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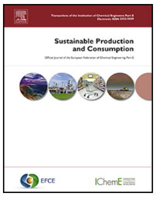

Sustainability assessment of economic, environmental and social impacts, feed-food competition and economic robustness of dairy and beef farming systems in South Western Europe

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ABSTRACT

The objective of this study was to evaluate the sustainability of cattle systems in South Western Europe by combining life cycle sustainability assessment (LCSA) with assessment of feed-food competition and economic robustness. We studied three cattle systems using different proportions of semi-natural pasture, and producing either only beef or milk and beef, i.e. a dairy system with Holstein breed in the lowlands of France with <5% of the total land used being semi-natural pastures (HolSy), a dairy system with Montbeliarde breed in the highlands of France with approximately 25% of the total land used being semi-natural pastures (MonSy), and a pure beef system with Parda de Montana breed in the highlands of Spain with >85% of the total land used being semi-natural pastures (ParSy). The functional unit for LCSA was 1000 kg protein of animal origin and the system boundary was from cradle to farmgate. The cattle production systems were assessed using 27 indicators (LCSA, feed-food competition and robustness). The results indicated that MonSy performed less well for 10 and ParSy for 14 out of the 27 indicators researched when compared to HolSy, the reference case. HolSy was less sensitive to a support payment decrease and had lower social impacts on farmers than the other two systems. MonSy had lower impacts on some environmental indicators, lower life cycle costs, lower social impacts on society, lower human edible feed conversion ratio (i.e. less feed-food competition) for fat and less sensitivity to a meat price decrease than the other two systems. ParSy had lower terrestrial and freshwater ecotoxicity, lower human edible feed conversion ratio and land use ratio for protein, lower social impact for the local community, and a higher internal rate of return than the other systems. ParSy had less sensitivity to feed and energy price increases, and increased rented land and loan interest costs than the other systems. Producing both meat and milk at the same farm increased vulnerability to economic changes. Semi-natural pasture based dairy in highland Europe needs support payments to keep the farm economically afloat in times of economic changes e.g. due to shocks.

1. Introduction

France and Spain are among the countries with the largest cattle numbers in the EU (specifically the largest and the fourth largest; EUROSTAT, 2022). Cattle systems in the EU can be defined based on the output they generate; dairy farming systems produce meat and milk, while suckler beef farming systems produce meat. Some are grassland based with low use of concentrates, whereas others are cropland based with high use of concentrates and forages produced from cropland. Cattle systems are also very variable in terms of their sustainability outcomes based on a number of factors, including the type of land used and land use intensity, the products produced and the amounts and types of inputs used.

While environmental sustainability of animal production has been extensively examined, the joint assessment of environmental, economic and social sustainability has received limited attention. More studies with this broad view of sustainability are required to identify opportunities for improvements while avoiding burden shifting.

The aim of the study was to broadly evaluate the sustainability of dairy and suckler beef production systems in south-western Europe. This was done by conducting a life cycle sustainability assessment

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Abbreviations: DM, dry matter; FPCM, fat protein corrected milk; IRR, internal rate of return; LCC, life cycle costs; LCSA, life cycle sustainability assessment; NPV, net present value; RUsP, relative unsustainability points; SHI, social hotspot index; SRT, social risk time.

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(LCSA), evaluating the environmental, economic and social impacts in different cattle systems, complemented by an analysis of the extent to which these systems lead to feed-food competition by assessing their feed conversion ratios accounting only for human-edible feed material (Mottet et al., 2017). We also investigate the ability of the cattle systems to remain economically viable over time. We study three different cattle systems using different proportions of semi-natural pasture and producing either only beef or milk and beef. The first system is a dairy system with Holstein breed in the lowlands of France with <5% of total land used being semi-natural pastures (HolSy). The second system is a dairy system with Montbeliarde breed in the highlands of France with approximately one fourth of the total land used being semi-natural pastures (MonSy). The third system is a pure beef producing system with Parda de Montana breed in the highlands of Spain mainly using semi-natural pastures (>85% of the total land use, ParSy). This study provides a broad perspective of sustainability, enabling comparisons of strengths and weaknesses of different systems.

2. Literature review

2.1. Background

All cattle production systems have environmental impacts, e.g. through their use of land for feed production and pasture, methane emissions leading to climate change, and nutrient losses leading to eutrophication (Arvidsson Segerkvist et al., 2021, 2020). However, low intensity grazing can help preserve biodiversity in semi-natural pastures formed by traditional farming practices over centuries (Bengtsson et al., 2019). Cropland based cattle systems depend heavily on off-farm inputs such as fertilizers and fossil fuels (Guyomard et al., 2021), and in these systems, feed-food competition is an issue as the human edible plant protein used as feed commonly exceeds the protein in the milk and meat produced (Peyraud, 2017). Further, cropland based cattle systems frequently have inferior animal welfare compared to grassland systems due to no or limited grazing (von Keyserlingk et al., 2017). Dairy production systems provide labour opportunities and contribute to economic activity in rural areas but they can also have negative impacts on the health and safety of workers and the local community (Chen and Holden, 2017). The economic viability of both cropland and grassland based cattle production systems in Europe is decreasing (Paas et al., 2021). Policies to mitigate climate change may put additional financial stress on dairy and beef cattle farms in Europe, as may increased instability of input and output prices.

2.2. Sustainability assessments

A literature review of sustainability studies for beef cattle by Arvidsson Segerkvist et al. (2021) and dairy cattle by Arvidsson Segerkvist et al. (2020) indicated that most papers cover only one or two of the sustainability pillars and the interactions between the three pillars is rarely studied in cattle systems.

Life cycle sustainability assessment (LCSA) is a tool designed for evaluating all three pillars of sustainability (Finkbeiner et al., 2010; Kloepffer, 2008). LCSA has been used to study suckler beef systems (Florindo et al., 2020) and grassland based dairy systems (Chen and Holden, 2018) but no LCSA study to date has analysed and compared dairy and beef cattle systems. LCSA is a useful tool for measuring how efficient systems are, in terms of impacts per product unit. The higher the impacts per unit product, the lower the efficiency of a system. However, as an efficiency measurement tool it fails to capture some important aspects such as the resilience of the farm, i.e. the capacity to cope with and adapt to different types of disturbances or having the capacity to transform (Röös et al., 2021). For example, variations in market conditions which farmers have limited possibilities to affect, may substantially affect farm profitability but an economically robust farming system can handle variability and remain effective. One other aspect is that LCSA only captures life cycle costs (LCC) but the economic sustainability of a farm depends on profitability. In addition, LCSA to date has failed to account for feed-food competition, i.e. accounting for how efficiently crops are used to produce food for humans (Röös et al., 2021; van Hal et al., 2019). Studies show that when this aspect is included in sustainability assessments, ruminants rather than monogastric animals are favoured (van Selm et al., 2022; Karlsson et al., 2020), contrary to studies based on LCA that measures environmental efficiency (Poore and Nemecek, 2018). Hence, when assessing the sustainability of livestock systems a broader range of sustainability aspects beyond those that are traditionally included in LCSA need to be considered.

3. Material and methods

3.1. Scope

3.1.1. System description

In HolSy, 96% of the land used for feed production is cropland and 4% is semi-natural pasture. It is a conventional system located in the lowlands of France in the West Atlantic region - Pays de Loire. In MonSy, 75% of the land used for feed production is cropland and 25% is semi-natural pasture. It is a conventional system located in the highlands of France in Central Mountain region – Auvergne. In ParSy, 12% of the land used for feed production is cropland and 88% is semi-natural pasture. It is a certified organic system located in the highlands of the Spanish Pyrenees. In HolSy, calving takes place all year round while it is seasonal in MonSy and ParSy. In all systems, animals are kept indoors during the cold season, i.e. from November to February and have access to grazing during the warm seasons. In Holsy cows graze on temporary pastures that are part of a cropland rotation. In ParSy, permanent pastures (semi-natural) are used, while MonSy uses both temporary and permanent pastures. In HolSy and MonSy, calves are kept for three weeks at the dairy farms and are then transferred to separate beef farms (not assessed here). In ParSy, calves are weaned at six months and slaughtered at 12 months (Teston et al., 2020). Production data on the French systems were obtained from l'Institut de l'Elevage (IDELE) (pers. comm. December 2021) while data on the Spanish system were obtained from Departament de Ciència Animal, Universitat de Lleida (UDL) (pers. comm. December 2021). The data represent averages from existing farms complemented with expert knowledge from these institutions. Farm characteristics are shown in Table 1 and in the Supplementary in Tables S1 and S2.

3.1.2. System boundaries

Common subsystems in all of the systems were pasture, animal housing, manure, production of maize silage, production of grass silage, production of hay, and production of vitamin and mineral mixes (Table 2). In addition to these, HolSy and MonSy included the subsystems production of wheat, soybean, and protein concentrate mix. Additional subsystems were production of powdered milk for HolSy and production of barley and alfalfa in ParSy. Inputs for all three systems included electricity, diesel and light oil fuel. Synthetic fertilizers and pesticides were used as inputs in HolSy and MonSy but not in ParSy because it was an organic production system. All crops were produced at the farms in France and Spain except for soybean meal which was farmed in Brazil and processed in France (Salou et al., 2017). Powdered milk and protein concentrate mix, made from rapeseed meal and vitamin and mineral premixes, were purchased to the farm. MonSy did not use powdered milk and ParSy did not use soybean, protein concentrate mix and powdered milk. We also included farm buildings and farm assets such as tractors in the analysis.

3.1.3. Functional unit

We used 1000 kg of protein as the functional unit not taking into account any differences between beef and milk in the protein profiles. For HolSy and MonSy, protein from beef includes culled cows, culled heifers,

Table 1
Farm characteristics of different production systems assessed for average farms.

	Unit	HolSy France	MonSy France	ParSy Spain
Cows	number	75	65	80
Replacement heifers	number	24	20	10
Calving rate	%	91	97	90
Surplus calves sold at 3 weeks	number/year	36	39	0
Calves raised for slaughter at 1 year	number/year	0	0	56
Surplus heifers sold at 1–2 years	number/year	6	10	10
Age at first calving	days	850	920	1000
Milk production	FPCM kg/(cow & year)	8500	7600	–
Carcass weight cow	kg/cow	330	340	290
Carcass weight[a] calf when sold	kg/calf	48	50	250
Total farmland area	ha	91	130	190
Pasture on cropland (temporary)	ha	33.5	26	0
Semi-natural pasture (permanent)	ha	3.5	30	160
Grazing duration	days/year	200	180	210
Grass based forage[b]/maize based forage	ratio[c]	1.04	3.15	1930.00
Grass silage/maize silage	ratio[c]	0.27	0.87	215.00
Forage from semi-natural pasture/total feed	ratio[c]	0.01	0.14	0.16

IDELE pers. comm. December 2021 and UDL pers. comm. December 2021.

[a] Surplus calves from dairy herds are sold live, but included in the LCSA with assumed carcass weight at 3 weeks.

[b] Forage includes intake from both pasture and fodder.

[c] This is a ratio of the yearly required dry matter resources in kg of feedstuffs shown in Table S1 in the Supplementary. For example, for HolSy grass based forage/maize based forage = (9800 + 143000 + 77000 + 82000) / 300000 = 1.04.

and surplus calves calculated as if they would have been slaughtered at three weeks of age. Most surplus calves from French dairy herds are sold and moved to farms in Italy where they are raised for slaughter. We, however, considered them as protein, calculated as if slaughtered at three weeks of age, when they left the farm. For ParSy, protein from beef included culled cows and heifers and calves raised for slaughter at 12 months.

We assumed that raw bone-free beef contained 23.2% protein (Williams, 2007) and that fat and protein corrected milk (FPCM) contained 3.3% protein (IDF, 2015). Allocation to impacts of co-products such as hides were not included.

Table 2
Subsystems included within the system boundaries used for the three cattle systems studied.

Subsystems and outputs	HolSy	MonSy	ParSy
Subsystem on-farm			
Animal production	X	X	X
Grazing semi-natural pastures		X	X
Grazing cropland pastures	X	X	
Hay and silage production	X	X	X
Alfalfa production			X
Wheat production	X	X	
Barley production	X	X	X
Manure	X	X	X
Subsystem off-farm			
Soybean	X	X	
Protein concentrate	X	X	
Milk powder	X		
Vitamin and mineral mix	X	X	X
Fertilizers	X	X	
Pesticides	X	X	
Energy	X	X	X
Farm machinery	X	X	X
Outputs			
Milk	X	X	
Beef	X	X	X
Surplus calves	X	X	

3.2. Evaluating sustainability

Sustainability of the systems was evaluated using LCSA, which includes the environmental, economic, and social impacts. This was complemented with indicators for feed-food competition and economic robustness.

3.2.1. Life cycle sustainability assessment

3.2.1.1. Environmental inventory and impact assessment. Yield data for grass and crop production in HolSy and MonSy were provided by IDELE (pers. comm. December 2021). In ParSy, barley yields were obtained from global agro-ecological zones (GAEZ) v4 (FAO, 2021) while yields for semi-natural pasture grass and maize silage (IDELE pers. comm. December 2021) as well as organic alfalfa (Nitschelm et al., 2021) were assumed to be similar to those in the French highlands. We used Agribalyse (2020), a database for French production, for inventory data. Due to the lack of Spanish data, it was assumed that the inputs required in ParSy were similar to those in highland certified organic agriculture production in France.

The enteric methane emissions were calculated based on the Tier II method (IPCC, 2019 Eq. (10.21)) with gross energy intake of the animals from the cattle systems, methane conversion factor as percent of gross energy in feed (6.3%; IPCC, 2019 Table 10.12) and energy content of methane (55.65 MJ/kg). The methane emissions from manure were calculated based on the Tier II method (IPCC, 2019 Eq. (10.23)), with volatile solids (VS) (IPCC, 2019 Eq. (10.24)), methane generation potential (0.13 m^3/kg DM for non-dairy cattle and 0.24 m^3/kg DM for dairy cattle; IPCC, 2019 Table 10.16), conversion factor from m^3 to kg methane (0.67) and methane conversion factors for manure (4% for non-dairy cattle with solid manure and 15% for dairy cattle with liquid manure system; IPCC, 2019 Table 10.17). VS were calculated based on a gross energy intake of 18.45 MJ/kg DM, feed digestibility of 70% for non-dairy cattle and 75% for dairy cattle, urinary energy of 4% and ash of 13% (IPCC, 2019 Eq. (10.24)). We assumed that beef cattle excreted 80% of nitrogen (N) consumed in urine and dung (Menezes et al., 2019) and dairy cattle excreted 75% of N (Powell et al., 2010). Direct nitrous oxide emissions on pastures were based on IPCC (2019) default emission factors for the Tier I method (IPCC, 2019 Table 4A) i.e. for urine on pasture 0.0077 kg/kg N excreted and for dung on pasture 0.0013 kg/kg N excreted. Direct nitrous oxide emissions from slurry manure were based on default emission factors for the Tier I method (0.005 kg/kg N excreted; IPCC, 2019 Table 10.21). Indirect nitrous oxide emissions were also based on default emission factors for the Tier I method (0.01 kg/kg volatized N and 0.24 kg/kg leached N; IPCC, 2019 Table 11.3).

In order to be able to assess potential trade-offs, we used ten environmental impact categories. These were climate change (GWP100), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial acidification (TAP100), fossil depletion (FDP), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), cropland use (LU cropland) and use of semi-natural pasture (LU pasture). We analysed the impact categories in OpenLCA 1.10 using Agribalyse 3.1 database and used Recipe midpoint (H) for characterization.

3.2.1.2. Economic inventory and impact assessment. In this article, we focus on the present value (PV) of LCC i.e. the current value of all LCC including future costs of a given period of time, as a measurement of economic sustainability. The expected life of the most durable investments (buildings) was assumed to be 20 years and the present value was calculated based on a 20 years' period. The costs considered in the LCC included investments (in buildings, inventory and machinery), operational costs, taxes, rental costs and costs for maintenance. Only costs directly related to the production of beef and milk were included and economic allocation was used for ancillary activities i.e. wheat production in HolSy. The PV of LCC was calculated as:

$$LCC_{PV} = \left(\sum_{t=0}^{T}\left(I_t/(1+i)^t\right) + \sum_{t=1}^{T} C_t/(1+i)^t\ \right) \tag{1}$$

where $t = 1, \ldots, T$ denotes time, I_t is the investment in period t, C_t is the cost in period t, and i is the discount (interest). The resale values of capital goods were included as negative investments. LCC_{PV} was calculated at farm level in € and then converted into € per 1000 kg protein produced.

3.2.1.3. Social inventory and impact assessment. The social inventory indicators in a previous S-LCA study on pigs by Zira et al. (2020) were used as a starting point for identifying relevant indicators to capture social sustainability issues in this study. These were adjusted to be applicable to cattle production, for example, some diseases affect pigs but not cattle, and social issues from the literature were added, e.g. the Welfare Quality protocol (2009). In order to validate the proposed issues and to suggest potentially missing issues, we then sent a survey to experts of European cattle production. The social issues and their origin are presented in Tables S7 to S11.

The stakeholder categories used in S-LCA in our study were workers, farmers, cattle, local community and society (see Tables S13 to S27). The assessed social sustainability issues were sorted under different impact subcategories including 8 subcategories for workers (e.g. health and safety), 6 subcategories for farmers (e.g. work satisfaction), 4 subcategories for cattle (e.g. good housing), 4 subcategories for local community (e.g. cultural heritage) and 3 subcategories for society (e.g. contribution to economic development).

Social risk depends on the time in each of the processes activities required to produce a functional unit. The effect of time is captured by the activity variable, *T* (UNEP, 2020). For workers and farmers, *T* is the work hours required by one person to complete tasks in a process for the functional unit. For example, it takes 1.7 h to produce wheat required for the production of 1000 kg protein calculated based on 6.5 h for a worker to produce wheat from a hectare in France (Recherche Appliquée des Chambres d'Agriculture, 2006). For the stakeholder category cattle, *T* was the number of animals required to produce the functional unit multiplied by the number of their life days for the functional unit, henceforth referred to as cattle-life-days. For local community and society, *T* was population density per hectare where the farms are located (EUROSTAT, 2022), multiplied by the number of hectares used in the cattle production system and the duration of the production process in days required for the functional unit, henceforth referred to as people-hectare-days (Zira et al., 2020). The activity variables used are shown in Table S28.

The social inventory indicators are measured using social risk (SR), which is a measure of the risk of negative social impacts in relation to a given reference point (Zira et al., 2020). SR takes a value between 0 and 1, with a value approaching 0 indicating a very small risk for an inventory indicator, values < 0.5 indicating that the inventory indicator has a lower risk, and values > 0.5 indicating a higher risk than the reference (REF). We used European averages as reference points for the inventory indicators except for salary where national values were used due to large variations in the cost of living between countries. SR was calculated as:

$$SR = 1 - EXP\left(LN(0.5) * \frac{IND}{REF}\right) \tag{2}$$

when a *higher* value reflects a more negative impact, and

$$SR = EXP\left(LN(0.5) * \frac{IND}{REF}\right) \tag{3}$$

when a *lower* value reflects a more negative impact (Zira et al., 2020).

The social impact assessment was as in Zira et al. (2020) based on the assessment of social risk time (SRT) which reflects the risk that a process has in the studied product system. As shown in Eq. (4), SRT depends on time, indicated by the activity variable (T), the social risk (SR), and the relative weight (W) of the inventory indicator in the total impact for a stakeholder (Zira et al., 2020). The weighting of subcategories for workers, farmers, local community and society was carried out by a panel of four experts and the weighting for animal welfare of cattle was carried out by two animal welfare experts. The weights are shown in Tables S29–S33 in the Supplementary.

$$SRT_{ij} = \sum_{k=1}^{K} \left(T_{ij} * SR_{ijk} * W_{ijk}\right) \tag{4}$$

where SRT_{ij} denotes social risk time for stakeholder i in subsystem j, T_{ij} denotes the activity variable in subsystem j for stakeholder i (e.g. workhours for workers), SR_{ijk} denotes the social risk for inventory indicator k (e.g. $k = 1 \ldots 14$ for *farmers* at the cattle farm) in subsystem j for stakeholder i, and W_{ijk} is the weight of inventory indicator k in subsystem j for stakeholder i. SRT for all relevant subsystems were summed to give a total SRT for each stakeholder, e.g. workers. A social hotspot index (SHI) was calculated for the stakeholders as in Zira et al. (2020) as the ratio of SRT relative to the worst possible SRT, i.e. when SR is equal to one. SHI reveals weaknesses in a production system without taking time into account because T cancels outs as it is present in the numerator and denominator of SHI.

3.2.2. Feed-food competition

Direct feed-food competition occurs when feed that can be used for humans is used for animals and indirect competition occurs when cropland is used for animal feed rather than human food (van Zanten et al., 2022). We considered both direct and indirect feed-food competition in this study. Direct feed-food competition for protein was assessed based on the human edible protein feed conversion ratio (FCR protein) which was calculated as the proportion of human edible protein in the feed required per kg protein produced. The human edible fat feed conversion ratio (FCR fat) was calculated in a similar way. The fraction of human edible protein for different feedstuffs is presented in Table S3. These fractions describe the potential maximum extraction rate based on today's technology which e.g. for maize silage is 45% (Ertl et al., 2015). We assumed that 100% of the fat in seed kernels and seed meals was edible for humans. Indirect feed-food competition for protein, was assessed based on land use ratio (LUR) which was calculated by multiplying the land required to produce 1 kg human digestible protein (HDP) from milk and meat by the maximum amount of HDP from food crops if the land was used for food crops instead of feed crops. The maximum amount of HDP from food crops was calculated based on wheat, potatoes, maize and soybean because these were the main crops grown in France (van Zanten et al., 2016) and on barley, which is the main crop grown in the Pyrenees, for Spain (FAO, 2021). The yields for the food crops were taken from FAOSTAT (2022).

3.2.3. Economic robustness

LCC was included in the LCSA, but to capture additional aspects of economic sustainability we also took the economic viability of farms into account. In order for a farming system to be economically sustainable, farmers need to be able to cover all costs of production and that farmers as well as other investors can obtain a reasonable return on the capital invested.[1] Furthermore, farmers need to have capacity to cope with and adapt to different types of disturbances. We examined economic robustness by looking at the rate of return on the required investments and how economically sensitive farms are to changes in prices, interest rates, and support payments – the more sensitive

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[1] The interest rate on loans reflects the return that banks or investors, depending on the perceived riskiness of the investment, require while the return that farmers require reflects the return on potential alternative investments (the alternative cost of capital).

farms are to such changes, the less robust and the less economically viable they may be.

Net present value (NPV) and the internal rate of return (IRR) are indicators widely used to assess how profitable a project is and to compare different projects (Dhavale and Sarkis, 2018). A higher NPV implies a higher IRR, reflecting a more robust farming system. NPV measures the present values of the difference between all cash inflows and all cash outflows over the life time of the investments and is calculated as

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+i)^t} - LCC_{PV} \tag{5}$$

where R_t is the revenue at time t, including revenues from beef and milk sold and from support as well as payments, and LCC_{PV} is previously defined according to Eq. (1). The internal rate of return (IRR) measures the return on invested capital and thus provides an indication of how economically viable a farm is. IRR shows the discount rate, i, that result in a NPV equal to zero, i.e. setting Eq. (5) equal to zero and solving for i. A higher IRR indicates a more profitable investment.

Data for costs and revenues in the different systems, presented in Tables S4–S6 in the Supplementary, were obtained from IDELE in France (pers. comm. December 2021) and CITA-Aragon in Spain (pers. comm. January 2022). The discount rate was assumed to be 1.2–1.5% based on the cost of borrowing money (the rate of return expected by investors), the life time was assumed to be 20 years for buildings and 10 years for machinery and inventory, and 50% of the investments were assumed to be financed by loans (and 50% by own capital).[2]

Given that the interest rates in a historic perspective have been exceptionally low in recent years, we also assessed how the farms would be affected by higher interest rates on borrowed capital (assuming unchanged alternative cost of own capital). Farms requiring larger investments will be more sensitive to such increases. Furthermore, we examined how the NPV of farms would be affected by specific decreases in revenues and increases of costs. For changes in revenues, we specifically examined the effects of 5% decreases in the producer price of milk, the producer price of meat and cattle, and support payments. Concerning changes in costs of some crucial inputs, we specifically examined 5% increases in feed prices, energy prices, and the rent of leased land.

3.3. Scoring of relative sustainability

In order to identify the strengths and weaknesses of different systems, all sustainability indicators are expressed as relative unsustainability points (RUsP). RUsPs are scores that present all sustainability indicators on the same scale relative to a reference system (Zira et al., 2021). We also used RUsP for feed-food competition and robustness indicators. The values can range between 0 and 1. HolSy was used as a reference and hence had an RUsP value of 0.5. Values > 0.5 for MonSy and ParSy reflect more negative impacts than HolSy while values < 0.5 reflect less negative impacts. Let *INDsys* denote values of the environmental, economic and social impact indicators for MonSy or ParSy and let *INDref* denote the impact indicator for the reference system HolSy. RUsP was calculated as

$$RUsP = 1 - EXP(LN(0.5) * INDsys/INDref) \tag{6}$$

when a *higher* value reflects a more negative impact, e.g. freshwater eutrophication, and

$$RUsP = EXP(LN(0.5) * INDsys/INDref) \tag{7}$$

when a *lower* value reflects a more negative impact, e.g. IRR.

4. Results

4.1. Relative sustainability points

RUsP were, with HolSy as the reference, calculated for 27 indicators related to the LCSA, feed-food competition and robustness assessment. MonSy had RUsP higher than 0.5 (i.e. lower sustainability) for 10 and ParSy for 14 out of 27 indicators (see Fig. 1). Using marine eutrophication (MEP) as an example on how the figure should be interpreted, MonSy (black bar) had a lower (i.e. more sustainable) and ParSy (grey bar) had a higher (i.e. less sustainable) RUsP for MEP than HolSy (dotted line). MonSy and ParSy had similar RUsP for land use, both for LU cropland (lower than HolSy) and for LU pasture (much higher than HolSy). ParSy had high RUsP for farmers and workers whereas MonSY had RUsP closer to the reference (HolSy).

4.2. Results of the LCSA and assessment of feed-food competition and robustness

Table 3 presents the results of the LCSA for 1000 kg protein for the three cattle systems assessed in this study. The environmental impacts are also presented for beef and milk per kg in Table S12. Figs. S1–S3 show how different subsystems contribute to the environmental impacts. The assessment results by indicator of social impacts are shown in Tables S13 to S27. In general, a higher value in Table 3 means a more negative impact (but this will be discussed for LU, semi-natural pasture in Section 5.2).

In this study, we present results for two indicators for social impacts, SRT and SHI, that represent different perspectives of social sustainability. Here is some guidance in how these measures should be interpreted (see Table 3). For workers, SRT was lower in MonSy (52 h) than in ParSy (220 h) indicating that the risk of negative impacts was higher in the latter system. The SRT is determined both by the time it takes for workers to produce the functional unit and the social risk (SR) during this time. It took a longer time for workers to produce 1000 kg protein in ParSy and the SR was higher for many indicators. Hence, the SRT was higher. SHI indicates level of risk when time is not taken into account. For workers the SHI value was higher in ParSy (0.61) than MonSy (0.50). For farmers, SRT in MonSy (61 h) was lower than in ParSy (260 h) while the SHI was similar in the two systems. Higher SRT in ParSy was due to more work hours being required per kg of protein produced as well as a higher risk (SR) due to more isolated farmers and failure of within family farm succession.

The SRT values for workers in Table 3, indicated risk assuming that the soybean certification schemes were effective which means that for example child labour is not used at soy farms (see Table S13). Assuming that the schemes were ineffective, the SRT for workers were 46 and 53 h and the SRT for local community were 270000 and 120000 people hectare days for HolSy and MonSy respectively (soybean was not used in ParSy).

Table 4 presents the results of the feed-food competition in terms of conversion ratios of human edible protein and fat as well as land use ratio for protein. The higher the human edible feed conversion ratio, the more human edible feed is required for producing one kg product (i.e. more unfavourable). The higher the land use ratio, the less protein production efficient the cattle production system is. Both dairy systems are net producers of human edible fat but none of the systems is a net producer of protein.

In Table 5, we present IRR and NPV (on farm level) for each system. These measures indicate how economically viable and robust each farming system is. Also presented are the effects, in terms of changes in the NPV, of decreases in revenues and increases in costs and the interest rate on borrowed capital, which indicate economic robustness. ParSy was considered more robust than the other systems as indicated by smaller NPV changes than in the other systems.

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[2] This can also be expressed in terms of an equity to loan ratio of 50:50, a debt-to-equity ratio of 1 or a capital gearing ratio of 50%.

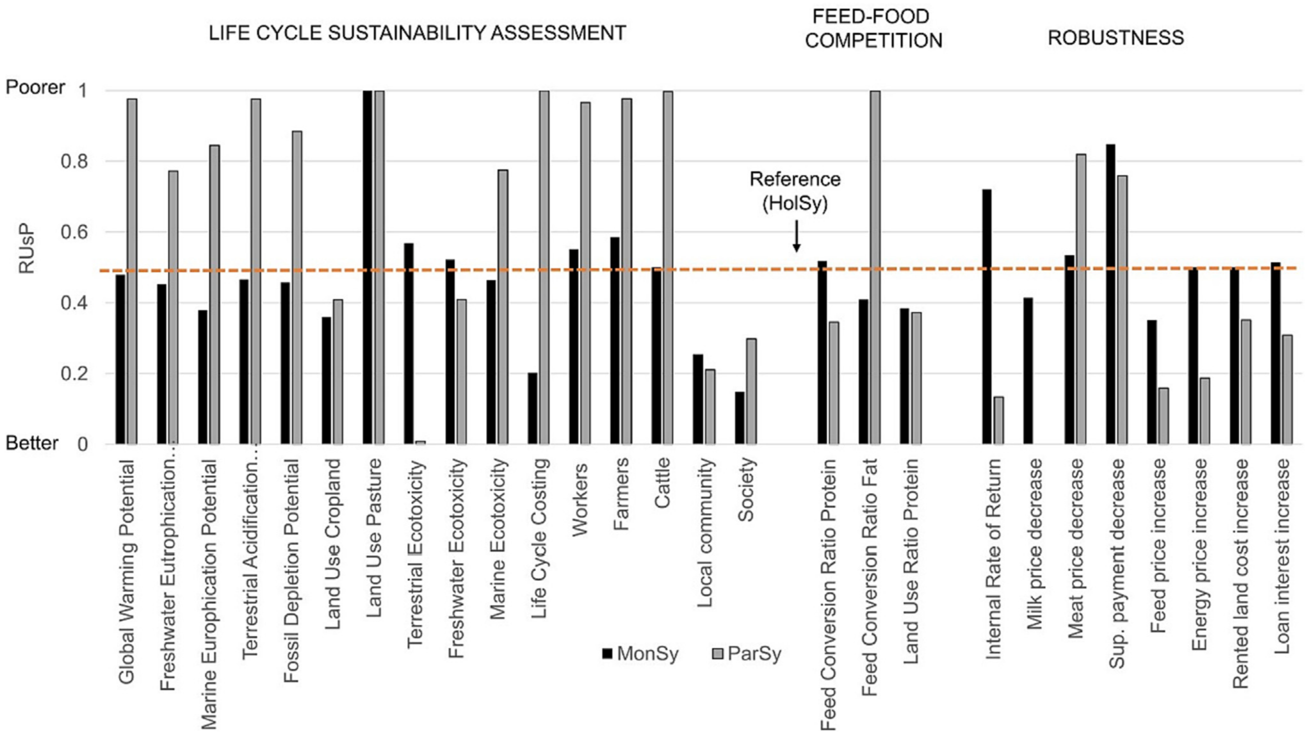

Fig. 1. Life cycle sustainability assessment, feed-food competition, and robustness indicators in relative unsustainability points (RUsP) with HolSy as the reference (RUsP = 0.5, dotted line).

5. Discussion

Only a few studies have focused on integrated assessment of environmental, economic and social aspects of cattle production systems (Florindo et al., 2020; Chen and Holden, 2018; White and Capper, 2013) and none to our knowledge examined and compared the feed-food competition and the economic robustness of such systems.

5.1. Life cycle sustainability assessment

MonSy had lower environmental impacts (lower RUsP values on seven out of 10 environmental impacts), lower life cycle costs and lower social impacts for society, compared to both HolSy and ParSy. This was because MonSy used less feedstuffs with high environmental impact and high economic costs such as soybean meal and protein concentrate mix per unit output of protein. HolSy had lower social impacts for farmers when compared to the other systems. This was partly explained by that HolSy was located in the lowland with highly productive arable land where the dependence on support payments was lower (farmers' uncertainty of the subsidy system was a social issue identified in the survey). Another reason was that since the population density was higher in the lowlands, the farmers could feel less isolated than in the highlands.

The reason why ParSy, an organic beef system, had lower impacts for cropland use, terrestrial and freshwater ecotoxicity, and lower social impacts on local community was that no soybean and pesticides were used. ParSy also had a higher internal rate of return compared to other systems, but was more dependent on support payments.

Our environmental impact results are not directly comparable to findings from other environmental LCA studies on cattle

Table 3
The life cycle sustainability assessment performance for the different systems per 1000 kg protein.

Indicator	Units	HolSy	MonSy	ParSy
Environmental				
Global warming potential 100	kg CO_2 eq	52,000	49,000	280,000
Freshwater eutrophication	kg P eq	3.8	3.3	8.1
Marine eutrophication	kg N eq	290	200	780
Terrestrial acidification 100	kg SO_2 eq	950	860	5100
Fossil depletion	kg oil eq	1700	1500	5300
Land use, cropland	m^2	79,000	51,000	60,000
Land use, semi-natural pasture	m^2	1600	18,000	420,000
Terrestrial ecotoxicity	kg 1.4 DCB eq	190	230	2
Freshwater ecotoxicity	kg 1.4 DCB eq	46	49	35
Marine ecotoxicity	kg 1.4 DCB eq	20	18	43
Economic				
LCC	euros	490	160	6300
Social[a]				
Workers	SRT in hours (SHI)	45 (0.50)	52 (0.50)	220 (0.61)
Farmers	SRT in hours (SHI)	48 (0.36)	61 (0.39)	260 (0.41)
Cattle	SRT in cattle life days (SHI)	1500 (0.52)	1500 (0.50)	13,000 (0.40)
Local community	SRT in people hectare days (SHI)	260,000 (0.44)	110,000 (0.50)	89,000 (0.31)
Society	SRT in people hectare days (SHI)	4 300,000 (0.34)	1,000,000 (0.32)	2,200,000 (0.44)

[a] SRT = social risk time, and SHI = social hotspot index (provided within parenthesis).

Table 4
Feed-food competition for the different systems.

Indicator	Units	HolSy	MonSy	ParSy
Human edible protein feed conversion ratio	kg edible protein in feed/kg protein produced	1.8	1.9	1.1
Human edible fat feed conversion ratio	kg edible fat in feed/kg fat produced	0.25	0.19	2.1
Land use ratio for protein	ratio	4.5	3.1	3.0

(e.g. Mazzetto et al., 2020; Salou et al., 2017) because of different functional units and cattle systems. In order to be able to compare with other studies we calculated the environmental impact using one kg FPCM and one kg meat liveweight as functional units. The results are shown in Table S12 and were comparable with results by Salou et al. (2017) e.g. for one kg FPCM at farm gate, GWP100 (1.4–1.5 kg CO_2 eq) and land use (2.0–2.3 m^2) for HolSy and MonSy. Our results for GWP100 for 1 kg beef live weight at farm gate for dairy systems (10–12.5 kg CO_2 eq/kg live weight) and suckler beef system (22.5 kg CO_2 eq/kg live weight) were within the range of previous studies in Europe (Laca et al., 2021). Our economic results confirm the findings by Mosnier et al. (2021) that the production of protein in dairy systems, sharing the costs between milk and beef, is less costly than in pure beef systems.

Based on SRT, our results indicate that the conventional system MonSy had better animal welfare than the organic system ParSy. This differs from our previous study on pigs in conventional and organic production systems in Sweden (Zira et al., 2020) where both SRT and SHI were lower for organic production. This was due to that cattle in MonSy and ParSy had access to grazing but only pigs in organic production had outdoor access. The poorer SRT result for ParSy was because of the low output of protein in the beef system, compared with a dairy system which produces both beef and milk. Thirteen of 20 cattle indicators showed better animal welfare for ParSy than the dairy systems, but many more cattle-life days were required to produce 1000 kg of protein from ParSy. However, SHI (not taking time into account) was considerably lower (i.e. better) for ParSy. Better animal welfare in the highland system MonSy (lower SHI) than in the lowland system HolSy is in line with the findings by Coignard et al. (2013) who studied overall health scores in French dairy cattle herds.

5.2. Feed-food competition

Results showed that all systems, even ParSy with its cropland use of only 14% of total land use and 7% of dry matter intake from cereals, had human edible feed conversion ratios greater than one for protein. Thus all systems used more human edible protein than they produced. The dairy systems had human edible feed conversion ratios less than one for fat indicating that they were net producers of human edible fat, while ParSy was not. Milk has lower fat content compared to meat, but the large quantity of milk compared to meat in dairy systems explains the higher fat production in dairy systems when compared to ParSy. The human edible feed conversion ratios only included direct feed-food competition but in HolSy, the non-edible feed was produced on cropland which could have been used to produce human food which explains why MonSy performed better than HolSy for indirect feed-food competition.

Even small amounts of grains in the cattle diets can result in direct and indirect feed-food competition for protein, which is demonstrated by ParSy's FCR and LUR values >1. For every kg of beef retail weight (containing 0.23 kg of protein and 0.03 kg of fat), 4.1 kg of cereals were used, containing 0.49 kg of protein and 0.09 kg of fat. For fat, ParSy was considerably worse than the other systems (despite mainly relying on semi-natural pasture) because of the low output of fat when only meat is produced. Dairy systems, on the other hand, perform well for fat (especially those using semi-natural pastures) because they have high output of fat from the milk. A 100% semi-natural pasture based system (not studied here) would avoid feed-food competition. Such a system is not possible in most parts of Europe due to the cold winters, requiring winter feed grown on cropland. On the other hand, winter feed from ley is favourable for crop rotation and can thus be regarded as a cropping system leftover (Karlsson and Röös, 2019). High use of semi-natural pastures raises another question – is it positive or negative? Abandonment threatens biodiversity of semi-natural pastures (Bengtsson et al., 2019). Relatively few semi-natural grasslands remain in Europe (Walden, 2018), and semi-natural areas are crucial for biodiversity conservation in Europe (Pe'er et al., 2022). Thus, high use of semi-natural pasture per kg protein produced could be seen as preferable and this should be kept in mind when interpreting Fig. 1.

Proteins of animal origin have a higher amino acid score than those of plant origin (Schaafsma, 2000). The consumption of protein of animal origin rather than plant based protein has, however, environmental, economic and social issues and many of them are related to feed production. For example, MonSy required 1.9 kg of human edible protein to produce 1 kg of protein of animal origin compared to 3.2 kg human edible feed required to produce 1 kg of meat from pigs and chickens (Mottet et al., 2017). ParSy required 13 ha (of which 86% was semi-natural pasture) to produce a tonne of meat which is around 9 times the acreage required in the production of chickens and pigs (100% cropland, Machovina et al., 2015). If only cropland area was to be compared between ParSy and pig and chicken systems, ParSy required 1.8 ha of cropland as compared to 1.4 ha for pigs and chicken (Machovina et al., 2015).

5.3. Robustness

From an economic perspective, ParSy was, with exception of producer prices, more robust than the other systems as indicated by a larger NPV and higher IRR, and by being less sensitive to changes in feed and energy prices as well as changes in the interest rate. This was due to that ParSy had lower feed costs associated with heavy reliance on grass forage from semi-natural pastures, did not use soybean at all, had lower initial investment costs and larger support payments. The dairy systems are more intensive, using more inputs but also generating more revenues from sales and less from support payments. Hence, they are more sensitive to changes in interest rates, producer prices and the prices of many inputs. Table 5 shows consequences of 5% decrease in milk and beef price. The percentage difference between current (2022) producer beef prices and the lowest prices in the European Union in the last five years was −8% (EC, 2021). An 8% lower price would result in a reduction in NPV of 22000 € in MonSy farms, 26000 € in HolSy farms and 75000 € in ParSy farms. Our results concerning NPV and IRR contradicts the findings by Florindo et al. (2017) who concluded that use of more grass forage in dairy production resulted

Table 5
Economic robustness for the different systems on farm level.

	HolSy	MonSy	ParSy
Internal rate of return, IRR	3.3%	1.7%	9.0%
Net present value (NPV), thousand euros/farm			
Without changes	201	51	266
Change in NPV…			
… with interest on loans increasing by…			
… 1%	−45	−47	−24
… 3%	−125	−129	−67
… 5%	−193	−200	−104
… with a 5% decrease …			
… in producer price of milk	−190	−147	
… in producer price of beef and cattle	−19	−21	−47
… in support payments	−18	−49	−37
… with a 5% increase …			
… in feed prices (incl. concentrates)	−32	−20	−8
… in energy prices (fuel & electricity)	−10	−10	−3
… in rent of leased land	−8	−8	−5

in larger NPV and higher IRR than using more concentrate. The high initial investment costs for MonSy (based on data from average farm by IDELE) but the same milk price for HolSy and MonSy resulted in MonSy being less profitable than HolSy.

5.4. Sustainability assessment combining LCSA with assessment of feed-food competition and robustness

The sustainability at farm level depends on the type of farming system as well as the extent to which semi-natural pastures are used and there are trade-offs between economic, social and environmental impacts, feed-food competition, and economic robustness. Compared to dairy systems mainly relying on cropland, beef systems mainly relying on semi-natural pastures for feed have less feed-food competition and are economically more robust but have higher impacts for most environmental indicators per kg of protein produced. For dairy systems, having more semi-natural pastures as compared to having more cropland results in less feed-food competition, lower life cycle costs, lower impacts for climate, eutrophication, acidification, and fossil depletion. Having more semi-natural pastures generates more support payments and thus make farm profitability less sensitive to changes in prices of inputs but more sensitive to policy changes. Many farmers cannot choose more or less semi-natural pasture – the farm is located where it is and has the land it has. Farmers can, however, to some extent control other impacts in the production chain. For example, farmers' decision to use certified soybean can reduce social impacts for the local community.

5.5. Limitations and methodological issues

In ParSy, all calves are reared at the farm where they are born while calves from dairy systems are transported to other farms for rearing at an age of three weeks. It would be interesting to follow the calves in the dairy systems until slaughter in future studies, considering that many of these calves are transported for many hours (often to Italy) and raised indoors (Padalino et al., 2021). It could affect environmental and social sustainability, and feed-food competition results for joint production of beef and milk, especially if these calves are fed on diets with soybean and cereals. Poor conditions during transport could also influence social impacts for animals.

Agriculture is responsible for the majority of human water use and it could thus be relevant to include water scarcity as an indicator in life cycle sustainability assessment. Due to lack of data it was not included in this study but it would be relevant to explore in future studies. We used protein as the functional unit in this study but milk and meat differ in nutrient content and health outcomes from consuming meat and dairy are also different. Therefore, including health impacts of milk and meat as an additional indicator (Jolliet, 2022) could be interesting in future studies. Although we only allocated impacts to milk and beef, there are non-commodity and non-marketable goods and services provided by cattle production systems. Examples are conservation of cultural landscapes, and preservation and enhancement of biodiversity when semi-natural pastures are used. Such services could be allocated impacts, alongside milk and meat, as recommended by Bragaglio et al. (2018). These services would be different across the systems considering that the use of semi-natural pastures differed between the systems, with 0.16, 1.8 and 42 ha used per 1000 kg protein for HolSy, MonSy and ParSy respectively. In MonSy and ParSy, support payments constituted a large proportion of farm revenue compared to HolSy reflecting the non-commodity and non-marketable goods and services they provide (e.g. preservation and enhancement of biodiversity).

Social sustainability is complex because different societies and individuals have different values and desires. We used the social sustainability issues from pig production that were relevant for cattle production as a starting point because the societies where the animal production system exists were similar. In our study, the social sustainability assessment was based on a reference including all humans (or cattle) in Europe. Having a reference made it possible to calculate relative sustainability points, but an alternative to the European average living conditions could be to use a specified goal (e.g. based on UN's Sustainable Development Goals) as a reference.

We did not use all the social issues raised by the stakeholders due to lack of data for some of the inventory indicators, but we have for transparency presented them in Tables S7 to S11. It is challenging to make inferences on animal welfare without visiting the herds, but visiting the farms as done by e.g. Coignard et al. (2013) is labourious. Likewise, it would have been very time-consuming to collect primary data from workers, farmers and citizens through e.g. interviews, instead of using data from the literature.

We made a simplification in the calculation of RUsP for social indicators by using SRT alone in the LCSA (Fig. 1), but social sustainability evaluations ought to include SHI as well as SRT (Zira et al., 2020). Both SRT and SHI are presented in Table 3. The results for cattle illustrates how SRT and SHI indicate different perspectives of social sustainability. Due to longer time required to produce one functional unit in ParSy, SRT was much higher for this system than for HolSy. SHI was, however, better for ParSy than for HolSy and this indicated better animal welfare in ParSy. A system with both a lower SRT and SHI is better in comparison to a system with a higher SRT and SHI. Given a limitation to only consider one of the two indicators as in Fig. 1, using SRT is more relevant since it is closer connected to the functional unit than SHI.

5.6. Improvements in the systems

HolSy and MonSy could be improved in terms of environmental impacts by having grass-clover silage instead of maize silage in the cattle diets. Holsy and MonSy could also be improved in terms of feed-food competition by sourcing of alternative fodder e.g. waste-products or roughage produced from marginal lands not suitable for arable crop production if such lands are locally available. Highlighting extrinsic values of pasture based livestock systems in marketing could potentially increase farm income in MonSy, if consumers are willing to pay a premium for such values. ParSy can be potentially improved for environmental and feed-food competition impacts by adding small amounts of additional fertilizer to increase barley yields. Adding fertilizers may however, create other risks such as eutrophication and biodiversity loss (Röös et al., 2018). A change from fossil fuels to bio-fuels in ParSy can reduce environmental impacts and reducing the working time can improve social impacts.

6. Conclusion

Cattle systems are complex and when comparing different systems, it is apparent that there are trade-offs between different sustainability aspects. For environmental, economic and social impacts, a semi-natural based dairy system is favourable for its low impacts on some environmental indicators, low life cycle costs and low impacts on society. A cropland based dairy system is favourable for low social impacts on farmers, and a semi-natural pasture based beef system (especially if organic) is favourable for its low terrestrial and freshwater ecotoxicity and low social impacts on the local community. For feed-food competition, a semi-natural pasture based beef system is favourable for reduced feed-food competition for protein, whereas dairy systems are better for reduced feed-food competition for fat, especially dairy systems based on pasture. For economic robustness, during periods of increased input prices and decreased output prices, cattle systems with support payments constituting a large proportion of farm revenue are more robust. On the other hand, high dependence on support payments can be a social issue for farmers.

Producing protein of animal origin using semi-natural pastures has environmental benefits for feed production, low feed production costs, good animal welfare and reduced dependence on off-farm inputs for feed production. Producing both meat and milk in the same system has positive environmental benefits but may be less profitable in highlands due to high input prices and decreased output prices. Dairy farmers in semi-natural pasture based systems in highland regions in Europe need support payments to keep the enterprise viable in times of increases in input prices and decreases in output prices.

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Declaration of competing interest

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Appendix A. Supplementary data

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