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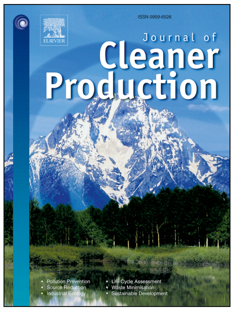

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CRediT author statement

Lennart Kokemohr: Writing - Original Draft; Conceptualization; Methodology; Software; Investigation; Data Curation; Visualization; **Neus Escobar**: Writing - Review & Editing; Methodological advice – Life Cycle Assessment; **Alexandre Mertens**: Writing - Review & Editing, Data and development of Belgium beef system; **Claire Mosnier**: Writing - Review & Editing, Data and development of French Beef system; **Giacomo Pirlo**: Writing - Review & Editing, Data and development of Italian Beef system; **Patrick Veysset**: Writing - Review & Editing, Data and development of French Beef system; **Till Kuhn**: Writing - Review & Editing; Methodological advice; Conceptualization; Supervision

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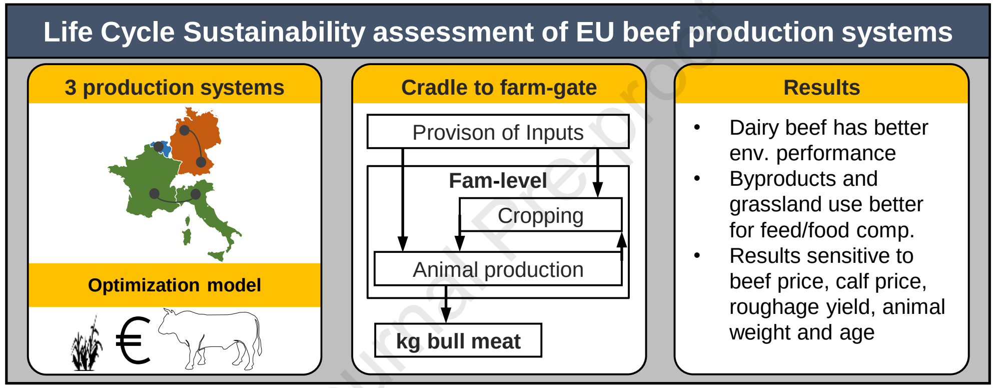

Life Cycle Sustainability assessment of EU beef production systems

3 production systems

Optimization model

€

Cradle to farm-gate

Provison of Inputs

Fam-level

Cropping

Animal production

kg bull meat

Results

- Dairy beef has better env. performance
- Byproducts and grassland use better for feed/food comp.
- Results sensitive to beef price, calf price, roughage yield, animal weight and age

Life Cycle Sustainability Assessment of European beef production systems based on a farm-level optimization model

Abstract

The European Union (EU) is among the largest beef producers in the world. Besides the economic turnover, beef production causes adverse environmental impacts such as climate change. The sector is known for high heterogeneity in production systems, partly explained by different natural and economic conditions. This study assesses the environmental, social, and economic performances of three typical beef production systems in the EU at the farm level. The farm optimization model FarmDyn is used in this study to carry out a Life Cycle Sustainability Assessment (LCSA) from cradle to farm gate; combined with a sensitivity analysis on prices, yields and animal traits. The assessed systems are a Belgian suckler cow farm that fattens its own offspring (BE); a system where calves raised in a French suckler cow farm are fattened on a farm in Italy (FR-IT); and a system where dairy bred calves from one farm are fattened on another farm, both located in Germany (GE-GE). The functional unit is 1 kg of carcass weight from young bulls. In addition to several environmental impact categories, the gross margin is estimated as an economic indicator. The social performance is measured with on-farm workload differentiated by tasks, and human calorie and protein conversion used for production. GE-GE performs better than the other systems in the environmental indicators because emissions are partially allocated towards dairy production. FR-IT shows the highest gross margin due to a higher beef price. BE and FR-IT use less human-consumable feed, as both systems employ grasslands and by-products for animal feeding. The sensitivity analysis identifies the price of beef and calves, the yield of roughage crops, and the weight and age of animals as major factors influencing the results. FarmDyn proves useful to perform LCSA of beef production on a farm-level as it integrates environmental, economic, and social indicators in a consistent framework; while considering price effects and farmers' behaviour in the context of farm heterogeneity and variability in management practices. Results thus provide valuable information to inform not only farmers' decision but the debate of sustainable beef production in the EU.

Keywords: *farm model; life cycle assessment; livestock; optimization model; sensitivity analysis; sustainability*

1. Introduction

Livestock production causes 13% of the global greenhouse gas (GHG) emissions (Herrero et al. 2016), around 33% of nitrogen (N) pollution (Uwizeye et al. 2020) and uses more than 40% of global arable land for feed production (Mottet et al. 2017). Concerns arise on the over-consumption of meat as food, given the low calorie-conversion efficiency of livestock (Wilson et al. 2019). According to Cassidy et al. (2013), an additional four billion people could be fed if all arable land were used to directly grow food instead of fodder or biofuels. However, livestock production contributes to the fight against hunger through the conversion of non-edible feedstuff into food for human consumption (Smith et al. 2013). Furthermore, the livestock sector contributes to the economy with a global production value of 1.2 trillion US$ in 2018 (FAO 2020). Despite the disadvantages of livestock production, the global consumption of livestock products has been rising (FAO 2020) and plays a crucial role in reaching the United Nations' Sustainable Development Goals (Mehrabi et al. 2020).

A large share of the global livestock production is concentrated in the European Union (EU), e.g., 20% in 2018 (FAO 2020). In 2017, the EU-28 agricultural sector generated 10% of the region's total GHG emissions with a production value of 170 billion €, with around 4 million people employed in livestock farms (Peyraud and MacLeod 2020). Within the EU, cattle constitute the largest share of the livestock population at around 50% of the total livestock units, with France, Germany and Italy having the biggest herds (Cook 2020). Beef slaughtered in EU slaughterhouses amounts up to 6.8 million tonnes carcass weight while the largest share is estimated for bulls[1] (34%), followed by cows (30%) and heifers (16%) (EUROSTAT 2021). Bull meat production systems in the EU are characterized by a high degree of heterogeneity. Systems differ by origin and breed of the animals, age and weight at slaughtering as well as the kind and origin of feed used (Hocquette et al. 2018). The highest stocking density of fattening farms can be found in the Benelux states and Northern-Italy (Ihle et al. 2017).

A common methodology to examine the environmental sustainability of agri-food products is Life Cycle Assessment (LCA) (Nguyen et al. 2010). The LCA framework can be extended to cover the economic and social dimensions, i.e., through Life Cycle Costing (LCC) and social LCA (SLCA). LCC is often applied to estimate costs and profits (Florindo et al. 2017), while SLCA aims to assess

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[1] Non-castrated male bovine animals aged 1 year or more

impacts of production on the workforce, the local community, consumers, value chain actors, and society (Achten et al. 2020). Life Cycle Sustainability Assessment (LCSA) provides an integrated methodological framework based on the three-pillar concept of sustainability first mentioned in the Brundtland report that combines LCA, LCC and SLCA (Zamagni 2012).

Several studies estimate environmental impacts of beef production in the EU, highlighting the role of emissions from enteric fermentation, fodder production and manure management (e.g. Angerer et al. 2021). Kamilaris et al. (2020) assessed the economic profitability of different beef production scenarios alongside their environmental sustainability. Bragaglio et al. (2018) added the protein conversion efficiency to account for the societal concern of feed vs. food competition in their LCA of beef production in Italy. Yet, there are no examples of a LCSA application to European beef production systems.

LCAs are generally conducted in a static setting, which does not consider the adaption of farmers to changing conditions and their potential consequences (Lan and Yao 2019). In contrast, mathematical modelling is a tool that captures decision-making, inter alia, in food production systems (Djekic et al. 2018). For instance, farm models, like the FarmDyn model, focus on a farm-scale analysis and are frequently used for assessing environmental impacts (Britz et al. 2021). Their scope at the farm-level as the key decision-making unit allows capturing economic, environmental, and social impacts of management scenarios and policies (Reidsma et al. 2018). In the LCA context, optimization models can provide insights on changes of the environmental performance of agricultural systems due to farmers' adaptation to changing conditions such as price or yield changes (Veysset et al., 2010). By definition, bio-economic models capture not only biophysical but also economic flows within and between farms and, therefore, are well suited to add the economic dimension to LCA (Crosson et al., 2011). The advantages of optimization models can also be utilized in large-scale sensitivity analysis (Pahmeyer et al. 2020). When carrying out LCA, methodological choices and input data lead to uncertainty that affects the reliability of the results and is commonly assessed by means of sensitivity and uncertainty analyses (Escobar et al. 2014). However, the potential of bio-economic farm models to carry out both LCSA and LCA remains underexplored.

The goal of this study is to assess the environmental, economic, and social performance of three beef production systems in the EU within a LCSA framework. The FarmDyn model is applied to assess sustainability trade-offs and benefits, while considering variability in prices, yields and animal performance, as well as farmers' behaviour in the different geographical contexts. The ultimate goal is to identify potential levers to increase the sustainability of typical EU beef production systems on a farm-level, informing cleaner production strategies for farmers and policy initiatives towards more sustainable beef production in the EU.

2. Materials and Methods

The LCSA is carried out according to the ISO standards 14040/44:2006 (ISO, 2006a, ISO, 2006b), which include the following steps: goal and scope definition, life cycle inventory (LCI) analysis and life cycle impact assessment (LCIA).

2.1 Goal and scope definition

The goal of this study is to compare the social, economic and environmental performance of three typical beef production systems in the EU, as observed in major producing countries, namely France, Germany, Italy and Belgium. The systems are defined from cradle to farm gate based on data from one year (2017), covering several representative farms that were selected from the Agri benchmark network (Chibanda et al. 2020), the International Farm Comparison Network (Hemme et al. 2000) and the SustainBeef project (Mosnier et al. 2021). They were chosen for being representative of dominant production systems in the EU. Impacts are calculated for each production system and each farm within a system separately. The functional unit (FU) is one kg carcass weight from slaughtered bulls. Carcasses from bulls constitute a different product compared to other cattle (heifers, bullocks, cull cow), given the different product qualities and prices. Co-products of bull production in the analysed systems are female calves (either sold, used for replacement or sold as heifers, depending on the system) and cull cow beef. In dairy herds, milk is also produced alongside the calves. Economic allocation is applied to allocate the impacts between the co-products. It is the preferred method for allocation because the necessary information on prices and economic flows is readily available in the used modelling framework. Furthermore, the complexity of the systems makes it difficult to consistently define causal relationships of physical flows throughout the different sub-steps (Mackenzie et al. 2017). The allocation is thus based on revenues. The specific prices are taken from the farm data described below. Where no exogenous market price exists, the optimization model is used to provide the shadow prices for the economic allocation (Seidel & Britz 2020).

The three systems are described below. Key characteristics are summarized in table 1.

- The first system represents beef production in Wallonia, Belgium (BE). It consists of one single farm that breeds and fattens (BE-BF) animals of the Belgian Blue breed on a mixed diet of silage, beet pulp, and bought and self-produced concentrates. While suckler cows are grazing during their lifetime, bulls are fattened indoors. Besides beef production, the farm grows rapeseed, cereals and sugar beet as cash crops. 48% of the Belgium suckler cows are managed on farms with comparable herd size in Wallonia (Eurostat 2016).

- The second system (FR-IT) starts with a suckler cattle farm in the Massif Central, France (FR-IT-B). It keeps a herd of suckler cows of the Saler breed that are cross-bred with bulls of the Charolais breed. A portion of the herd is used to breed pure Salers-animals for replacement. The mountainous conditions only allow for permanent grasslands. Therefore, the feed consists of grazing, hay and bought concentrates. 16% of the French suckler cow herd is located in the Auvergne-Rhône-Alpes region (Eurostat 2016). The male offspring is transferred 800 km via lorry to Veneto (Italy) after weaning. The Italian farm (FR-IT-F) fattens the bulls with high daily weight gains (around 1.3 kg/day). The diet consists of maize silage as the main crop grown, beet pulp and concentrates. 31% of the bulls in Italy are managed on farms with comparable herd size in Northeast Italy (Eurostat 2016).
- The third system (GE-GE) starts with a dairy farm in Bavaria, Germany, which has a herd of Simmental Fleckvieh dairy cows (GE-GE-B). The farm produces milk, calves and grows fodder and cash crops, together with grasslands. Cows are fed a diet of maize and grass silage with complementation of concentrates. 16% of the German dairy cows are managed on farms with comparable herd size in Bavaria (Eurostat 2016). The 6-week-old male offspring is transported over 600 km via lorry to the North-West of Germany. The second farm (GE-GE-F) is involved in weaning, fattening and cash crop production. The weaning and fattening are based on a diet of maize silage and bought concentrates. 14% of the bulls in Germany are managed on farms with comparable herd size in North-Rhine-Westphalia (Eurostat 2016).

Table 1 Overview on the systems and farms under analysis

System	**BE**	**FR-IT**		**GE-GE**	
Farm [a]	**BE-BF**	**FR-IT-B**	**FR-IT-F**	**GE-GE-B**	**GE-GE-F**
Country	Belgium	France	Italy	Germany	Germany
Location	Wallonia	Massif Central	Veneto	Bavaria	North Rhine-Westphalia
No. sold male animals per year [b]	56	38	324	48	280
No. of cows	115	79	-	120	-

Breed	Belgian Blue	Charolais & Salers	Charolais & Salers	Simmental	Simmental
Live weight at butchering [c]	640 kg	380-390 kg	700 kg	85 kg	720 kg
Age at selling [d]	20 months	9 months	17 months	1.5 months	18.7 months
Dress percentage	70 %	-	57 %	-	55 %
Arable land	49 ha	-	33 ha	39 ha	70 ha
Grassland	61 ha	96 ha	-	60 ha	-
Other activities generating co-products	cash crop	-	-	dairy, cash crop	cash crop

"a" Indices B and F stand for breeder and fattener. "b" for breeding farms, this is the number of sold male calves, for fattening farms this is the number of butchered bulls. "c" for breeding farms, this is the weight at which the bull calves are transferred to the fattening farm. "d" for breeding farms, this is the age at transfer of bull calves, for fattening farms this is the age at butchering.

The system boundaries include all stages to deliver 1 kg of bull carcass weight from cradle to farm gate. As can be seen in figure 1, this refers to feed production (cultivation, seeding, fertilizing, pesticide application, liming and harvest), breeding (recreational activity in the herd, care taking of cows, heifers and calves), and fattening, as well as transport of animals between farms in FR-IT and GE-GE. Impacts associated with the production of agricultural inputs and services are included within the system boundaries, i.e., machinery production and operation, energy, concentrates, fertilizer and pesticide production.

In BE and the breeding farm in FR-IT, manure is handled as solid manure, whereas on the other farms, it is handled as liquid. In all systems, the amount of manure generated per FU is reused for fertilization and does not constitute a by-product from the system. Impacts from transport of the bulls to the slaughterhouse as well as from processing of the meat are excluded from the system boundaries.

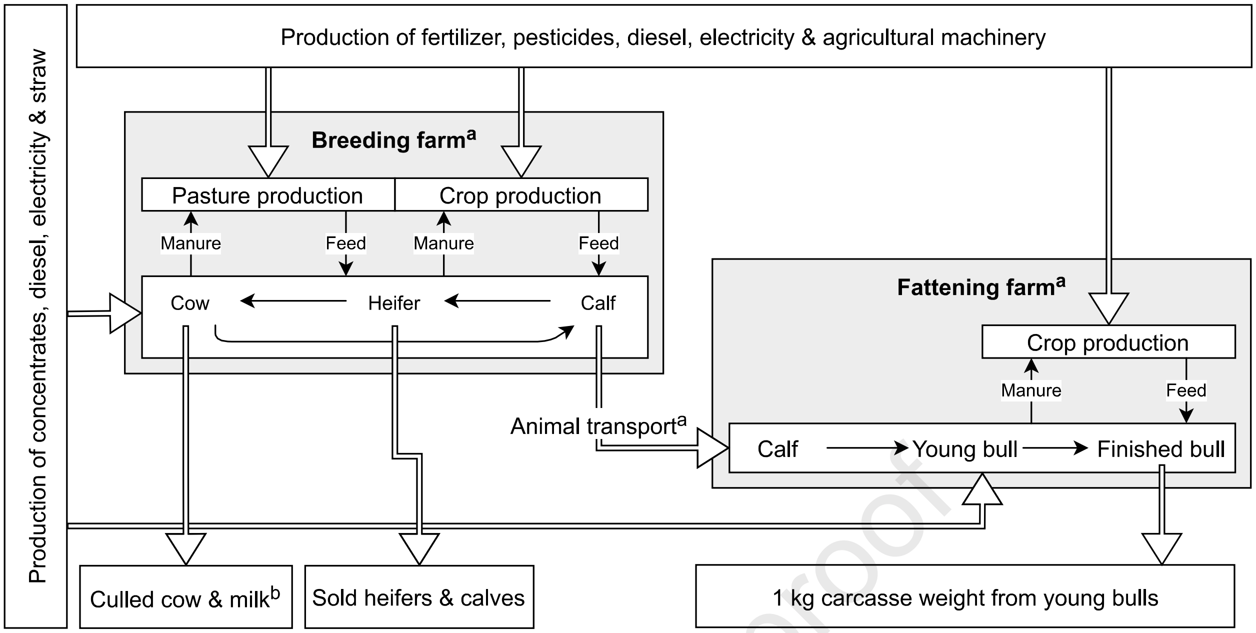

Figure 1: System boundaries of the analysed beef production system. "a" in the Belgium system breeding and fattening are integrated in one farm which spares animal transport. "b" milk is only a co-product on the dairy farm of the German system

2.2 Life cycle inventory

The LCI of the inputs and outputs entering and leaving the system boundaries is generated with the optimization model FarmDyn (Britz et al. 2014). FarmDyn captures economic as well as bio-physical processes. The model simulates farm management options, while the outcome represents the economically optimal distribution of agricultural activities and practices, maximizing the farms profit. FarmDyn was originally developed to enhance sustainability of agricultural systems and was recently expanded to depict cattle farming systems in the European context (Kuhn et al. 2020; Pahmeyer and Britz 2020). Each farm operates as an individual entity, which means that the farm program (including cash crop and dairy production) is optimized subject to boundary conditions such as prices or farm endowments. Farmers' decisions include, inter alia, which animals to keep, how to feed them, which crops to grow and how to fertilize them. As for animal production, FarmDyn captures herd demographics (calving, raising periods, replacement, and selling) per month. The feed requirements are calculated using the methodology of the feed planning tool Zifo2 (LfL 2016), by considering dry matter, fibre, protein, energy and nutrient intake as well as animal performance and lactation periods. The requirements can be met with a variety of bought and self-produced feedstuff. The composition of nutrients in each feed is taken from LfL (2020). The resulting feed use is shown in Table S1 of the Electronic Supplementary Material (ESM).

Crop production options are farm-specific by considering the respective yields, fertilizer needs and land endowments. FarmDyn includes both cash and fodder crops, namely wheat, barley, rapeseed, sugar beet, and maize silage. Grassland is differentiated by different means of harvest (silage, hay, baling, grazing), seasonality, productivity and quality of the harvest.

On-farm emissions from the optimal activities after profit maximization are estimated according to the methods specified in Table 2, including methane (CH_4), ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), particulate matter emission ($PM_{2.5}$), nitrate (NO_3-) and phosphorus (P). Emissions arising through the production of major farm inputs are based on the Ecoinvent database version 3.6 (Wernet et al. 2016). These refer to the provision and transport of externally bought feedstuff, bedding material, fertilizers, pesticides; as well as diesel used in agricultural machinery for field and stable operations including cultivation, harvest, manure management and spreading. The field and stable operations cover provision and operation of machines as well as energy consumption. In FR-IT and GE-GE, impacts on the breeding farms are calculated per kg of live weight of transferred animals, which are subsequently implemented as emission factors into the optimization problem of the fattening farm.

Price data and work endowments are modelled based on the farm data from the Agri benchmark network (Chibanda et al. 2020), the International Farm Comparison Network (Hemme et al. 2000) and the SustainBeef project (Mosnier et al. 2021). Prices not covered in the above-mentioned sources as well as work time requirements are taken from farm planning data (Achilles 2016). The human-consumable share of protein and calorie content of the feedstuff and meat are based on Laisse et al. (2016), Ertl et al. (2016) and Wilkinson (2011).

Table 2. On-farm emissions included in the environmental life cycle inventory and associated estimation methods.

Source / Sub-source	Pollutant	Methodology	Tier[a]
Enteric fermentation	CH_4	IPCC (2019)	2
Manure management	CH_4	IPCC (2019)	2
	NH_3, N_2O, NO_x, N_2	EEA (2016)	2
	Particulate matter	EEA (2013)	2

Pasture	CH_4	IPCC (2019)	2
	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field & Pasture / Manure application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field & Pasture / Fertilizer application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field / Lime application	CO_2	IPCC (2019)	1
Field / Crop residues	N_2O, N_2	IPCC (2019)	1
Field	Particulate matter	EEA (2016)	1
Field & Pasture	NO_3^-	Richner (2014)	
	P	Prasuhn (2006)	
Indirect N_2O	N_2O	IPCC (2019)	1

[a] In IPCC (2019) tiers represent three different levels of methodological complexity with tier 1 being the basic method and tier 3 being the most complex method.

2.3 Life cycle impact assessment

The LCIA employs the ReCiPe methodology to quantify the following environmental impact categories at the midpoint level (hierarchist perspective) (Huijbregts et al. 2017): global warming potential (GWP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine water eutrophication potential (MEP), particulate matter formation potential (PMFP) and fossil fuel depletion potential (FDP). These have been identified as the most relevant categories for the based on a comprehensive literature review of LCAs on beef production by de Vries et al. (2015).

The economic performance is measured with the contribution margin (CM) per kg of carcass weight. The CM is the revenues from a product deducted by variable costs to produce such product. This includes revenues from sold beef, costs of buying concentrates, costs of producing roughages, feed costs for rearing, operation and maintenance of machinery, costs of buying animals, variable stable costs and other variable costs. Roughage production costs are measured based on the shadow prices given by the model (Seidel & Britz 2020).

As for the social performance, working time (WT) on farm per FU is considered, differentiated by type of work, i.e., feeding and taking care of the herd, work for calving, field work, stable maintenance, fertilization and management and office work. Further social indicators considered are the human-consumable calories (HCC) and protein (HCP) used to produce one kg carcass weight. The indicators are included to represent the contribution of beef production to human nutrition as this has been an ongoing societal debate (Mosnier et al. 2021).

2.4 Sensitivity analysis

FarmDyn allows performing a global all-at-once sensitivity analysis to examine the influence of parametric uncertainty on the LCA results. The following parameters involved in the economic optimization as well as allocation are varied: the beef price, the price of calves and weaned calves, the milk price, and the price of concentrates. Additionally, the spatial and biological variability in the systems is considered through variations in the yield of major roughage crops (grass and maize) and animal parameters such as the weight and age at butchering, and the weight of weaned calves (Table S2 in ESM). Using Latin Hypercube Sampling, a sample of 1,000 draws with simultaneously changed levels of the aforementioned parameters is created, covering the full range of possible factor level permutations. Because the distributions of the varied parameters are unknown, uniform distributions without correlations are assumed. In FR-IT and GE-GE, the spatial and temporal separation of the farms are considered by using separate sets of 1,000 draws on each farm for crop yields and concentrate prices, respectively. The remaining parameters are similar on the farms in the systems. For each draw, the management decisions on each farm are optimized considering the changed parameters. The results of each optimized farm are combined in a single data frame for each system and are then rescaled to have a mean of zero and a standard deviation of one. This *standardization* allows the comparison of measurements that have different units. The data frame is analysed through a regression analysis via ordinary least squares. The resulting regression models are considered as meta-models and indicate the relative influence of the parameters on the results.

3. Results

3.1 Sustainability assessment

GE-GE shows the lowest values across all environmental impact categories, followed by FR-IT and BE (Figure 2). BE has a GWP of 32.3 kg CO_2eq. per FU, compared to 27.7 kg in FR-IT and 12.0 kg in GE-GE. In the latter, impacts from the breeding stage are partially allocated to the co-product milk. FR-IT performs better than BE due to the shorter lifespan of the animals. Enteric fermentation constitutes the largest source of GWP across systems (46.5% - 62.4 %). Second largest GHG emission sources are input production in GE-GE and FR-IT, and on-field emissions in BE, all accounting for >20% of the GWP, respectively. This is due to the larger share of self-produced feeds in BE. In FR-IT and GE-GE imported concentrates add emissions (included in upstream input production).

The FEP sums up to 6.78 g P eq. per FU in BE, 5.67 g in FR-IT and 1.33 g in GE-GE. The greatest contribution to FEP in BE is input production, specifically imported concentrates, with a share of 55.3%. In FR-IT, emissions from pastures (76.5%) dominate because of more grazing on the breeding farm. In GE-GE, on-field emissions account for the largest share of FEP (62.4 %) as maize silage is grown, which is prone to nutrient loss.

MEP is related to N leaching from fields and pasture, and NH_3 emissions from the concentrate production and manure management. Total emissions of MEP sum up to 48.6 g N eq. per FU in BE, 33.3 g in FR-IT and 26.3 g in GE-GE. In BE, crop production for self-produced feed accounts for the largest share of the impact (58.7%). In FR-IT and GE-GE, the largest share is associated with input production (>37%), specifically imported concentrates.

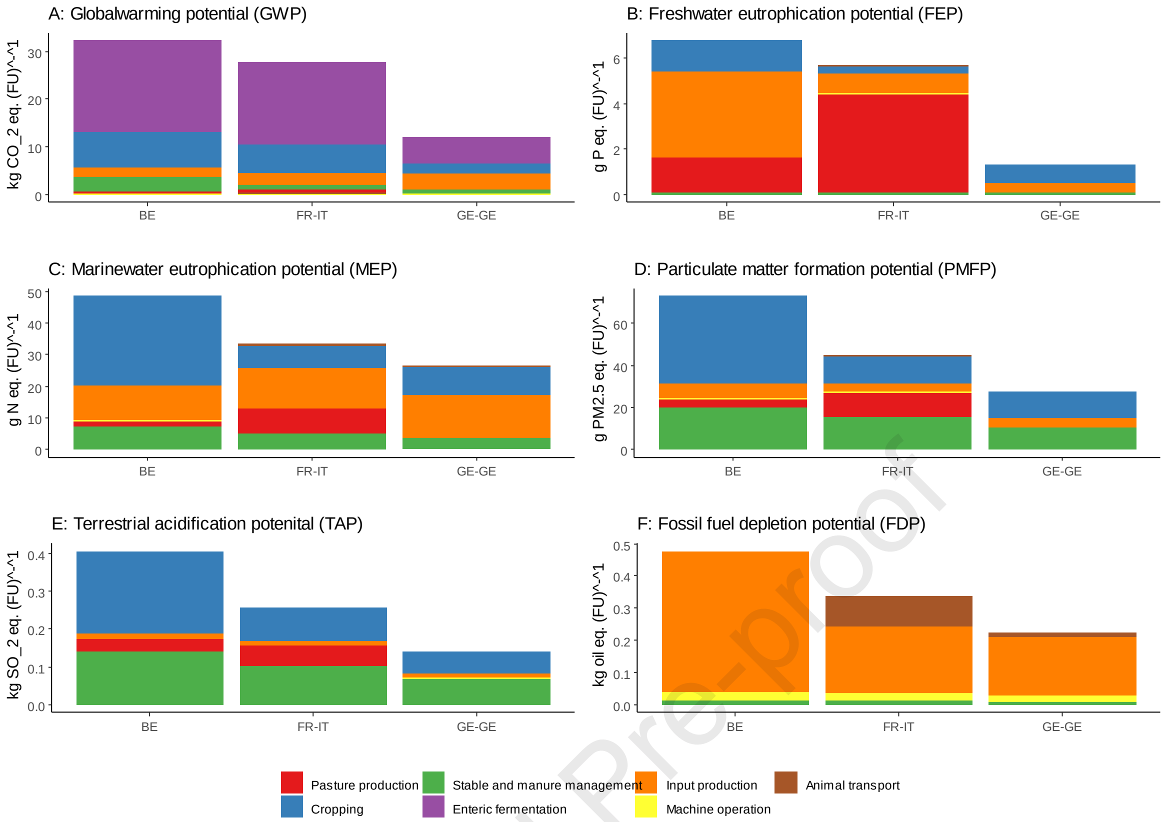

Figure 2 Environmental impacts of the beef production systems per kg of bull carcass. BE indicates the Belgium system, FR-IT the French-Italian system and GE-GE the German system. FU stands for 1 kg carcass weight from slaughtered young bulls

The PMFP is estimated at 72.9 g in BE, 45.1 g in FR-IT and 27.3 g PM eq. per FU in GE-GE. The TAP sums up to 0.40 kg in BE, 0.26 kg in FR-IT and 0.14 kg SO_2 eq. per FU in GE-GE. Both PMFP and TAP are mainly caused by NH_3 emissions. Crop production and manure management are the prevailing emission sources in all systems. The allocation to the co-product milk leads to a better performance of GE-GE. FR-IT performs better than BE due to the shorter lifespan of the animals. The contribution of pastures to the PMFP and TAP in FR-IT is associated with the grazing in the breeding farm.

As for FDP, BE consumes 0.48 kg oil eq. per FU, followed by FR-IT (0.34) and GE-GE (0.23). Provision of inputs accounts for the largest share across systems. The transport of live animals in FR-IT contributes 28.1% to overall FDP compared to 7.11% in GE-GE because of a longer transport distance and higher weight of the transferred animals in FR-IT.

3.2 Economic and social indicators

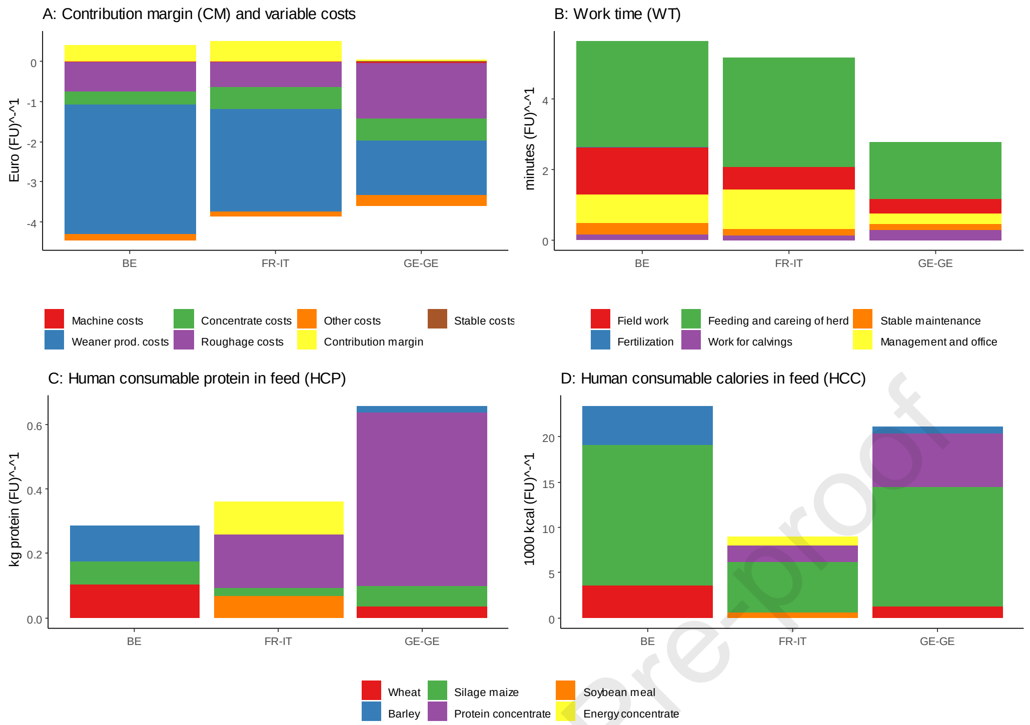

Figure 3 Economic and social indicators assessed with FarmDyn for the three systems. BE indicates the Belgium system, FR-IT represents the French-Italian system and GE-GE the German system. FU stands for 1 kg carcass weight from slaughtered young bulls

The CM per FU is estimated at 0.39 € in BE, 0.50 € in FR-IT and 0.03 € in GE-GE. In BE and FR-IT, weanling production with suckler cows leads to the largest cost share with 71.6% and 66.0%, respectively. In GE-GE, calves are bought at a young age from dual-purpose dairy breeds resulting in lower costs (38.1%). In GE-GE, roughage production accounts for the largest share of costs with 38.3%. Roughages are produced on arable land that bares opportunity costs because of the competition with cash crops. Feed concentrate costs are higher in systems with intensive fattening (FR-IT and GE-GE) because of the higher nutrient need for the higher weight gain.

As for the social performance, BE entails the highest workload with 5.63 minutes per FU, followed by FR-IT (5.17) and GE-GE (2.79). In GE-GE, less time is spent on calf production compared to BE and FR-IT because of the allocation towards milk production. The routine of sustaining the herd including feeding constitutes the largest share of workload, followed by field and management work. In BE, the WT is longer because cereals for feeding are produced on-farm. FR-IT entails additional workload compared to BE and GE-GE because there are no shared efforts with other farming branches, like management work.

All systems are net protein- and energy-consumers, meaning that more human-consumable protein and energy are fed than produced. In BE, 0.29 kg human-consumable protein are fed per FU, followed by FR-IT with 0.36 and GE-GE with 0.66. BE and FR-IT benefit from the high intake of grass, which offers a source of protein non-edible by humans. GE-GE has the highest HCP. Here, bulls receive maize as roughage. Since maize is rich in energy, diets must be balanced by adding protein in the form of concentrates which have a high share of human consumable protein.

FR-IT has the lowest HCC at 8,900 human-consumable kcal in the feed per FU, followed by GE-GE at 21,110 and BE at 23,300. The age of the animals determines the comparative result because the energy required for maintaining their metabolism adds up over the lifetime of the animals. In addition, the feeding of concentrates as energy supplement and the larger share of maize silage in the ration further reduce the efficiency in BE and GE-GE. In FR-IT, beet-pulps (considered as non-consumable by humans) are used to a larger extent, increasing the efficiency.

3.3 Sensitivity analysis

The regression output of all meta-models including R^2, adjusted R^2, Residual Std. Error and F-Statistic is shown in the ESM table S3-S5. This sub-section focuses on GWP, CM, and WT, as representation of the environmental, economic, and social dimension. The beta coefficients of the regression models for GWP, CM and WT and the 95% confidence interval are shown in figure 4.

The beef price is among the factors with the greatest influence on the indicators. In all systems, a higher beef price leads to a higher CM as this implies higher revenues. In BE, a higher beef price leads to a higher GWP and WT because more emissions and work time are credited to beef production in the allocation. In FR-IT, the beef price has little influence on the GWP and WT as the fattening is limited by the endowment of stables and hence the herd size is constant with increasing prices. Furthermore, it is a specialized fattening farm and no allocation is applied.

Variation in the animal weight impacts the performance of all systems. A share of the costs and work tasks are constant per animal. When these are related to a higher weight per animal it results in higher CM and lower WT per FU. A higher share of concentrates in the animals' ration is needed to sustain the higher weight gain, causing additional emissions that increase GWP, e.g., in GE-GE. However, the efficiency gain can outweigh these emissions, overall reducing GWP per FU, e.g., in BE. With a higher weight, the revenues of animals increase. A higher revenue for bull calves leads to higher emissions and time associated with the bull-calf production during the breeding stage due to allocation. The higher price for the heavier calves bares higher costs on the fattening farm and causes a lower CM. A higher price of calves and weaners can also lead to less bulls fattened due to higher costs on the fattening farm, e.g. in GE-GE. Less bulls fattened implies that costs and labour are distributed over less output, which decreases CM and increases WT per FU. Furthermore, the self-produced roughages can be utilized better, which reduces GWP.

With a higher concentrate price, concentrates are used in smaller amounts, hence reducing GWP. At the same time, the higher prices translate into higher feed costs, which slightly reduces the CM. The smaller amount of concentrates increases the relative share of on-farm produced feed, which increases the WT.

The impact of changes in yield of maize and grassland depends on how the yield is used: If additional yield is used to replace low-emission concentrates, the GWP rises (e.g. in FR-IT), if it is replaced with feedstuff with a high emission load the GWP decreases (e.g. maize yield in BE).

In all cases, increasing yields results in reduced feed costs and increased CM. WT increases with higher amounts of self-produced feed. However, WT savings are also possible, when the land is better utilized or the additional yield is utilized in grazing, which spares feeding time.

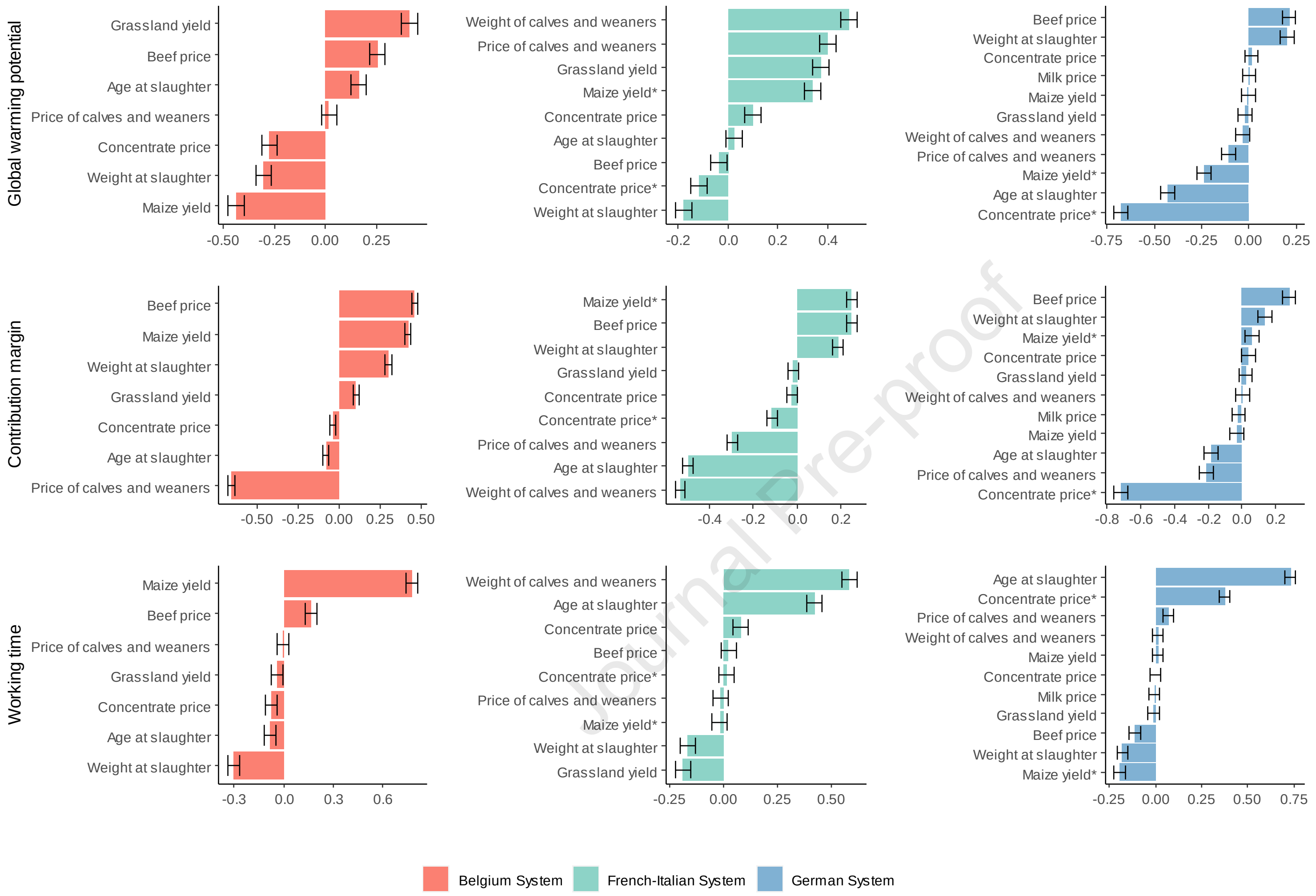

Figure 4 Tornado diagram showing the influence of each parameter in the sensitivity analysis on the results in terms of global warming potential, contribution margin and working time. The standardized coefficients indicate the relative importance of each coefficient in the

related regressions. The unit of measurement is one standard deviation. The error bars indicate the 95% confidence intervals. Factors marked with a '' are specific to fattening farms.*

4. Discussion

The results suggest that the system fattening dairy breed bulls is favourable for the analysed environmental indicators compared to the fattening of beef breed bulls. This is in line with previous findings, for example Nguyen et al. (2010). Carbon sequestration through grassland production is not considered, which could improve the performance of grass-based systems. However, recent research by Hammar et al. (2022) found that a forage-grain beef system resulted in lower GWP compared to an extensive grazing system even with consideration of carbon sequestration. Still, cattle can be important to sustain current carbon pools under grassland (Conant et al. 2017). Huerta et al. (2016) found extensive systems to outperform intensive systems in several environmental impact categories indicating that the results depend on assumptions, used indicators, the location and further characteristics of the analysed system.

A comparison of the results with the literature can be found in the ESM (S6) including information on the FU and the scope of the respective studies. Here the FU is kg carcass weight from slaughtered bulls without the consideration of slaughtering and retail. This inconsistency was chosen as it allows the consideration of different dressing percentages of the different cattle breeds while compromising on the comparability with other studies. However, the contribution of the slaughtering and retail stage on the entire life cycle is reduced compared to the agricultural stage (e.g., Huerta et al. 2016).

A major contribution of this study is that it includes indicators beyond the common environmental impact categories in LCA to assess and compare the sustainability of beef farms under a LCSA approach. The results show that the system with dairy breed bulls (GE-GE) has the lowest CM and the highest HCP pointing at a trade-off between environmental and other sustainability indicators. Kamilaris et al. (2020) found that intensive systems had a lower GWP, too, but their research shows that intensive systems were more profitable. The contrasting results are caused by a higher beef price in FR-IT and BE. A high HCP is also found in the literature (Bragaglio et al. 2018; Wiedemann et al. 2015).

In this study, WT, HCC, and HCP are proposed as social indicators in the LCSA. Due to the novelty of the approach, comparison to the existing literature is limited. The WT is calculated using German farm planning data (Achilles 2016), which does not necessarily cover all particularities of the analysed systems at the same level of detail as for environmental and economic indicators.

However, the data enables consideration of economies of scale of stables, different mechanization levels and plot sizes. The WT indicator would benefit from a detailed representation of the work types and a weighting of tasks by, for example, health hazards, employment potential or personal fulfilment of the workers. In addition, WT spent in upstream processes like the production of inputs should be included to gain insight on affected stakeholders outside the farming community and align with the scope of the LCA. Other indicators of societal concern could be animal welfare or human health (Paris et al. 2022). Implementing these kinds of indicators in FarmDyn is difficult as quantifiable metrics and databases are not readily available.

The results indicate the potential of farm-level models in the application for LCSA as they offer the technical detail to capture farm heterogeneity and present a framework to integrate economic and social indicators. Another advantage is the utilization of the linear optimization to obtain shadow prices where information on market prices is scarce, e.g., the costs of roughage production.

In the context of the sensitivity analysis, the farm-model captures the performance of the system when conditions change. These conditions differ within systems and time, adding uncertainty to the results. The model simulates farmers' decisions on production and management activities in response to changing conditions. The sensitivity analysis points to the prices of beef and male calves as influential parameters for the sustainability performance. Within the framework proposed, higher prices tend to impact the systems through adjustments in the activities as well as in allocation factors, which are estimated based on economic criteria. In view of the lack of agreement on the allocation method (e.g. Wilfart et al. 2021), economic allocation is preferred here over physical allocation, because the two major co-products obtained (meat and milk) have two very distinct markets with stable demand for both, while prices are highly variable. FarmDyn captures country-specific, detailed prices and economic flows, hence offering advantages to carry out consistent economic allocation, relative to conventional LCA approaches. Furthermore, physical allocation is not established for suckler cows because their milk is only used for weaning and yields are unknown (Kyttä et al. 2022).

Finally, the study contributes to the debate on meat production and consumption in the EU, considering multiple dimensions of sustainability. Despite declining consumption of beef meat in the EU, production will likely not vanish (Hocquette et al. 2018). Levers to improve the sustainability of existing production systems according to the results could be the efficient usage of feedstuff non-edible by humans, e.g. industry by-products and grasslands and the integration of dairy and beef production (van Selm et al. 2021). Decision-makers should be aware of farm heterogeneity and the possibility of trade-offs between sustainability dimensions. Multi-criteria decision-making (MCDM) tools offer the possibility to combine indicators in a single score and choose options “close to the optimum” using subjective weights (Saeidi et al 2022). However, the goal of this study is to compare the systems' performance and identify tradeoffs and hotspots in each system among sustainability dimensions and not to rank systems. Performing MCDM analysis would arguably come at the cost of losing detail and complexity and can result in misleading conclusions.

5. Conclusion

The model FarmDyn is used to carry out a LCSA of three bull-beef production systems in major producing EU countries including a comprehensive sensitivity analysis. Potential trade-offs between different dimensions of sustainability are identified underlining the need to consider economic and social indicators when comparing the sustainability of beef production. The dairy-based bull fattening system shows better results in environmental indicators while economic profitability, social indicators favoured the systems which utilized grasslands and industry by-products in feeding. FarmDyn enabled the inclusion of price effects in the sensitivity analysis and the economic allocation. Additional indicators would be needed to better represent the social dimension of beef production, although this entails methodological challenges mainly related to data availability. Future research should focus on the application to a larger farm sample to estimate the extent of the observed findings and gain more representative results. The application of MCDM could combine the indicators in a single score and help identifying favourable systems.

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Highlights (max. 85 characters per point total 5 points)

- 3 EU beef production systems are assessed with Life Cycle Sustainability Assessment
- The FarmDyn model allows consideration of price effects and farmers' behaviour
- Dairy-bull fattening shows better results in environmental indicators
- Socioeconomic indicators favoured the use of grasslands and by-products in feeding
- Results are sensitive to prices, yields and the animals' performance

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: