Agricultural Systems 218 (2024) 103984

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Assessment of food-feed competition for producing milk in cow dairy farms

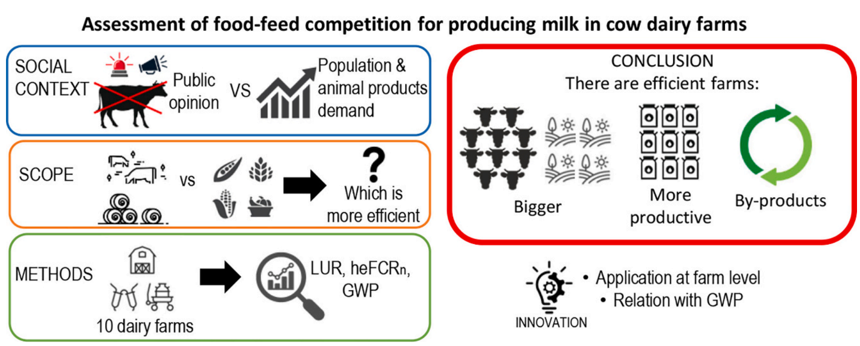
Nicola Maria Palladini *, Giulia Gislon, Anna Sandrucci, Maddalena Zucali, Alberto Tamburini, Luciana Bava

University of Milan, Dipartimento di Scienze Agrarie e Ambientali, via Celoria 2, 20133 Milan, Italy

HIGHLIGHTS

- The role of animal husbandry and its contribution to the food supply chain is crucial.
- Efficiency of 10 dairy farms to produce food in terms of feed-food competition was evaluated.
- Land use ratio, Human-edible Feed Conversion net Ratio and Global Warming Potential was considered.
- Human-edible Feed Conversion net Ratio has a good correlation with Global Warming Potential.
- More productive farms and use of by-products enhance the sustainability and reduce feed-food competition.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kairsty Topp

Keywords:
Feed-food competition
Sustainability indices
Livestock
Milk
Cow

ABSTRACT

CONTEXT: The demand for animal products is increasing worldwide, despite concerns about their negative impact on the environment, animal welfare, and human health. It is crucial to understand the role of animal husbandry and assess its contribution to the food supply chain.

OBJECTIVE: This study aimed to analyse the efficiency of dairy farms in producing food by evaluating the competition between animal and human in terms of feed - food soil utilization and net nutrients.

METHODS: The study used three approaches: Land Use Ratio (LUR), Human-edible feed conversion net ratio ($heFCR_n$) for energy and protein and Global warming potential (GWP) evaluation. A group of 10 dairy cattle farms in Northern Italy was selected, based on herd size and farm management practices, in order to provide a representative sample of the intensive dairy systems in this region.

RESULTS AND CONCLUSION: The three indices ($heFCR_n$ energy, $heFCR_n$ protein, LUR) were correlated with each other and with Global Warming Potential (GWP) per kg of Fat Protein Corrected Milk (FPCM). The $heFCR_n$ protein index was found to be particularly related to GWP ($R^2 = 0.88$). The LUR, applied at the farm level, identified high variability (1.07 ± 0.8) among individual farms with herd size ($R^2 = 0.82$), milk production ($R^2 = 0.86$), land availability ($R^2 = 0.77$) and by-products use ($R^2 = 0.49$) inversely correlating with LUR. The study suggests increasing milk production and using by-products in animal rations as important strategies for reducing food-feed competition in terms of energy and protein supply. Further studies are needed to evaluate amino acid profiles in plant-based and animal-based products.

* Corresponding author.
E-mail addresses: nicola.palladini@unimi.it (N.M. Palladini), giulia.gislon@unimi.it (G. Gislon), anna.sandrucci@unimi.it (A. Sandrucci), maddalena.zucali@unimi.it (M. Zucali), alberto.tamburini@unimi.it (A. Tamburini), luciana.bava@unimi.it (L. Bava).

https://doi.org/10.1016/j.agsy.2024.103984
Received 5 December 2023; Received in revised form 23 April 2024; Accepted 26 April 2024
Available online 14 May 2024

SIGNIFICANCE: The novelty of this study is to consider, at the same time, different indices associated to sustainability of the farm process along with GWP of milk production, and the application of the LUR at the farm level. The high variability of the results among farms suggests that, from a scientific point of view, is not possible draw simply conclusions about food-feed competition but this evaluation could give important indication to identify possible strategies, which can be implemented in practice.

1. Introduction

In recent years, the livestock sector has faced numerous criticisms from public opinion regarding its environmental impact, animal welfare, and human health, and the attention to these issues is steadily growing (Te Velde et al., 2002; Alonso et al., 2020). Even within the scientific community, studies have emphasized the negative impacts of the livestock farming on the environment and human health (Sá et al., 2020; Williams et al., 2023). However, despite these concerns, the demand for animal products worldwide is increasing: global meat production increased by 5% in 2021, compared to the previous year, with an estimated meat production of 339 Mt., according to the OECD-FAO (2022). Additionally, global liquid milk production increased by 1.1% in 2021, reaching approximately 887 Mt. Population growth and rising per capita income in emerging countries are the primary drivers behind the increasing demand for animal source foods (FAO, 2023a, 2023b, 2023c). Given these factors, it is essential to understand the current role of animal husbandry and evaluate its contribution in the food supply chain.

Animal husbandry requires the use of land for feed production, thereby reducing the available space for cultivating crops intended for direct human consumption. Nevertheless, animal-source food (ASF) (e.g., milk, meat, eggs) have some superior nutritional characteristics compared to plant product-based food that could be cultivated on the same land. Indeed, animal products have amino acid profiles, nutrient compositions, and digestibility traits that are often deficient in plant-based foods (Pereira and Vicente, 2013; Schönfeldt et al., 2013; Elmadfa and Meyer, 2017; Wu, 2020). The key question is whether the high nutritional value of ASF exceed the competition with plant-based foods or if it would be more advantageous to allocate the land for growing crops directly consumable by humans.

Ruminant animals are particularly interesting in this regard, as they have the ability to convert plant materials, which are indigestible or poorly digestible by humans, into food products with high biological value (Oltjen and Beckett, 1996; Rinehart, 2008; Lee et al., 2021). This opens up the possibility of valorizing particularly many plant-derived by-products such as corn gluten feed and meal, brans, middling, molasses, sugar beet pulp, and by-products from breweries, distilleries, and biofuels in the feeding of ruminants. On a global scale, the proportion of by-products consumed by dairy cattle as feed represents 4.7% (GLEAM 3, n.d., FAO). Furthermore, some of these by-products are rich of bioactive components, which promote ruminal metabolism, enhance animal health, and improve the quality of derived products (Correddu et al., 2020).

According to Mottet et al. (2017), animal production, in its various forms, plays an integral role in the food system, converting crops into highly nutritious, protein-rich food, transforming co-products into edible goods, contributing to crop productivity through manure, and valorising marginal lands, (Mottet et al., 2017). Cattle, sheep and goats, are particularly noteworthy in this regard, as 60% of the world's agricultural land is too rocky, steep, or arid, for crop cultivation, making livestock grazing the only way to utilize these surfaces (FAO, 1997).

Therefore, rearing animals that can be fed with non-competing feedstuffs represents an important strategy for the rational use of land. In Italy, agricultural land covers only 41.5% of the total surface of the country, largely due to the extension of medium and high-altitude land (CREA, 2022). Agricultural land is predominantly devoted to crops (57%), followed by permanent pastures and meadows (25%) and permanent crops (17% orchards, olives and vineyards). The production of raw materials for animal feed is limited, forcing the import of high quantity of concentrate feed, in particular protein feed: in 2020, in Italy, a total of 2,497,251 tons of cakes and extraction meals was imported (Assalzoo, 2022).

In this context, discarded materials from food production could play a strategic role as feed. This aspect is particularly crucial for the dairy sector in northern Italy. Indeed, four regions of Northern Italy (Lombardy, Emilia-Romagna, Veneto, and Piedmont) represent 80% of the total cow's milk delivered in Italy (ISMEA, 2021). However, it is essential to ascertain whether the current feed rations given to cattle result in a net protein gain during their conversion to animal products, or if there is a loss of protein compared to the direct consumption of vegetables by humans. This helps to determine whether animal nutrition competes for agricultural land with human nutrition, a phenomenon known as feed-food competition. The production of ASF contributes to environmental impact as all other human activities (Janzen, 2011; Augstburger et al., 2018).

To define the feed-food competition, two approaches could be considered. The first is based on the Land Use Ratio (LUR), which evaluates protein yield obtainable from potential food crops compared to the protein obtained from animals fed with feed crops. The LUR helps identify livestock production systems that use land efficiently in terms of food supply (Van Zanten et al., 2019). Until now the LUR has been applied to case systems (van Zanten et al., 2016; Møller et al., 2022), analyzing different livestock systems (dairy cattle, pig, hens).

The second approach considers the portion of protein or energy from feed that could be used directly for human consumption and relates this portion to the protein or energy obtained from animal products. This type of index has been successfully applied in studies aiming to evaluate the sustainability of livestock rearing in mountain areas, particularly in extensive systems with large use of pasture. In these systems the inclusion of concentrate in the feeding rations is used to improve the productivity of grazing animals, even though it could increase the nutrient surplus at the farm and soil level (Flach et al., 2021; Verduna et al., 2020).

In some studies, the indices proposed to study food/feed competition were associated with the evaluation of environmental impact of milk through the Life Cycle Assessment (LCA) approach. This allowed for a, better understanding of the complexity of food production system, at the regional level (Van Hal et al., 2019; Hennessy et al., 2021) or at the local level (Berton et al., 2020).

The aim of this study is to assess the feasibility of dairy farming in producing animal-source food (ASF), as protein and energy sources, by analyzing the competition between feed *and* food which refers to the competition in land utilization, as well as between animal and human diets, and how this relates to environmental impact, expressed as Global Warming Potential. The novelty of the study lies in applying these metrics at farm scale level, focusing on high-producing lowland farms, to identify strategies for improving sustainability of livestock farming.

2. Materials and methods

A group of 10 dairy cattle farms in Northern Italy was selected using a pre-questionnaire based on herd size (above 80 cows), milk production per cow (above 20 kg/d) and farm management practices (no pasture, use of concentrate feed, milk sold to a dairy factory), in order to provide a sample representative of the intensive dairy systems of Northern Italy. In these farms animals were kept indoors all year round and fed Total

Mixed Rations including conserved forages and concentrates (Supplement 1). A questionnaire was administered to the selected farmers, for collecting information on farm management practices, herd composition, feed rations, crops, manure management, feed purchased, milk and meat production. For calculating the indices, the system boundaries considered comprised the entire farm, with all inputs and outputs included in the evaluation (Fig. 1).

2.1. Land use ratio (LUR)

Land Use Ratio (LUR) is a measure of land-use efficiency, calculated using the method developed by Van Zanten et al. (2016) with modifications. LUR is an index for the potential of currently utilized land in order to maximize protein production, with a LUR value <1 indicating that it is more efficient to allocate land for feed production rather than for food.

The equation for calculating the Land Use Ratio (LUR) is as follows:

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

Where: LO_{ij} is the land area (m^2) occupied for a year to cultivate the amount of feed ingredient i ($i = 1$, n) in country j that is needed to produce 1 kg ASF whereas HDP is the Human Digestible Protein obtainable from the land area if it was assigned to food crops.

Starting from the diets of each animal category, the feeds used in the rations were aggregated to obtain the total feed consumed by the herd including lactating cows, dry cows, heifers and calves. The composition of the concentrates was determined by using a rationing software (Cornell-Penn-Miner, CPM Dairy, 2004). Yields for on farm crops were obtained from the questionnaire, while, for the purchased feed cultivated in Italy (e.g., wheat, barley), or in other countries (e.g., soybeans, sunflower, maize), yield data from external databases were used (ISTAT, 2022; FAOSTAT, 2021). Moreover, it was assumed that all soybeans in the concentrates originated from Brazil, while sunflower and maize came from Ukraine, sorghum from the US and wheat, barley and linseed from Italy (FEFAC, 2022; Assalzoo, 2022). To calculate LUR, all by-products were excluded, because they were derived from land cultivated for food or energy, rather than feed. The feed considered as by-product included secondary products of grain, rice and maize processing, as well as extracted meals (soybean, sunflower).

Five major crops were considered as potential food crops: maize, potato, rice, soybean and wheat (Van Zanten et al., 2016). These crops were assigned based on the suitability index of the land for each crop. The suitability and potential yields of these crops were obtained from Global Agro-Ecological Zones (GAEZ v4 dataset) database (IIASA, FAO, 2022): land was considered suitable for food crops if it had a suitability index (as calculated by Fischer et al., 2021) >55,000 (Van Zanten et al., 2019). The GAEZ modelling framework assesses land suitability, potential attainable yields and potential crop production under specified management assumptions and input levels, for both for rain-fed and irrigated conditions (GAEZ4_Glossary (IIASA and FAO, 2022).

The suitability at the farm level was evaluated considering the precise location of each farm. For crops cultivated off the farm, an average

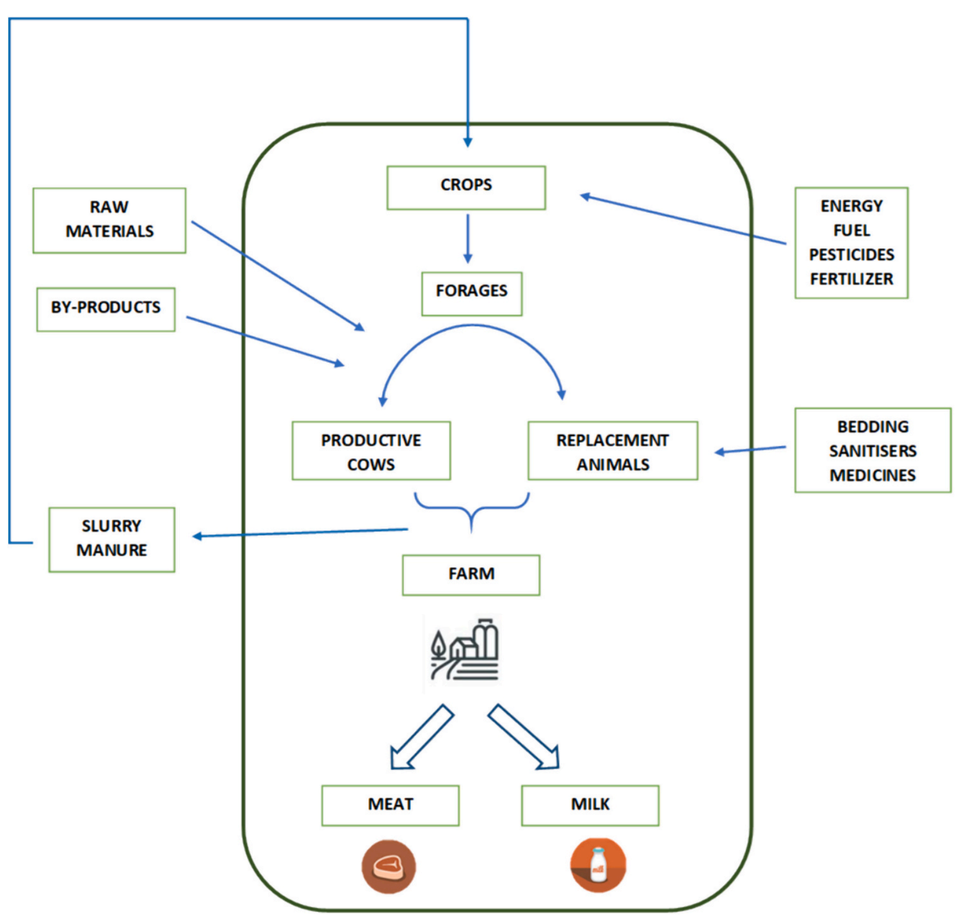


Fig. 1. System boundaries for the calculation of indices.

country suitability was considered. The period covered in the GAEZ climate model was 2011–2040, which allowed the evaluation of a long-term climatic scenario.

Milk production was expressed as Fat Protein Corrected Milk (FPCM), following the formula provided by The International Dairy Federation (IDF, 2015):

$$\mathbf{FPCM}(\text{kg}) = milk\ production\ (kg) \times [0.1226 \times fat\ (\%) \times 0.0776 \times protein\ (\%) + 0.2534]$$

The protein from both milk and meat of culled cows and calves were taken into account, while meat from animals that died for injury or disease were excluded because they do not contribute to food meat production. The consumable portion of meat was calculated assuming a carcass yield of 57% (ISTAT, 2022) and a real consumption yield of 50.7% (Russo et al., 2017), resulting in real edible kilograms per year (0.3 kg of real edible meat per kg of animal).

For the calculation of human digestible protein (HDP) in milk, meat, and in the five food crops, the protein content (g/kg DM) and the protein digestibility from Van Zanten et al. (2019) were used.

2.2. Human-edible feed conversion net ratio (heFCR$_n$)

The human-edible Feed Conversion net Ratio (heFCR$_n$) is defined as the potential human-edible input via feedstuffs as gross energy (GE) and crude protein (CP) divided by human-edible output in the form of animal products. The heFCR$_n$ was calculated modifying the index defined by Berton et al. (2020) (heFCR). In particular, it takes into account the energy and protein content of both feed and the resulting milk and meat products:

$$\mathbf{Energy} : \frac{Human\ edible\ MJ}{ASF\ (milk\ and\ meat) MJ}$$

$$\mathbf{Protein} : \frac{Human\ edible\ CP}{ASF\ (milk\ and\ meat) CP}$$

Values <1 indicate that the conversion of feed into animal products is efficient, in terms of feed-food competition.

Starting from the diets of each animal category, the feed used in the rations was aggregated to obtain the total feed consumed by the herd (including lactating cows, dry cows, heifers, and calves), similar to the approach used for the LUR calculation. The amount of CP and GE of each feedstuff were multiplied by kilograms of dry matter of the respective feedstuff, and subsequently by the edibility coefficient. Edible coefficients for energy and protein were assigned based on Ertl et al. (2015; medium scenario), and the energy and protein content in the diet, along with the portion of edible energy and protein was calculated accordingly. Moreover, edible coefficients of 0.15, 0.3, 0.8 were considered for sorghum and triticale silages, linseed and soy oil, respectively (Table 1). The Feedipedia database (2021–2022) was used for obtaining the dry matter, energy and protein content of individual feed. To calculate the heFCR$_n$, the edible portion of by-product was considered according to Ertl et al. (2015).

For the determination of heFCRn, the farm food production was based on FPCM (IDF, 2015), and meat. According to Ertl et al. (2015), for milk, an energy content of 3.17 MJ/kg and a protein content of 34 g CP/kg FPCM were considered, while for meat values of 6.48 MJ/kg and 190 g CP/kg were used. Similar to the approach used in calculating the LUR, meat from culled cows and calves was considered, excluding animals that died due to injury or disease. The portion of real edible meat (real edible kg/year) was calculated using the same approach applied for LUR. Finally, the heFCR$_n$ for energy and protein was calculated by relating potentially edible energy and protein to the energy and protein derived from animal products (i.e., milk and meat).

Table 1
Edible coefficients of the feed for Protein (P) and Energy (E).

FEED	P	E
Wheat (Ertl et al., 2015)	0.80	0.80
Barley (Ertl et al., 2015)	0.65	0.65
Maize (Ertl et al., 2015)	0.80	0.80
Rye (Ertl et al., 2015)	0.80	0.80
Bran (Ertl et al., 2015)	0.10	0.10
Peas (Ertl et al., 2015)	0.80	0.64
Soybeans (Ertl et al., 2015)	0.92	0.64
Soybeans extract meal (Ertl et al., 2015)	0.71	0.43
Soybeans cake (Ertl et al., 2015)	0.71	0.54
Sunflower extract meal (Ertl et al., 2015)	0.30	0.12
Sunflower cake (Ertl et al., 2015)	0.30	0.25
Rapeseed extract meal (Ertl et al., 2015)	0.59	0.26
Rapeseed cake (Ertl et al., 2015)	0.59	0.36
Maize silage (Ertl et al., 2015)	0.29	0.29
Sorghum silage	0.15	0.15
Triticale silage	0.15	0.15
Linseed	0.30	0.30
Soy oil	0	0.80

2.3. Global warming potential

The evaluation of Global Warming Potential (GWP) of milk production on the ten farms was performed through LCA method, structured following ISO 14040- and ISO 14044- LCA methodology (ISO 14040, 2006, ISO 14044, 2006). An attributional LCA approach was applied considering the same system boundaries used for the LUR and HeFCR$_n$ indices. The functional unit (FU) was defined as one kilogram of FPCM, and GWP was expressed as CO_2 eq/kg FPCM. Allocation between milk and meat was performed using a physical method (IDF International Dairy Federation, 2015). System boundaries encompassed the production lifecycle from cradle to farm gate. On farm emissions were calculated following IPCC guidelines (2019a,b). More detailed information regarding on farm emissions can be found in Rota Graziosi et al. (2022). Emissions associated to off-farm activities were calculated by using the Ecoinvent V3.8, 2021 and Agri-footprint V6, 2022 databases. Direct Land Use Change (LUC) related to soybean meal and oil was included in the assessment using the values from the Agri-Footprint database for Soybean meal, from crushing (solvent), at plant/BR Economic and Crude soybean oil, from crushing (solvent), at plant/BR Economic. Life cycle impact assessment was performed using Simapro software with the EF method (EF 3.0 adapted V1.03). Differences between biogenic and fossil methane were taken into account.

2.4. Evaluation of percentage of by-products in the animal rations

All materials resulting from primary main processing for human food production were classified as by-products. The proportion of by-products in the animal ration was calculated as fed, using the formula:

$$\left(\frac{kg\ by-product}{kg\ tot\ feed}\right)^{*}100$$

The LUR takes into account the unit of land, which is inseparable and thus assignable only to the main product. For this reason, the soybean cake (extracted meal) was also considered as a by-product, because oilseed meal and cake are non-competing for land (Sandström et al., 2022; Rashwan et al., 2023). In 2022/2023 the total oil-crop production was 640.9 million tonnes with 253.7 million tonnes of oils and fats and 164.0 million tonnes of meals and cakes produced. Utilization figures were 253.1 and 161.3 million tonnes, respectively (Food Outlook, FAO, 2023a). The $heFCR_n$ accounts for the edible portion, thus the value of the by-product depends on the percentage of edibility: wheat bran, soybean, sunflower and rapeseed meal are considered food-competing because they have a potential edible portion. The GWP considers the impact, which, being dynamic, is distributed across both the main product and the by-product.

2.5. Statistical analysis

Descriptive statistics and regression analysis were performed using Microsoft Excel. Statistical analyses were conducted using SAS 9.4 (2012, SAS Institute Inc., Cary, NC), utilizing Multiple Correspondence Analysis: to explore the relationship among farm size, farm milk production level, Utilized Agricultural Area (UAA), percentage of by-products used in the animal diets, heFCRn for energy, heFCRn for protein, LUR and GWP (Proc CORRESP; SAS). Variables were classified on the basis of mean value for farm size, farm milk production level, Utilized Agricultural Area - UAA, percentage of by-products used in the diet, GWP, while $heFCR_n$ for energy, $heFCR_n$ for protein and LUR were classified as above or below 1. Principal component regression was carried out using R software (RStudio, version: 2023.06.2 + 561) to identify the farm factors with the greatest influence on LUR. The analysis included the first five principal components, which explained the majority of the variability (98.88%). Additional components were not included as they did not contribute substantially to the model (Fig. 2).

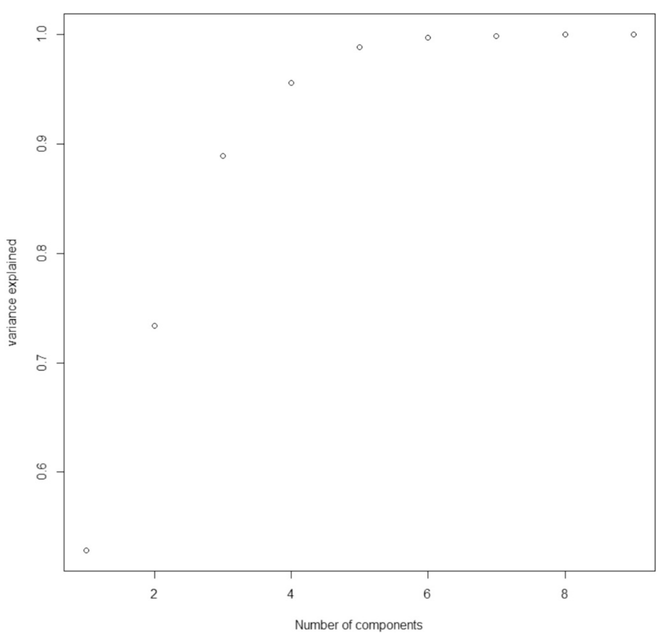


Fig. 2. Principal component and variance explained of farm variables.

3. Results

Table 2 showed the main characteristics of the dairy farms under study. The ten farms had an average of 208 ± 171 mature cows, and produced 2008 ± 1959 t of milk per year. The milk produced per hectare averaged 28.3 ± 21.1 t FPCM/ha per year, indicating that their high level of intensivity. The average protein content (CP% on DM) of the rations (Supplement 1) was: 15.8 ± 1.6% for lactating cows, 12.6 ± 2.6% for dry cows, and 13.2 ± 3.5% for replacement animals (heifers and calves). In terms of energy content (EG MJ/kg DM), the average values were: 17.5 ± 0.5 MJ/kg DM for lactating cows, 17.1 ± 0.34 MJ/kg DM for dry cows, and 17.3 ± 0.3 MJ/kg DM for replacement animals. The replacement rate was 44.2 ± 9.0%, on average. (See Table 2.)

Utilized agricultural area (UAA) was on average 72.9 ± 47.7 ha, allocated as follows: 36.0 ± 55.7 ha for arable crops (mainly maize), 8.6

Table 2
Coefficients of the Principal component regression (PCR) with Land Use Ratio (LUR) as dependent variable (y).

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	1.07	0.16	6.79	0.002	**
x_pcrPC1	−0.32	0.08	−4.21	0.014	*
x_pcrPC2	0.01	0.12	0.05	0.964	
x_pcrPC3	0.04	0.14	0.25	0.812	
x_pcrPC4	0.12	0.21	0.56	0.605	
x_pcrPC5	−0.29	0.31	−0.94	0.400	

Table 2
Characteristics of the studied farms.

Farm	FPCM sold[a]	FPCM cow[b]	Animals[c]	UAA[d]	LU[ef]	RR	By-prod[g]	UAA[d] arable	UAA[d] grassland[h]	UAA[d] permanent grassland[i]	Suit[l]	DE[m]
1	470	20	90	30	3.7	26	6	29.8	0	0	7.5	0.8
2	657	32	70	40	2.6	44	12	0	0	40	6.0	1.3
3	793	25	108	51	3.4	48	19	0	28	23.0	5.9	1.2
4	894	30	97	52	3.4	55	9	40.8	11.5	0	7.8	1.2
5	927	32	100	56	2.5	40	16	6	10	40	3.7	1.1
6	1155	23	190	104	2.7	40	0	44	13.3	46.7	7.7	0.9
7	1365	34	118	17	7	45	5	14.9	1.6	0.5	7.5	1.5
8	3434	29	397	110	4.9	37	20	7.3	87.8	15	5.6	1.2
9	3966	38	330	94	6	53	22	87.5	6.5	0	7.7	1.5
10	6420	34	580	175	3.3	54	16	130	5	40	7.5	1.2

[a] FPCM sold: Fat Protein Corrected Milk, tons/year.
[b] FPCM cow: Fat Protein Corrected Milk, kg head/d.
[c] Animals: number of mature cows.
[d] UAA: Utilized Agricultural Area, ha.
[e] LU: Livestock Unit per hectare.
[f] RR Replacement rate (%).
[g] By-prod: Percentage of by-products used in the diet.
[h] grassland: Crops >1 year (e.g. lucerne).
[i] permanent grassland: Crops >10 year (e.g. permanent grassland).
[l] Suit: Average suitability index of farmland (index proposed by GAEZ /1000). Index >5.5 = suitable.
[m] DE: Dairy Efficiency.

± 11.6 ha for grassland (grassland over 1 year old, e.g. lucerne) and 20.5 ± 19.8 ha for permanent grassland (grassland over 10 years old) (Table 1). The suitability index of farmland averaged 6.7 ± 1.4. Dairy Efficiency was on average 1.2 ± 0.2.

3.1. Land Use Ratio

The results related to the LUR index are presented in Fig. 3.

On the average, the LUR was 1.07 ± 0.8, with results showing high variability (Fig. 3). The relationship between LUR and GWP of milk production in the 10 studied farms is depicted in Fig. 4. On average, the GWP was 2.05 ± 0.3 kg CO_2 eq/kg FPCM displaying considerable variability (from a minimum of 1.56 kg CO_2 eq/kg FPCM to a maximum of 2.51 kg CO_2 eq/kg FPCM) mainly influenced by the milk production per cow and the amount of purchased feed. A strong correlation between LUR and the GWP of milk production emerged ($R^2 = 0.60$; Fig. 4): farms with greater GWP exhibited unfavourable LUR values.

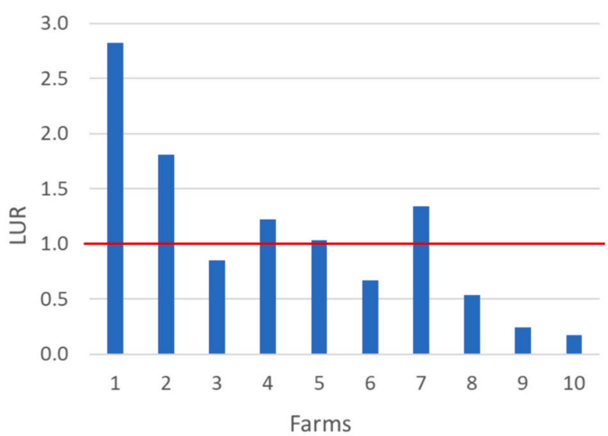


Fig. 3. Land Use Ratio (LUR) of the 10 studied farms.

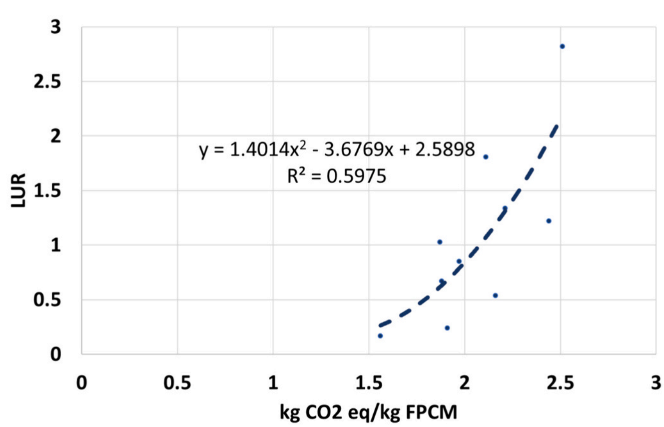


Fig. 4. The relationship between land use ratio (LUR) and GWP of milk production of the 10 studied farms (kg CO_2 eq/kg FPCM).

A negative relationship was also found between LUR and the percentage of by-products in the animal ration ($R^2 = 0.50$;Fig. 5): the farms with a higher percentage of by-products in the ration tended to have lower LUR values. Additionally, an inverse relationship between Dairy efficiency and LUR emerged ($R^2 = 0.20$).

A relationship between LUR and Utilized Agricultural Area (UAA) has been highlighted ($R^2 = 0.77$): farms with the largest UAA had lower LUR values. Additionally, those with highest number of animals exhibited the lowest LUR ($R^2 = 0.82$), and those with the highest milk yield showed lower LUR values, as well ($R^2 = 0.86$; Fig. 5). Relationships also emerged between GWP and annual milk sold ($R^2 = 0.42$), number of animals ($R^2 = 0.38$), and UAA ($R^2 = 0.52$): farms with highest milk production, number of animals, and UAA tended to have the lowest GWP per kg FPCM.

3.2. Human edible feed conversion net ratio ($heFCR_n$)

The indices of $heFCR_n$ were calculated for the ten farms and results are reported in Fig. 6.

On average, $heFCR_n$ was 1.87 ± 0.92 for protein (Fig. 1A) and 1.95 ± 0.89 for Energy (Fig. 1B).

The $heFCR_n$ for protein showed a strong relationship with GWP (kg CO_2 eq/kg FPCM) ($R^2 = 0.88$) (Fig. 7A), as did the $heFCR_n$ for energy (kg CO_2 eq./kg FPCM) ($R^2 = 0.65$) (Fig. 7B). Farms with higher GWP per kg FPCM also exhibited more unfavourable $heFCR_n$.

3.3. Multiple correspondence analysis

Fig. 8 shows the Multiple Correspondence Analysis among farm characteristics, LUR, $heFCR_n$ for energy and protein, and GWP expressed in terms of kg of CO_2 eq./kg FPCM. Dimension 1 explained almost 50% of the variability, while dimension 2 explained approximately 34%. The figure shows the existence of relationships between LUR values below 1, UAA above 73 ha, a number of mature cows exceeding 150, and annual milk production above 1000 tons. Conversely, LUR values above 1 were associated to UAA below 73 ha, a number of mature cows below 150, and milk production below 1000 tons. Values of GWP per kg of FPCM above 2 were associated with both $heFCR_n$ values for energy and protein above 1.5, as well as with percentages of by-products in the cattle diet below 12.5% on a dry matter basis. Conversely, GWP values per kg of FPCM below 2 were related to the inclusion of by-products in the diet above 12.5% of the dry matter.

3.4. Principal Component Regression (PCR)

The principal component regression (PCR) revealed an inverse correlation (−0.32) between LUR and PC1. The PC1 is statistically significant and explains the majority of LUR variability (Table 2). Principal component (1 and 2) and the relationship with the original variables are shown in Fig. 9. Farms with lower LUR, which produce more milk, and have more animals, UAA and by-product percentage in animal diets, tend to exhibit lower $heFCR_n$ and GWP, confirming the results of the linear regression: larger and more productive farms have lower LUR. Moreover, LUR showed correlations with the other indices, $heFCR_n$ and GWP. Farms tend to be grouped on both the PC1 and PC2 axes. Farms 1, 7 and 4 have high LURs while farms 8, 9, 10 have lower LURs as evidenced by their grouping on PC1. Similarly, farms tend to be grouped on

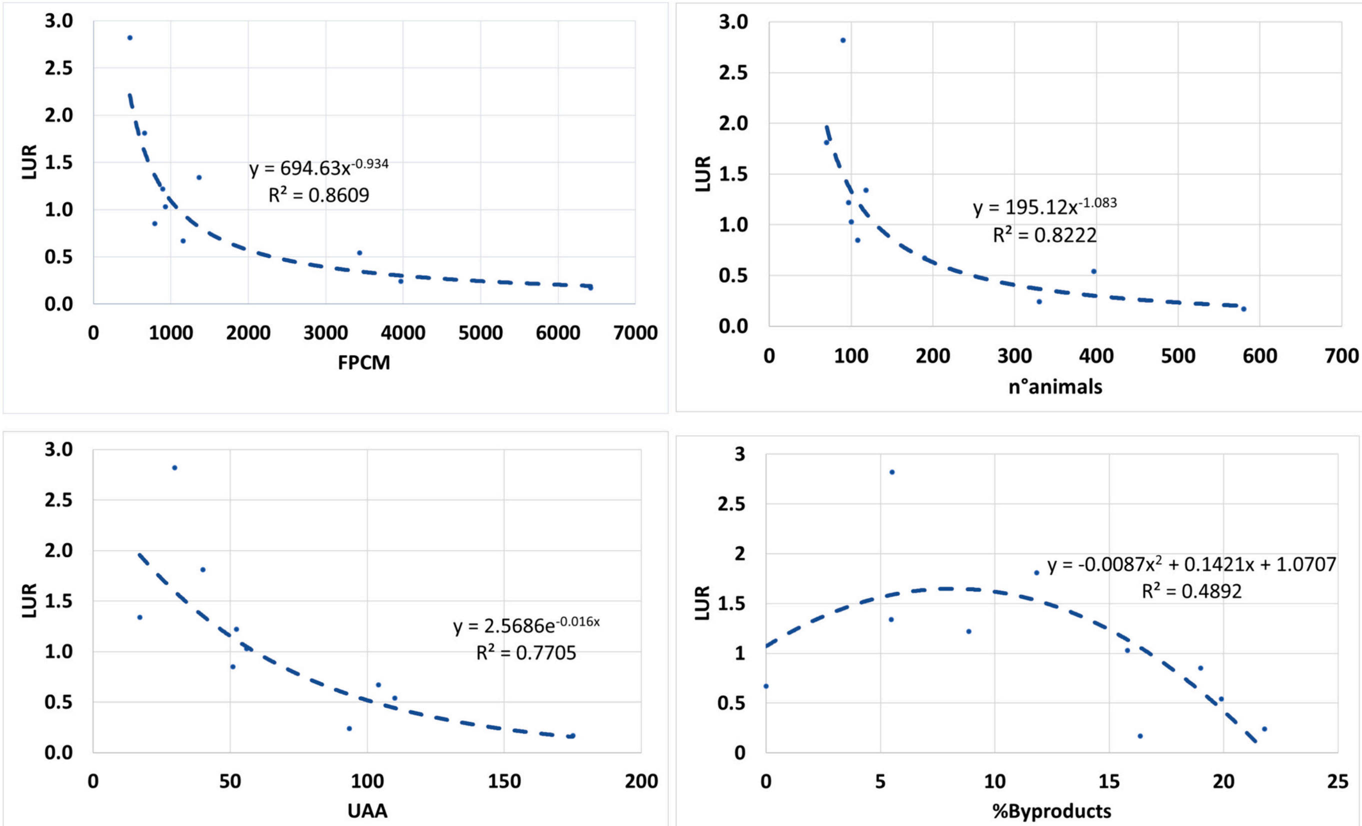


Fig. 5. The relationship between land use ratio (LUR) and milk sold (FPCM, tons), number of animals (mature cows), Utilized Agricultural Area, percentage of by-products in the animal ration of the 10 studied farms.

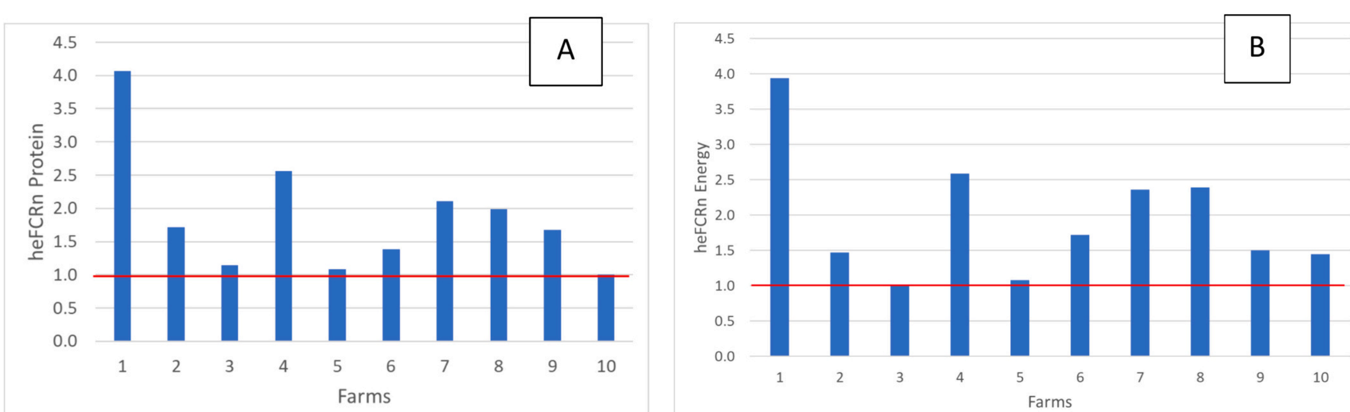


Fig. 6. The human edible feed conversion net ratio ($heFCR_n$) for Protein and Energy of 10 farms studied.

PC2 with farms 2, 3, 5, 6 having lower animal density (livestock unit per hectare, LU), while farms 1, 7, 8, 9, 10 higher animal density.

However, PC2, primarily associated with the animal load on the farm (LU), does not show a significant relationship with LUR.

4. Discussion

In farms with LUR values below 1, the land allocated for feed did not compete with food crops, as the Human Digestible Protein (HDP) produced on the farm exceeded what could potentially be produced by using the land, both on and off farm, for food cultivation. These results may be explained by the farm size (annual milk production and number of animals) as these farms were characterized by larger herds and higher amount of milk delivered. Another relevant factor is meat production associated with milk: more productive farms, typically the largest ones in this study, tend to have a higher replacement rate (Rougoor et al., 1997), resulting in increasing culling of mature cows and greater meat production, thereby contributing to the HDP produced by the farm. However, maintaining a balanced replacement rate is crucial, in order to prevent the increase of unproductive animals and the increment of farm costs and resource wastage. One potential strategy is to utilize semen from fast-growing beef breeds on cows with low genetic value (Ahmed et al., 2023).

The influence of farm characteristics on LUR, and the other indices is evident. It is noteworthy that the animal load did not affect LUR, showing the importance of optimizing production system efficiency by combining inputs effectively (Hansson, 2008).

In this study, the land suitability among the farms was similar, as

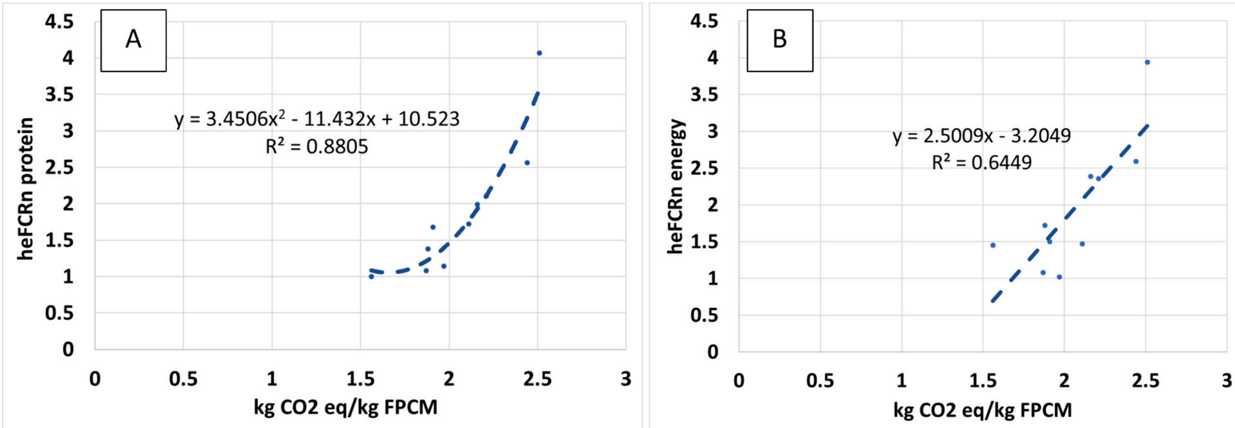


Fig. 7. Relationship between human edible feed conversion net ratio ($heFCR_n$) for Energy and Protein and Global Warming Potential of milk production (kg CO_2 eq/kg FPCM) in the 10 studied farms.

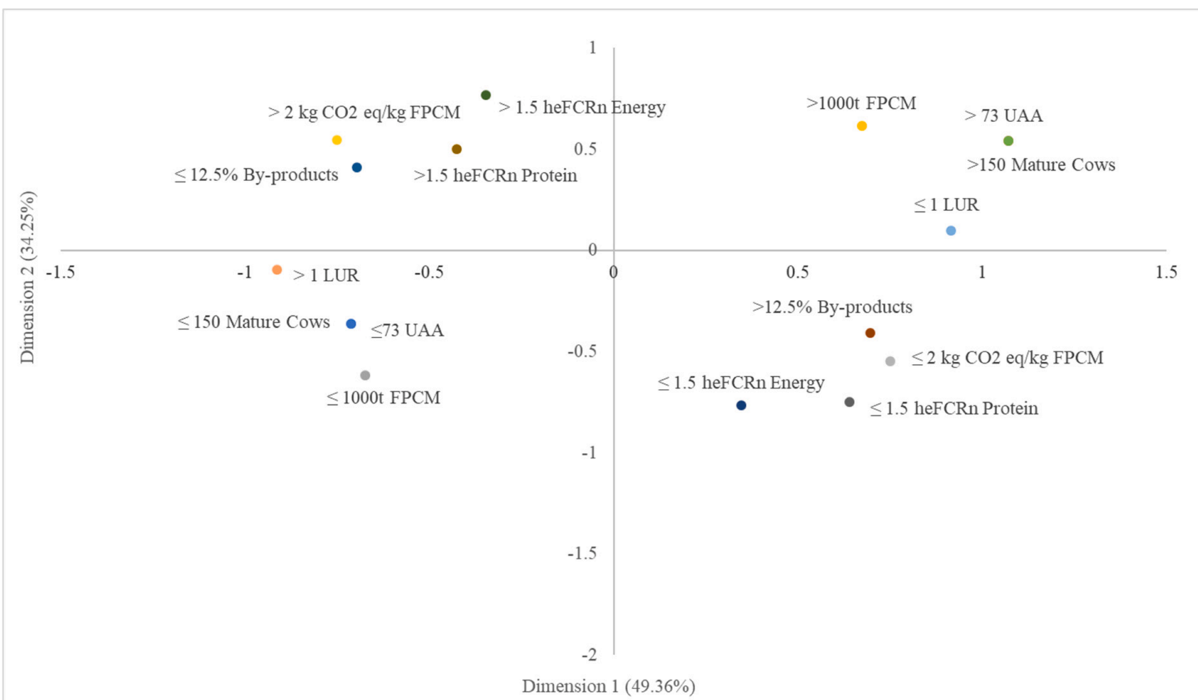


Fig. 8. Multiple correspondence analysis between Human edible feed conversion net ratio ($heFCR_n$) for protein and energy, Land Use Ratio (LUR), percentage of by-products in animal ration (%By-products), milk produced (tons), number of animals, Utilized Agricultural Area (UAA), Global Warming Potential (kg CO_2 eq/kg FPCM).

they were all intensive and located in the same region characterized by strong vocation for agriculture. Hence, farm management and external feed emerged as the primary factors driving variability. However, examining farms located in different territories, soil fertility may become a predominant factor. In this study, soil fertility did not have relevant effects as some of the most efficient farms, in terms of land use efficiency, exhibited high suitability indexes.

On average, the LUR was consistent with previous studies: Van Zanten et al. (2019) obtained a value of 1.39 based on a representative animal ration and farm type (dairy cows on sandy and peat soils). The present study revealed remarkable differences in the land use efficiency among the 10 farms, ranging from highly efficient to highly inefficient farms (min = 0.2, max = 2.8), indicating that the average value may not be representative. It is important to analyse the most efficient farms to identify the factors that can mitigate feed-food competition. This study showed that land dedicated to food crops does not always outperform livestock in producing HDP; in addition, the superior biological value of animal-origin proteins, which is not accounted for in LUR calculation, should be considered.

All farms obtained $heFCR_n$ value >1 for both energy and protein, indicating inefficiency in converting feed into food, as the human edible portion (energy and protein) in animal rations was not fully compensated by the Animal Source Food (ASF) produced. However, in grass based farms, the feed food competition was lower due to extensive pasture use (Verduna et al., 2020). Nevertheless, some farms in the present study exhibited values slightly exceeding 1, suggesting that minor changes in animal rations or in milk production levels could enhance efficiency. The large variability among farms indicates significant potential for improvement.

Given the intensive traits of the farms and the extensive use of

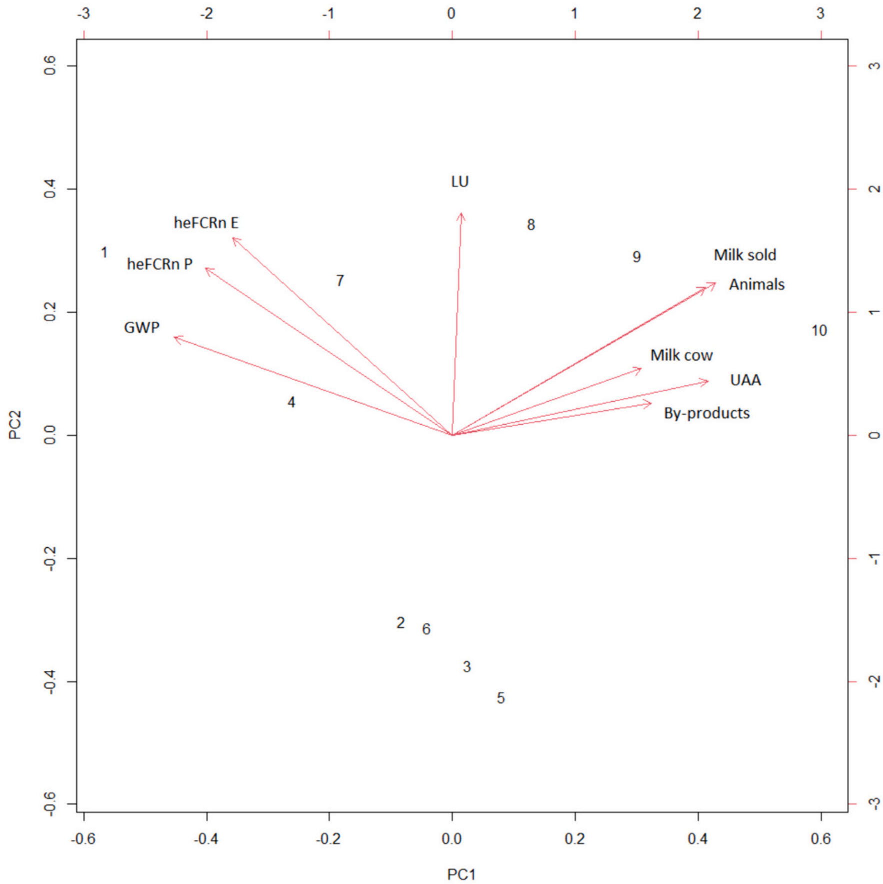


Fig. 9. Relationship between Principal component and original variables of the 10 studied farms. Milk sold: Fat and protein corrected milk (tons/year); Milk cow: fat and protein corrected milk per head (kg cow/d); Animals: number of mature cows; UAA: Utilized Agricultural Area; By-products: percentage of by-products in the animal ration; LU: Livestock unit (LU/ha); heFCRn E: human edible feed conversion net ratio for Energy); heFCRn P: human edible feed conversion net ratio for Protein; GWP: Global warming Potential CO_2 eq/kg FPCM. PC1 is statistically significant and explains 32% of LUR variability (the dependent variable).

concentrate feed, feed-foodcompetition on the ration was expected. Concentrate feeds generally contain raw materials with a significant human edible portion (Berton et al., 2020). One potential strategy to reduce competition could be the utilization of raw materials in animal rations derived from non-edible by-products or alternative protein sources with a high nutritional profile (Van Zanten et al., 2019) such as algae, insects, meat and bone meals. Verduna et al. (2020) indicated that the replacement of cereal grains and pulses in cow diets with by products in grazing system reduces food-feed competition thereby improving the sustainability of traditional dairy systems, reducing also the risk of generating nutrient surplus (Flach et al., 2021). Generally speaking, values for $heFCR_n > 1$ for protein do not necessarily reflect a loss, as protein produced by animal systems tends to be of higher quality, compared to plant-based protein (Ertl et al., 2015). As reported by the same authors, milk amino acid patterns have a more favourable biological value, when compared to plant-based food.

The $heFCR_n$ index for protein was found to be highly correlated with the GWP of milk production, confirming the high environmental impact of protein sources in animal feed. Efficient utilization of protein feed, tailored to the physiological stages of the animals, can result in lower GWP of milk production. Balancing feed composition and maintaining an adequate amount of competing feed (concentrates) is crucial to maximize feed conversion efficiency and production, thus reducing food-feed competition and environmental impact. An appropriate amount of concentrate feed rich in protein could reduce the utilization of soybean meal enhancing the sustainability of the dairy cow systems (Rota Graziosi et al., 2022) and lowering GWP of milk production.

A positive relationship was observed between $heFCR_n$, LUR and GWP: farms with lower values of the indices also had lower emissions of kg CO_2 eq/kg FPCM (Berton et al., 2021). The most efficient farms, typically the largest and most productive, made the optimization of resource use possible (Van der Meulen et al., 2014). This point highlights the feasibility of sustainability in terms of reduced GWP and feed vs food competition within the livestock sector suggesting that optimizing farm management to maximize production with minimal resources investment is a viable strategy that aligns with economic sustainability. This perspective could offer an intriguing solution for countries like Italy, where competition for land use in agriculture and food production is heightened by limited fertile land availability.

The LUR showed a relationship with the percentage of by-products in animal rations. Generally speaking, the use of by-products for animal feed offers advantages also in terms of circularity, a critical topic for resource enhancement (de Boer and van Ittersum, 2018). By-products do not compete with human nutrition, and do not impact land use, since the land is cultivated for human food and by-products are considered waste; livestock farming transforms them into valuable products. It is noteworthy that there would seem to be an optimal utilization of by-products (between 15% and 20% of the animal diet), as excessive utilization can affect diet digestibility and feed conversion efficiency, depending on the type of by-product (Neto et al., 2015).

It must also be specified that extraction meal is a by-product. This emphasized that one of the strategies to reduce competition is to maximize the efficiency of the diet to avoid wasting protein resources. Indeed, farms with higher efficiency, in term of protein source, exhibited superior dairy efficiency.

The use of by-product in animal diets enhances land use efficiency, as it allows for increased production of derived products from the same land area. It is important to note that in the LCA perspective and for the evaluation of GWP, the land use is allocated among food product and by-products. Interestingly, farms with lower GWP, also had lower LUR and tended to use more by-products in the rations, showing that pursuing circularity could be a beneficial strategy for achieving economic, environmental and feed-food competition sustainability (Van Zanten et al., 2019; Ramirez et al., 2021; Freeman et al., 2022). However, a critical issue may arise regarding the availability of these by-products, which are often scarce or not transportable over long distances. Safety and regulation concerns are also significant, in particular for animal and food by-products (Van Raamsdonk et al., 2023) (Meijer et al., 2023).

The three indices exhibited a notable relationship, especially $heFCR_n$ for the protein with LUR. This relation is important as both metrics focus on protein: LUR considers land use, while $heFCR_n$ evaluates the human edible portion of feeds.

5. Conclusion

The novelty of this study lies in its comprehensive analysis of farm efficiency in producing food considering, at the same time, different indices linked to the sustainability of the farm process, alongside the Global Warming Potential of milk production. Notable relationships were observed among the three indices (human edible Feed Conversion net Ratio for energy and protein, $heFCR_n$ and Land Use Ratio, LUR) and Global Warming Potential, expressed per kg of FPCM. In particular, GWP resulted showed a close relationship with the $heFCR_n$ protein index, confirming the pivotal role of protein in animal feed for ensuring sustainability of milk production. Herd size, farm milk production, land availability and use of by-products in animal rations were found to be inversely correlated with LUR.

As illustrated in this study, the key strategies for increasing overall sustainability, in terms of GWP and animal-human competition, include increasing feed conversion efficiency and consequently milk production per cow and the use of by-products in the rations. These measures likely align with economic sustainability objectives. Further studies, encompassing different management systems, should be conducted for confirming these results. Additionally future researches should integrate an evaluation of the aminoacidic profile of both plant-based and animal-based products, in order to provide a comprehensive understanding of sustainability of milk production.

CRediT authorship contribution statement

Palladini Nicola Maria: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Gislon Giulia:** Writing – review & editing, Methodology, Formal analysis. **Sandrucci Anna:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Zucali Maddalena:** Writing – review & editing, Formal analysis. **Tamburini Alberto:** Validation, Formal analysis. **Bava Luciana:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103984.

References

Ahmed, R.H., Schmidtmann, C., Mugambe, J., Thaller, G., 2023. Effects of the breeding strategy beef-on-dairy at animal, farm and sector levels. Animals 13 (13), 2182.
Alonso, M.E., González-Montaña, J.R., Lomillos, J.M., 2020. Consumers' concerns and perceptions of farm animal welfare. Animals 10 (3), 385.
Assalzoo, 2022. Annuario.
Augstburger, H., Jacobi, J., Schwilch, G., Rist, S., 2018. Agroecosystem service capacity index–a methodological approach. Landscape Online 64, 1–48.
Berton, M., Bittante, G., Zendri, F., Ramanzin, M., Schiavon, S., Sturaro, E., 2020. Environmental impact and efficiency of use of resources of different mountain dairy farming systems. Agric. Syst. 181, 102806.
Berton, M., Bovolenta, S., Corazzin, M., Gallo, L., Pinterits, S., Ramanzin, M., Sturaro, E., 2021. Environmental impacts of milk production and processing in the eastern Alps: a "cradle-to-dairy gate" LCA approach. J. Clean. Prod. 303, 127056.
Correddu, F., Lunesu, M.F., Buffa, G., Atzori, A.S., Nudda, A., Battacone, G., Pulina, G., 2020. Can agro-industrial by-products rich in polyphenols be advantageously used in the feeding and nutrition of dairy small ruminants? Animals 10 (1), 131.
CPM Dairy Ration Analyzer v3.07bs. (2004).
CREA, 2022. L'agricoltura italiana conta. https://www.crea.gov.it/documents/68457/0/ITACONTA+2022_ITA_WEB.pdf/e1c4f49f-5fc4-12eb-180a-07327db02f90?t=1671525618819.
de Boer, I.J., van Ittersum, M.K., 2018. Circularity in Agricultural Production. Wageningen University & Research.
Elmadfa, I., Meyer, A.L., 2017. Animal proteins as important contributors to a healthy human diet. Ann. Rev. Anim. Biosci. 5, 111–131.
Ertl, P., Klocker, H., Hörtenhuber, S., Knaus, W., Zollitsch, W., 2015. The net contribution of dairy production to human food supply: the case of Austrian dairy farms. Agric. Syst. 137, 119–125.
FAO, 1997. Livestock & the Environment—Meeting the Challenge.
FAO, 2023a. Food Outlook, Biannual Report on Global Food Markets. November.
FAO, 2023b. Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes – an evidence and policy overview on the state of knowledge and gaps. FAO, Rome. https://doi.org/10.4060/cc3912en.
FAO, 2023c. Pathways towards lower emissions – a global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems. Rome. https://doi.org/10.4060/cc9029en.
FAOSTAT, 2021. Crops and livestock prpducts. https://www.fao.org/faostat/en/#data/QCL. Visited 12/01/2023. FAO, Rome.
FEFAC, the European Compound Feed Manufacturers' Federation, 2022. Feed & Food Statistical Yearbook. https://fefac.eu/statistics/.
Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D., Tramberend, S., 2021. Global Agro-Ecological Zones v4 – Model documentation. Rome, FAO. https://doi.org/10.4060/cb4744en.
Flach, L., Kühl, S., Lambertz, C., Gauly, M., 2021. Environmental impact and food production of small-scale mountain dairy farms at different supplementation levels. J. Clean. Prod. 310, 127429.
Freeman, K.K., Valencia, V., Baraldo, J., Schulte, R.P., van Zanten, H.H., 2022. On-farm circular technologies for enhanced sustainability: the case of Uruguay. J. Clean. Prod. 372, 133470.
GLEAM (Global Livestock Environmental Assessment Model) 3.0 Dashboard Assessment of greenhouse gas emissions and mitigation potential. https://www.fao.org/gleam/dashboard/en/.
Hansson, H., 2008. Are larger farms more efficient? A farm level study of the relationships between efficiency and size on specialized dairy farms in Sweden.
Hennessy, D.P., Shalloo, L., Van Zanten, H.H.E., Schop, M., De Boer, I.J.M., 2021. The net contribution of livestock to the supply of human edible protein: the case of Ireland. J. Agric. Sci. 159 (5–6), 463–471. https://www.assalzoo.it/wp-content/uploads/2023/02/Annuario_2022_web.pdf.
IDF International Dairy Federation, 2015. A common carbon footprint approach for dairy. The IDF guide to standard lifecycle assessment methodology for the dairy sector. In: In the Bulletin of the IDF no 479/2010. International Dairy Federation, Brussels, Belgium.
IIASA, FAO, . Global Agro-Ecological Zones (GAEZ v4.0). https://gaez.fao.org/pages/data-viewer. IIASA, Laxenburg, Austria and FAO, Rome, Italy.
IPCC. 2019a. IPCC (Intergovernmental Panel on Climate Change). Emissions from Livestock and Manure Management. Chapter 10 in Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, Vol 4 (2019): Agriculture, Forestry and Other Land Use.

IPCC. 2019b. IPCC (Intergovernmental Panel on Climate Change). N2O emissions from managed soils, and CO2 emissions from lime and urea application. Chapter 11 in Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, Vol 4 (2019): Agriculture, Forestry and Other Land Use.
ISMEA (Istituto di servizi per il mercato agricolo alimentare), 2021. SETTORE LATTIERO CASEARIO. SETTORE, SCHEDA DI.
ISO 14040, 2006. Environmental management — Life cycle assessment — Principles and framework.
ISO 14044, 2006. Environmental management — Life cycle assessment — Principles and framework.
ISTAT, 2022. Crops and Livestock. http://dati.istat.it/Index.aspx?DataSetCode=DCSP_COLTIVAZIONI. Visited 12/01/2023.
Janzen, H.H., 2011. What place for livestock on a re-greening earth? Anim. Feed Sci. Technol. 166, 783–796.
Lee, M.R.F., Domingues, J.P., McAuliffe, G.A., Tichit, M., Accatino, F., Takahashi, T., 2021. Nutrient provision capacity of alternative livestock farming systems per area of arable farmland required. Sci. Rep. 11 (1), 1–8.
Meijer, N., Van Raamsdonk, L.W., Gerrits, E.W., Appel, M.J., 2023. The use of animal by-products in a circular bioeconomy: Time for a TSE road map 3? Heliyon 9, 3.
Møller, H., Samsonstuen, S., Øverland, M., Modahl, I.S., Olsen, H.F., 2022. Local non-food yeast protein in pig production–environmental impacts and land use efficiency. Livest. Sci. 260, 104925.
Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Secur. 14, 1–8.
Neto, S.G., Oliveira, R.L., de Lima, F.H.S., de Medeiros, A.N., Bezerra, L.R., Viégas, J., de Freitas Neto, M.D., 2015. Milk production, intake, digestion, blood parameters, and ingestive behavior of cows supplemented with by-products from the biodiesel industry. Trop. Anim. Health Prod. 47, 191–200.
OECD/FAO, 2022. OECD-FAO Agricultural Outlook 2022-2031. OECD Publishing, Paris. https://doi.org/10.1787/f1b0b29c-en.
Oltjen, J.W., Beckett, J.L., 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74 (6), 1406–1409.
Pereira, P.M.D.C.C., Vicente, A.F.D.R.B., 2013. Meat nutritional composition and nutritive role in the human diet. Meat Sci. 93 (3), 586–592.
Ramirez, J., McCabe, B., Jensen, P.D., Speight, R., Harrison, M., Van Den Berg, L., O'Hara, I., 2021. Wastes to profit: a circular economy approach to value-addition in livestock industries. Anim. Prod. Sci. 61 (6), 541–550.
Rashwan, A.K., Bai, H., Osman, A.I., Eltohamy, K.M., Chen, Z., Younis, H.A., Yap, P.S., 2023. Recycling food and agriculture by-products to mitigate climate change: a review. Environ. Chem. Lett. 21 (6), 3351–3375.
Rinehart, L., 2008. Ruminant Nutrition for Graziers. National Sustainable Agriculture Information Service (ATTRA).
Rota Graziosi, A., Gislon, G., Colombini, S., Bava, L., Rapetti, L., 2022. Partial replacement of soybean meal with soybean silage and responsible soybean meal in lactating cows diet: part 2, environmental impact of milk production. Ital. J. Anim. Sci. 21 (1), 645–658.
Rougoor, C.W., Dijkhuizen, A.A., Huirne, R.B.M., Mandersloot, F., Schukken, Y.H., 1997. Relationships between technical, economic and environmental results on dairy farms: an explanatory study. Livest. Prod. Sci. 47 (3), 235–244.
Russo, V., Danieli, P.P., De Angelis, A., 2017. Consumo reale di carne e di pesce in Italia: dal consumo apparente al consumo reale con il metodo della detrazione preventiva delle perdite. Consumo reale di carne e di pesce in Italia 1–286.
Sá, A.G.A., Moreno, Y.M.F., Carciofi, B.A.M., 2020. Plant proteins as high-quality nutritional source for human diet. Trends Food Sci. Technol. 97, 170–184.
Sandström, V., Chrysafi, A., Lamminen, M., Troell, M., Jalava, M., Piipponen, J., Kummu, M., 2022. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. Nat. Food 3 (9), 729–740.
Schönfeldt, H.C., Pretorius, B., Hall, N., 2013. The impact of animal source food products on human nutrition and health. South African J. Anim. Sci. 43 (3), 394–412.
Te Velde, H., Aarts, N., Van Woerkum, C., 2002. Dealing with ambivalence: farmers' and consumers' perceptions of animal welfare in livestock breeding. J. Agric. Environ. Ethics 15 (2), 203–219.
Van der Meulen, H.A.B., Dolman, M.A., Jager, J.H., Venema, G.S., 2014. The impact of farm size on sustainability of dutch dairy farms. Int. J. Agric. Manag. 3 (1029-2016-82294), 119–123.
Van Hal, O., Weijenberg, A.A.A., De Boer, I.J.M., Van Zanten, H.H.E., 2019. Accounting for feed-food competition in environmental impact assessment: towards a resource efficient food-system. J. Clean. Prod. 240, 118241.
Van Raamsdonk, L.W., Meijer, N., Gerrits, E.W.J., Appel, M.J., 2023. New approaches for safe use of food by-products and biowaste in the feed production chain. Journal of Cleaner Production 388, 135954.
van Zanten, H.H., Mollenhorst, H., Klootwijk, C.W., van Middelaar, C.E., de Boer, I.J., 2016. Global food supply: land use efficiency of livestock systems. Int. J. Life Cycle Assess. 21 (5), 747–758.
Van Zanten, H.H., Van Ittersum, M.K., De Boer, I.J., 2019. The role of farm animals in a circular food system. Glob. Food Sec. 21, 18–22.
Verduna, T., Blanc, S., Merlino, V.M., Cornale, P., Battaglini, L.M., 2020. Sustainability of four dairy farming scenarios in an alpine environment: the case study of Toma di Lanzo cheese. Front. Vet. Sci. 7, 569167.
Williams, E., Vardavoulia, A., Lally, P., Gardner, B., 2023. Experiences of initiating and maintaining a vegan diet among young adults: a qualitative study. Appetite 180, 106357.
Wu, G., 2020. Important roles of dietary taurine, creatine, carnosine, anserine and 4-hydroxyproline in human nutrition and health. Amino Acids 52 (3), 329–360.

Further-reading

Feedipedia - Animal Feed Resources Information System - INRAE CIRAD AFZ and FAO © 2012–2022. https://www.feedipedia.org/. Visited 12/01/2023.