and 3 % less in the circular FnF scenario. The quantity of wheat and oats produced for sale was the same in all scenarios (1060 t FM wheat, 497 t FM oat), while in the FnF scenario the quantity of barley sold was increased by 70 % to 497 t FM. In the circular FnF, the barley was replaced by fava beans (total yield of 238 t FM).

In terms of total edible FM (i.e. assuming typical losses until retail and that the 74 t FM of soybean meal could additionally be available for human consumption since not used as animal feed anymore), the FnF scenario produced 14 % more edible FM while the circular FnF scenario produced the same amounts of edible FM than the baseline (Fig. 4). Regarding the nutritional value, the FnF scenario produced 15 % more calories and 20 % resp. 25 % more proteins and DIAAS adjusted proteins compared to the baseline. The circular FnF scenario produced 3 % less calories than the baseline, but 31 % and 52 % more protein and DIAAS adjusted protein respectively. Across scenarios, the beef delivered 4–7 % of all DIAAS adjusted protein, while legumes contributed to 0–41 % and cereal to 55–93 %. The produced calories resulted from cereals (85–99 %), 0–14 % from legumes and 1 % from beef.

4.2. N-circularity

The nitrogen use efficiency (NUE) of the baseline was 48 %, 54 % for the FnF and 56 % for the circular FnF scenario (Table 2). The nitrogen self-sufficiency of the animal production was 90 % for the baseline and increased to 100 % in both FnF scenarios. For the crops, the nitrogen self-sufficiency was 8 % for the baseline, 6 % for the FnF and increased to 55 % for the circular FnF scenario.

4.3. Environmental impacts

4.3.1. Livestock

The baseline system beef impact for climate change was 21.3 kg CO_2eq. per kg LW. Compared to the baseline, the FnF scenario showed lower impacts per kg LW for climate change and land occupation (−1 % and −11 %), but between 6 and 15 % higher impacts for all other impact categories (Fig. 5). The circular FnF scenario showed 6–38 % lower impacts than the baseline for all impact categories except for terrestrial acidification (+5 %).

The environmental impact was dominated by on-farm forage production (all impact categories), enteric fermentation (climate change), manure management (acidification) and stall infrastructure (material,

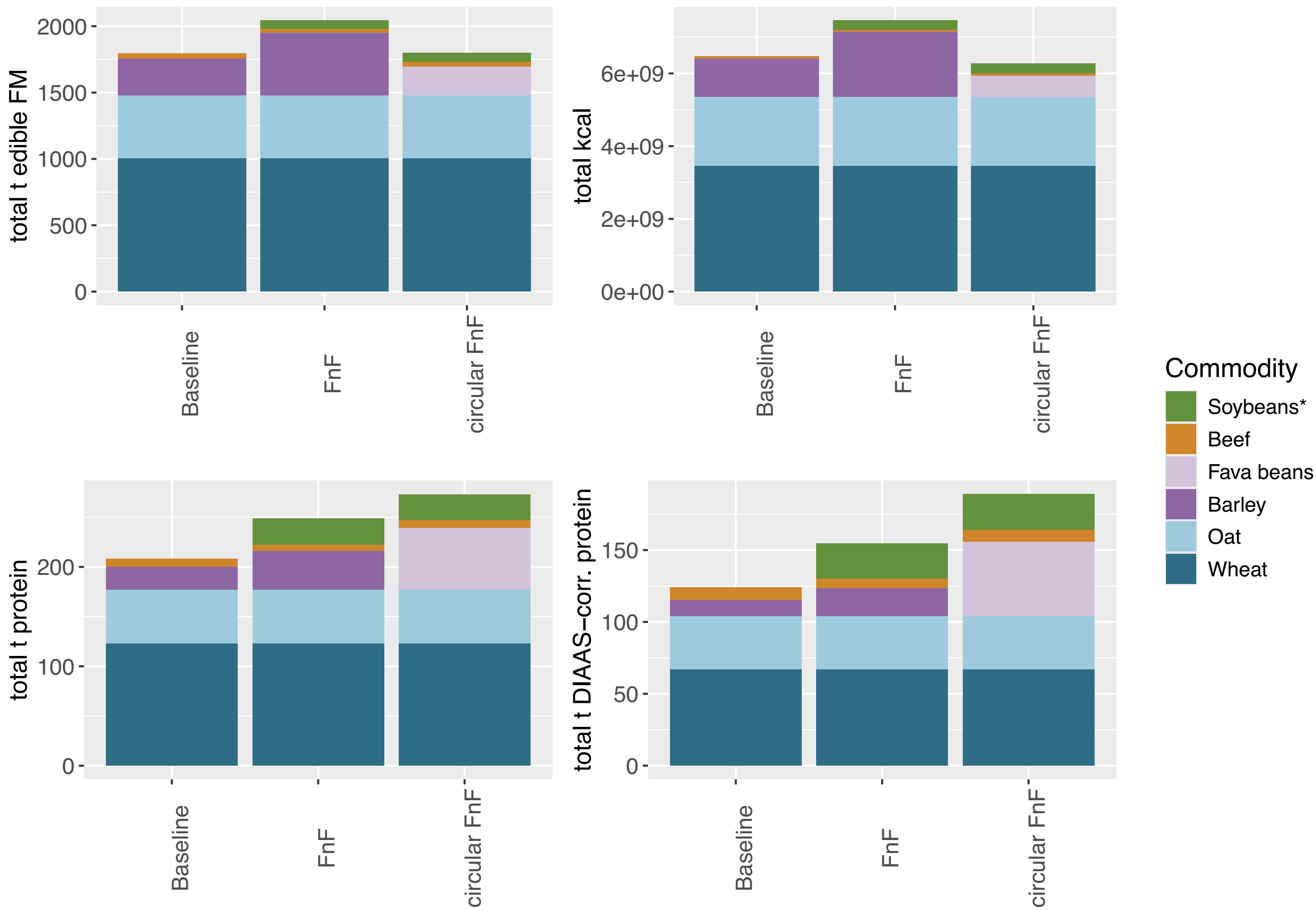

Fig. 4. Total amount of food produced on the farm and on external fields (imported soybeans that were previously used for feed, marked with asterisk) in the three scenarios based on edible fresh matter (FM), calories (kcal), protein and DIAAS corrected protein. For all indicators, typical losses until retail are considered.

Table 2
Nitrogen inputs and outputs (in kg N / farm/ yr), nitrogen use efficiency and nitrogen self-sufficiency (in %) of the three scenarios. Inputs and outputs calculated according to the EU Nitrogen Expert Panel (2016). Inputs and outputs not present in this case study are not displayed.

Parameter	Baseline	FnF	Circular FnF
Inputs			
Mineral fertilizers	68,457	69,508	33,048
Feed and fodder (import)	5145	0	0
Biological nitrogen fixation	0	0	35,538
Atmospheric N deposition	6149	6149	6149
Seed and planting material	1149	1149	1654
Manure (net import)	-5	−2	−3
Outputs			
Crop products, incl. straw	36,392	39,712	40,458
Livestock (net)	2419	1837	2278
Nitrogen use efficiency (NUE)	48 %	54 %	56 %
Nitrogen self-sufficiency livestock production	90 %	100 %	100 %
Nitrogen self-sufficiency crop production	8 %	6 %	55 %

energy and water use). For the baseline, external feed production was relevant for climate change, land occupation and freshwater eutrophication, on-farm concentrate for energy use, land occupation and water scarcity.

4.3.2. *Effect of including soil organic carbon*

When including SOC into the GWP calculation of 1 kg live weight beef, impacts change marginally for all scenarios (Table 3). For the circular FnF scenario, accounting for SOC changes would reduce the climate impact by 1.3 % over a 20-year time horizon and by 0.5 % over a 100-year time frame. For the other scenarios, accounting for SOC would alter the GWP of beef between −0.2 % and + 0.1 %.

4.3.3. *Crops*

The environmental impacts of 1 kg wheat and 1 kg oats remained unchanged between the baseline and the FnF scenario (Fig. 6 and Figs. S1–S2 in SI). For the circular FnF scenario, the impacts of both crops were lower than the baseline for climate change, energy use, material use and water scarcity (between −13 % and − 3 %). For land use, they were the same as the baseline. Higher impacts than the baseline were

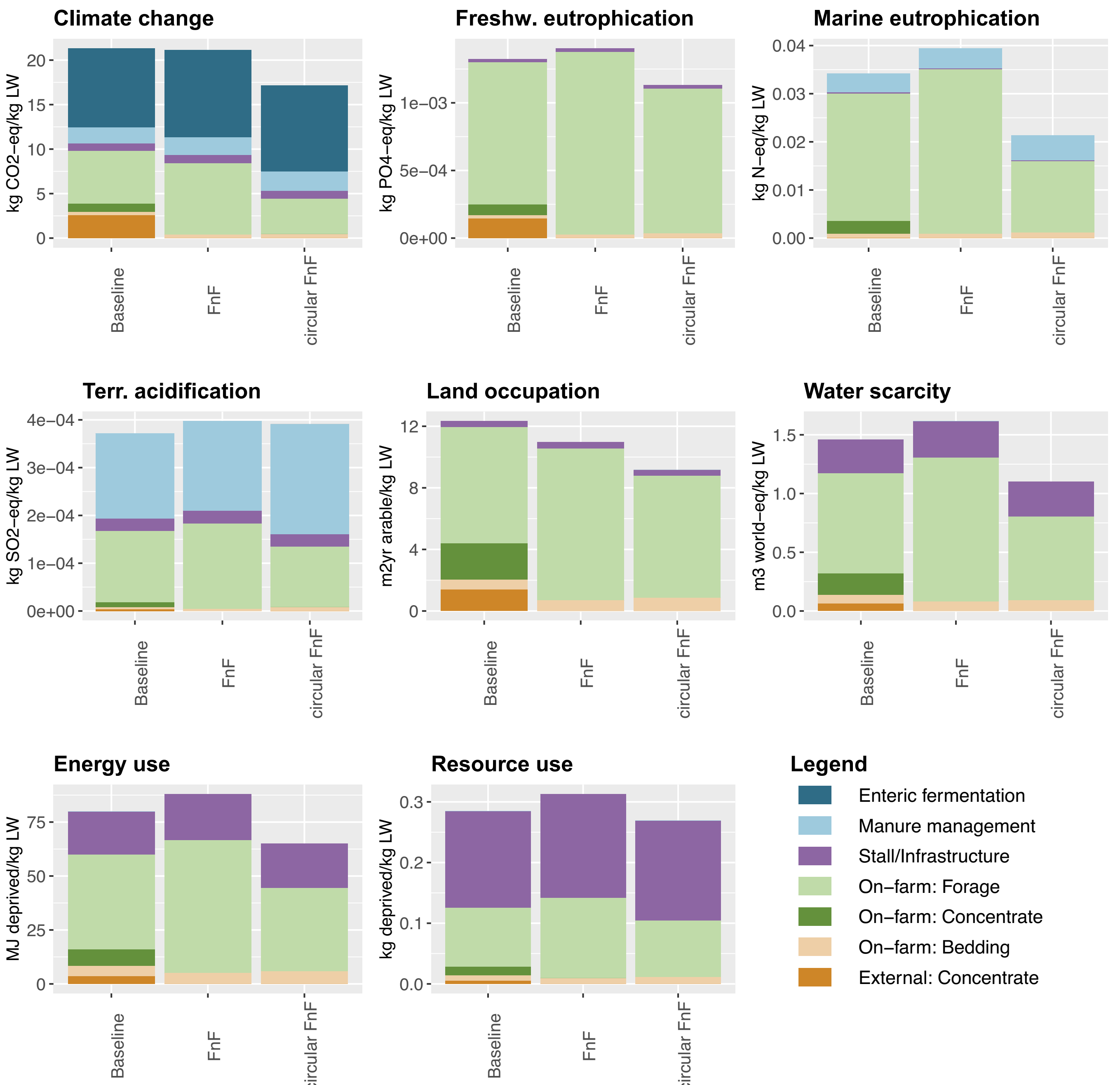

Fig. 5. Environmental impacts per kg of life weight of the three scenarios for the eight selected impact categories.

Table 3
GWP/kg live weight in kg CO2-eq. for the different scenarios, without accounting for SOC and with different accounting methods.

SOC accounting	Baseline	FnF	Circular FnF
Without SOC	21.33	21.14	17.14
Tier 2, 20 years	21.31	21.18	16.91
Tier 2, 100 years	21.32	21.15	17.05

calculated for freshwater eutrophication (+3 and + 7 %) and terrestrial acidification (+27 and + 60 %). For marine eutrophication, impacts per kg wheat were 3 % lower in the circular FnF scenario compared to the baseline but 5 % higher for oat. For both wheat and oats, the main environmental impacts were due to fertilization, emissions in the field, harvesting activities, land use and tillage. Using the per hectare FU, impacts showed a very similar trend to per kg (Figs. S3 and S4 in SI) as the crop yields were assumed to be constant between scenarios.

4.3.4. *Whole farm impacts, assessed per hectare*

The baseline climate change impact of the farm's crop and livestock outputs was 6445 kg CO_2eq. per ha agricultural area. The FnF scenario showed reduced environmental impacts per 1 ha for climate change (−13 %) and land use (−4 %) while the others remained unchanged (Fig. S5 in SI). The circular FnF scenario lowered the impacts for all categories compared to the Baseline. Climate change (−20 %), water scarcity (−17 %), energy use (−16 %) and freshwater eutrophication (−11 %) saw the largest impact reductions, while all others ranged between −2 to −4 %. The same trends can be seen between the scenarios FnF and circular FnF with exception of land use, which increases by 1 %.

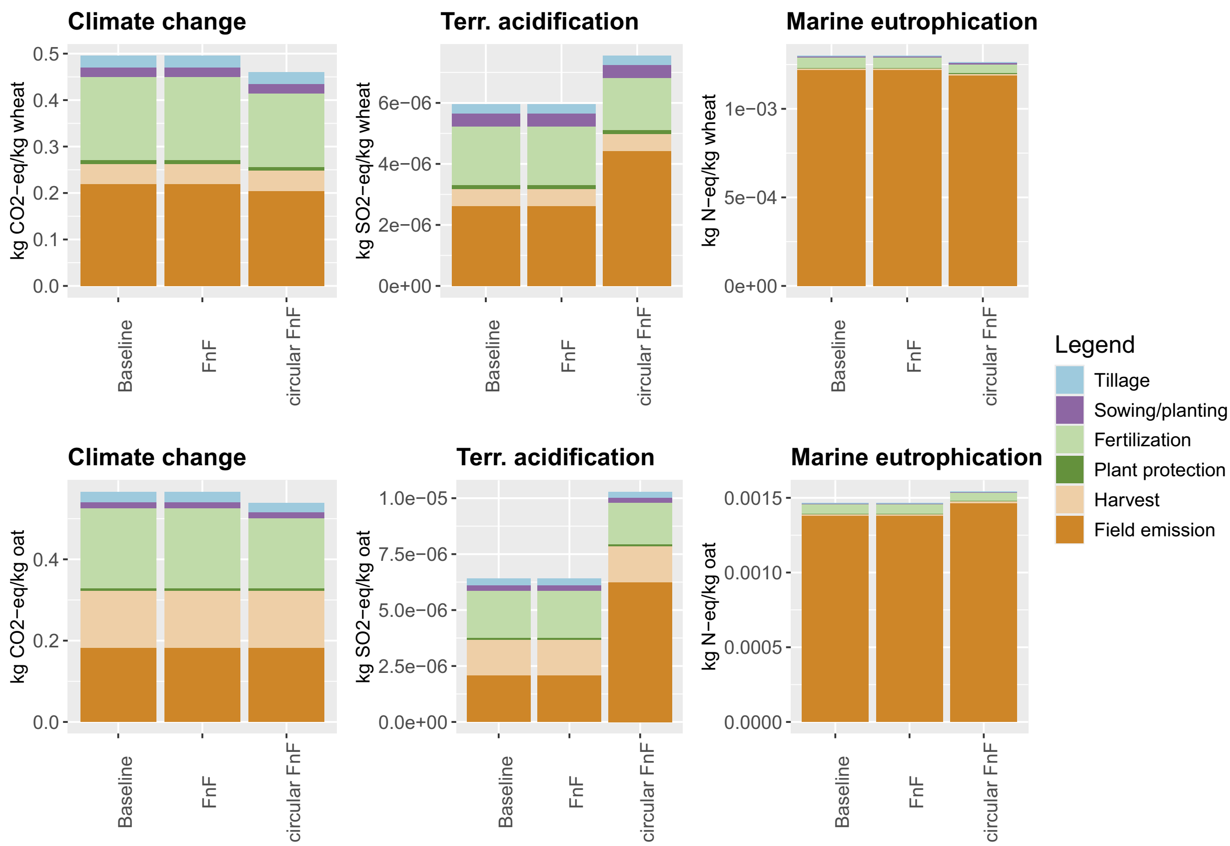

Fig. 6. Environmental impacts per kg of wheat (top row) and oat (lower row) of the three scenarios for three selected impact categories.

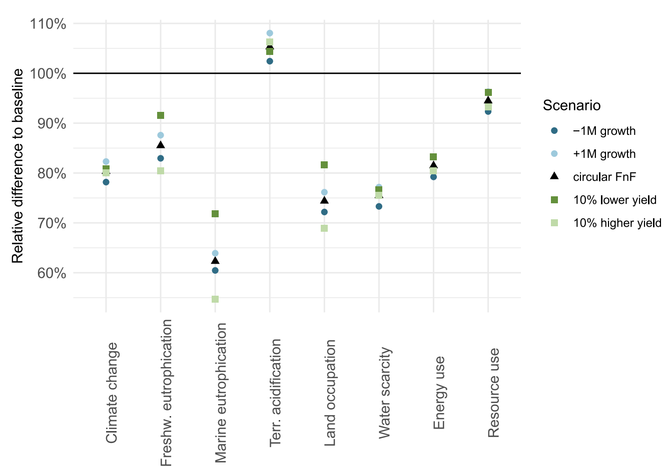

Fig. 7. Sensitivity analysis for changing grassland yields and animal growth in the circular FnF scenario. Relative results compared to the baseline, per kg LW of beef. Black triangles represent the default circular FnF scenario. Dots and squares are the results from sensitivity analyses of the circular FnF scenario.

4.4. Sensitivity analysis

If grassland yields in the circular FnF scenario would be 10 % lower or higher, environmental impacts of 1 kg live weight of beef changed from – 3 % to +3 %. A one month shorter or longer finishing period to reach slaughter weight resulted in slightly larger changes in environmental impacts of beef (−12 % to +15 %). The strongest changes occurred for freshwater and marine eutrophication and land use. Overall, a 10 % change in grassland yields or a 1 month change in animal growth period both did not result in a different ranking of the scenario circular FnF against the baseline (Fig. 7).

5. Discussion

5.1. Trade-offs and synergies of feed-no-food scenarios

5.1.1. FnF scenario

The FarmLCA model highlighted potential trade-offs and synergies involved in transitioning a typical Scottish mixed beef and cereal farm to a fully grass-fed beef system (FnF scenario). While beef production was reduced to three quarters of the baseline level, reallocating crops from livestock feed to human consumption led to a 15 % increase in total calorie output and a 25 % increase in DIAAS-corrected protein compared to the baseline scenario. This is in line with Van Zanten et al. (2018), that a forage exclusive production is preferable from a food system perspective. Elimination of external feed also led to a 100 % N-self-sufficiency for the livestock and improved nitrogen use efficiency. However, the reduced livestock sustained on the grassland led to less manure and therefore increased mineral fertilizer use, reducing N-self-sufficiency for crops. In terms of environmental impacts of beef production, the baseline beef impact for climate change of 21.3 kg CO_2eq. per kg LW was within the range (19.2–23.1 CO_2eq. per kg LW) of values from similar farm assessments (McAuliffe et al., 2023a; Sykes et al., 2019). However, Sykes et al. (2019) highlight the large uncertainties in emission modelling for beef systems which can make result comparisons difficult. For the FnF scenario, an additional two months to reach slaughter weight resulted in higher methane emissions from enteric fermentation, which was also confirmed by previous studies (e.g. Doyle et al., 2023; McGee et al., 2022). However, the overall climate impact per kg live weight remained similar to the baseline due to lower GHG emissions from on- and off-farm concentrate feed production, as also found by Herron et al. (2021). For marine and freshwater eutrophication, terrestrial acidification, water scarcity, energy and material use, impacts of beef per kg live weight were increased due to a longer finishing period. This resulted in higher on-farm forage consumption, increased manure production and extended use of stall/infrastructure—all of which contribute to increased emissions and resource use. Impacts on biodiversity due to land use could be decreased by avoiding imported soybeans in feed from areas vulnerable to potentially high species loss due to agricultural activities. Also, the whole farm impacts for 1 ha were affected by the reduced beef production, where fewer animals and respective methane emissions as well as lower feed import reduced climate change and land use impacts. In contrast to the livestock changes, for the main crops, wheat, oat and barley, no management changes occurred and thus no changes in environmental impacts were observed. The calculated baseline climate change impacts of 0.49 kg and 0.57 CO_2eq. per kg FW for wheat and oat respectively are comparable to inventory values from ecoinvent (Wernet et al., 2016) with ranges between 0.42 and 0.62 kg CO_2eq. per kg FW for wheat and 0.42 and 0.58 kg CO_2eq. per kg FW for oats.

5.1.2. Circular FnF scenario

In the circular FnF scenario, N-fixing plants were introduced both in the permanent grassland as well as in the crop rotation resulting in strongly reduced mineral fertilizer inputs. In the livestock system, increased productive lifespan of cows slightly reduced the number of replacement animals required. Combined with improved forage quality and reduced feed losses, this led to greater efficiency and allowed to sustain a larger herd than in the FnF scenario on the same land. These agroecological innovations allowed for only a slight reduction in beef production compared to the baseline (−6 %), while still feeding cattle on non-human edible forages. The circular FnF scenario produced slightly less calories than the baseline, but 1.5 times more DIAAS adjusted protein. This was due to the change in crop rotation (protein-rich fava beans replacing energy-rich barley) and the soybeans previously used for feed would now be available for human consumption. N-self-sufficiency was strongly increased to 55 % for crops due to the increased use of legumes in the crop rotation and 100 % for livestock, due to omitting off-farm concentrates, whilst the overall nitrogen use efficiency of the farm was increased to 56 %. The environmental impacts of beef production were also lower than in the baseline, due to a reduced contribution from forage production and avoided impacts of on- and off-farm concentrate feed production. The only exception was terrestrial acidification, where the longer rearing period and higher nitrogen content in manures due to legume (clover) consumption, resulted in increased impacts from housing and manure management. Furthermore, the increased N content in forage residues, as well as the tillage to add legumes to the permanent grassland led to slightly higher impacts than the baseline. For the wheat and oat production, replacing mineral fertilizers with manure and N-fixing clover as pre-crops (in case of wheat) resulted in a reduced impact of fertilization, but higher field emissions due to manure application for terrestrial acidification (ammonia) and freshwater eutrophication (nitrogen oxides). Slightly lower dinitrogen monoxide emissions resulted from a reduced mineral fertilizer application. Environmental impacts for 1 ha of whole farm decreased for all categories compared to the Baseline, due to a combination of the results for single products as reported above. Only exception is an impact increase of 1 % for biodiversity, land occupation where increased seed and P—K fertilizer use on legume grasslands affected the whole farm impacts.

Sensitivity analyses showed that the results of the circular FnF scenario are robust to variations in key assumptions. A ± 10 % change in grassland yields or a one-month shift in the rearing period of beef cattle had no effect on the ranking of scenarios across any of the environmental impact categories considered. This indicates that the scenario outcomes are primarily driven by structural changes in the system—such as feed self-sufficiency, nitrogen cycling, and the crop rotation—rather than by marginal changes in productivity assumptions.

Although the crop rotation and fertilization were adapted and C inputs into soils increased in the circular FnF scenario, no strong changes in SOC were estimated. This reflects that only factors modifying carbon inputs with limited carbon accumulation trends (i.e. changes in crop rotation and fertilization) were adapted in this scenario but not soil management (e.g. no-till) or biochar application. This is in line with Pelaracci et al. (2025), reviewing 263 LCA studies, who concluded that in systems without deliberate carbon-building interventions, additional SOC accumulation is generally modest and comparable across scenarios. This supports the use of simplified SOC accounting methods (e.g. IPCC Tier 2) when long-term land use remains unchanged even though these methods still have limitations (Pelaracci et al., 2025). Practices such as diversified rotations or greater residue return can enhance carbon inputs with a global potential of 0.3–1.5 Pg of CO2 eq. per annum (Paustian et al., 2016), but they also stimulate microbial activity and soil respiration. This results in an increased carbon turnover, but only to a small increase in stable, long-term carbon pools (e.g. Lehmann and Kleber, 2015; Paustian et al., 2016), which is usually the focus of LCA studies modelling SOC changes, although other goals might be defined at the onset of a study (ISO, 2006).

5.1.3. Challenges and opportunities for implementing FnF strategies

The results of the circular FnF scenario showed that converting a typical mixed Scottish farm to fully grass-based beef production can result in an overall higher food production, especially in terms of DIAAS adjusted protein, while reducing environmental impacts and the farm's reliance on external inputs such as concentrate feed and mineral fertilizer. However, more trade-offs were observed in the FnF scenario without further optimizing the farm to best use the synergies between crop and livestock production.

To implement such circular FnF scenarios, multiple challenges and opportunities exist for different actors of the food system. First, farmers could reduce their reliance on external feed and fertilizers but would have to implement manyfold changes on their farm related to e.g. crop rotation, grassland and herd management, feed production and waste management, sales channels. Increasing the longevity of female beef cows could be achieved by combined breeding efforts and improved management (Roberts et al., 2015), and could have the advantage of lower replacement costs for farmers (Clasen et al., 2024). While diversifying crop rotations is known to have many benefits (Renard and Tilman, 2019; Weiner et al., 2024; Yang et al., 2024), it can result in lower profitability and higher management complexity and requires access to knowledge, technology and markets (Rodriguez et al., 2021). A grass-based beef production, on the other hand, provides clear economic benefits due to avoided costs of concentrate feed (Doyle et al., 2023; Klopatek et al., 2022). For the processing industry, a sufficient quality of crops is needed to allow producing food at a constant quality standard required by markets. For example, wheat with a too low protein content is currently not used for human feed due to a limited baking quality. In addition, the meat quality can be affected by the feeding strategy, which would affect processers and consumers. Klopatek et al. (2022) found higher meat quality for the concentrate fed beef compared to grass-fed beef, while Doyle et al. (2023) report that the total fatty acid concentration did not differ between feeding strategy, but a nutrient index, accounting for a range of beneficial and harmful macro and micro nutrients including Selenium, was higher in the grass-based system. Finally, to implement FnF scenarios, consumers would need to shift towards more plant-based diets, eating more legumes directly instead of eating beef produced with legume concentrate feed. Although challenging, due to the important role of food in cultures and the strong habits around food consumption, shifting diets may also bring health benefits to individuals and societies (Willett et al., 2019).

5.2. Strength and limitations of FarmLCA

The case study demonstrated the potential of FarmLCA to capture the existing connections between different elements of farms and therefore to show potential synergies or trade-offs of agroecological innovations, which are often non-linear and require holistic, dynamic assessment at the farm scale (Prost et al., 2023). This contrasts with typical LCA studies that often consider production systems (such as crops or livestock) as independent systems. The many direct and indirect impacts related to the circular FnF scenario show the complex nature of adapting farm systems and the importance of using a tool that identifies these interactions to fully understand the consequences, both positive and negative.

The coupled farm system model with an LCA also allows to capture of upstream effects, such as climate effects of imported concentrate feeds or mineral fertilizer production, but also additional environmental impacts such as eutrophication or land use impacts. Thereby, it allows to go beyond other studies that evaluated feed-no-food scenarios, only assessing climate impacts (Doyle et al., 2023; McGee et al., 2022). In addition, FarmLCA also optionally allows the assessment of costs and revenues for the adoption of different agroecological inventions to support informed decision making on the farm or policy design.

With the calculation of additional indicators, such as food production or N-self-sufficiency, it yields valuable information on consequences for the food system of agroecological transition. This gives a more holistic view of the consequences of farm management changes on different environmental targets, economic impacts on farms, food security as well as efficient use of nutrients and dependency of farms on external inputs.

As with all LCA work (Alhashim et al., 2021), FarmLCA is data-intensive and requires substantial user expertise, making it more suitable for research applications than for direct use by farmers or advisors. The implemented gap-filling routines support data entry in data-limited situations and plausibility checks allow to validate uncertain input data and to construct more realistic future scenarios. The tool does not include predictive models for crop or livestock productivity; thus, future scenarios must rely on user-defined assumptions and should be accompanied by sensitivity analyses to ensure robustness. Whilst limitations remain regarding the connection of crops through a rotation as previously discussed (Costa et al., 2020; Goglio et al., 2018a), FarmLCA includes decision support for recommended fertilization that incorporates adjustments, such as reductions in nitrogen following leguminous crops. Through this approach, each crop remains accountable for its emissions, but systemic impacts such as reduced mineral inputs across a rotation due to biological nitrogen fixation are included. However, temporal dynamics in N-cycles are not directly modelled. To assess the impacts of crop rotations in more detail considering links between the different elements in the crop rotation, further steps are required.

Whilst the tool is focussed on foreground activities, another limitation is the use of standard data for external inputs, including for example the impacts of ploughing 1 ha of land or 1 kg of externally sourced feed. This simplification allows for many processes to be included, making the model highly adaptable to different farming systems and practices but can result in loss of detail, e.g. SOC is not modelled for external feed ingredients as we rely on original inventory assumptions. Whilst a shortcoming, most farmers would not be able to identify the regions used to source their compound feed and therefore, practices are difficult to identify and general assumptions taken within original inventory compilation are assumed to be best knowledge, and potential errors can be accommodated for through sensitivity analysis.

The Excel-based implementation facilitates straightforward scenario modifications and instant results, which enhances its suitability for participatory modelling activities. However, it restricts the integration of a broader set of impact assessment methods or more complex models such as required for pesticide emission (Birkved and Hauschild, 2006) or spatially-explicit biodiversity impacts (de Baan et al., 2013). To better capture the impacts of agro-ecological innovations on biodiversity along the supply chains, the available indicators would need to be expanded to better capture impacts of agricultural land management (Zhen et al., 2025). Whilst multi-farm assessments or complex scenario modelling are not possible with single assessment files, the use of multiple files and external processing using R or Excel make this possible, and results could also be incorporated into wider assessments using e.g. agent-based modelling. Currently, there is no built-in functionality for exporting inventory data, which complicates integration with other LCA tools or databases.

5.3. *Applicability of FarmLCA*

The FarmLCA can be applied for various farm types across Europe and using a range of data sources. So far, the implemented models are not adapted to other pedo-climatic regions or production systems, which is a typical constraint of many LCA-based tools (OECD, 2025). However, it can perform ex-ante assessment of potential future changes in farm management (e.g. due to policy changes) and its consequences on the farm as a system (e.g. on feed and manure availability, and potential changes in relying on external inputs). Moakes, S. and Oggiano, P., 2025 applied the tool to evaluate the environmental and economic performance of mixed and agroforestry-based systems compared to conventional agriculture, using a large dataset of *real farms* distributed across Europe collected within the “MIXED” project. The tool has also be applied using *experimental data of on-farm trials* (see e.g. Weiner et al., 2024) to analyse the economic and environmental impacts of introducing grain legumes into rainfed bread wheat rotations in northern Spain. In addition, plot level assessments of crops can be performed, for example based on *data from long-term trials* assessing the environmental and economic costs and benefits of reduced tillage in organic farming (e.g. Grosse et al., 2023). To assess the environmental performance of applying bio-based fertilizers, the FarmLCA was used to model field emissions and inputs used based on *primary LCA data on bio-based fertilizers production* as well as *field trials* conducted to test the agronomic performance of the different fertilizers (Landert et al., in prep.). For livestock, FarmLCA has been applied to assess the impact of increasing productive lifespan of dairy cows in Switzerland (Leiber et al., 2025; Lozano-Jaramillo et al., 2025; Pfeifer et al.), using *statistical data* from herd books both at farm and national scale.

The FarmLCA tool also proves useful for *participatory modelling* with farmers, an approach still under-utilized with LCA studies (Jouini et al., 2019). Thereby, scenarios on how future farm management could look like to fulfil climate targets can be elaborated in a participatory process with farmers and the climate impacts and potential environmental synergies and trade-offs analysed with the FarmLCA tool (Oggiano et al., 2025). Future developments would include improved data entry and automation of manual material allocation including feeding and manures, as well as use of more complex modelling approaches for crop, livestock and emission estimation as well as wider scientific collaboration, subject to LCA inventory licensing rules.

6. Conclusions

FarmLCA allows a better understanding of the implications of agroecological innovation, by considering a farm as an interconnected system, linking livestock with forage and crop production, instead of disconnected production units. This helps to identify potential trade-offs and synergies between food production, nitrogen use efficiency and circularity and environmental impacts. The case study showed that identified trade-offs associated with shifting to fully grass based beef diets can be mitigated with a more circular approach, including agricultural management adaptations such as the use of legumes, increasing longevity, reducing feed waste etc. Such analyses can support the development of sound agroecological win-win strategies and policies that address several dimensions of food production and minimize trade-offs.

CRediT authorship contribution statement

Simon Moakes: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Philipp Oggiano:** Writing – review & editing, Software, Formal analysis, Data curation, Conceptualization. **Jan Landert:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Catherine Pfeifer:** Writing – review & editing, Funding acquisition, Conceptualization. **Laura de Baan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104560.

Data availability

Data will be made available on request.

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