Relationship between milk intrinsic quality scores and the environmental impact scores of dairy farms

Mathieu Lepoivre, Claire Laurent, Bruno Martin, Paul-Marie Grollemund, Raphaëlle Botreau, Françoise Monsallier, Sophie Hulin, Pauline Gerber, Christophe Chassard, Mauro Coppa

Italian Journal of Animal Science

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjas20

Relationship between milk intrinsic quality scores and the environmental impact scores of dairy farms

Mathieu Lepoivre, Claire Laurent, Bruno Martin, Paul-Marie Grollemund, Raphaëlle Botreau, Françoise Monsallier, Sophie Hulin, Pauline Gerber, Christophe Chassard & Mauro Coppa

To cite this article: Mathieu Lepoivre, Claire Laurent, Bruno Martin, Paul-Marie Grollemund, Raphaëlle Botreau, Françoise Monsallier, Sophie Hulin, Pauline Gerber, Christophe Chassard & Mauro Coppa (2024) Relationship between milk intrinsic quality scores and the environmental impact scores of dairy farms, Italian Journal of Animal Science, 23:1, 1220-1232, DOI: 10.1080/1828051X.2024.2392796

To link to this article: https://doi.org/10.1080/1828051X.2024.2392796

Published online: 20 Aug 2024.

ITALIAN JOURNAL OF ANIMAL SCIENCE
2024, VOL. 23, NO. 1, 1220–1232
https://doi.org/10.1080/1828051X.2024.2392796

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Relationship between milk intrinsic quality scores and the environmental impact scores of dairy farms

Mathieu Lepoivre[a], Claire Laurent[a], Bruno Martin[a], Paul-Marie Grollemund[b], Raphaëlle Botreau[a], Françoise Monsallier[c], Sophie Hulin[d], Pauline Gerber[d], Christophe Chassard[a] and Mauro Coppa[e]

[a]Université Clermont Auvergne, INRAE, Aurillac, France; [b]Université Clermont Auvergne, CNRS, LMBP, Aurillac, France; [c]Chambre d'Agriculture du Cantal, Aurillac, France; [d]Pôle Fromager AOP Massif Central, Aurillac, France; [e]Department of Agricultural, Forest and Food Sciences, University of Turin, Turin, Italy

ABSTRACT
This study aimed to study the relationship between milk quality for cheese manufacturing and farm's environmental impacts in grass-based mountain systems. Beforehand, the multi-criteria evaluation methodology proposed by Botreau et al. and Rey-Cadilhac et al. was adapted to a routine use. Milk quality scores were constructed by weighing traits possibly predicted by spectroscopic analyses currently available in milk labs into 4 dimensions: health, nutritional, technological and sensory. Environmental impact scores were constructed by combining 6 indicators of the CAP'2ER® software in 5 dimensions: greenhouse gas emissions, eutrophication, air acidification, consumption of space and non-renewable energies and ecosystem biodiversity. The study sample included 15 dairy farms located in the French Massif Central mountains. An analysis of variance was carried out to study the effect of system's types on milk quality and environmental impact scores. A principal component analysis was used to study the relationship between milk quality and environmental impact dimensions scores. No correlation has been established between overall milk quality and overall environmental impact scores. High scores for the nutritional and biodiversity dimensions and low scores for the resource consumption dimension, were associated with farming practices such as a high proportion of grasslands in the usable agricultural area, low stocking rate and low productivity per cow. This demonstrates the importance of defining specific priority objectives, on a farm-by-farm basis, in order to drive changes in agricultural practices. The multi-criteria evaluation model tested here appeared sensitive, but it needs to be tested on a larger scale and in different contexts.

HIGHLIGHTS

- We developed an operational method for multi-criteria assessment of intrinsic milk quality and environmental impacts
- We did not find correlations between overall quality and overall environmental impact scores
- Some dimensions of milk quality were correlated with some environmental dimension

ARTICLE HISTORY
Received 10 April 2024
Revised 19 June 2024
Accepted 5 August 2024

KEYWORDS
Multi-criteria assessment; dairy cow; cheese-making; environmental assessment; life cycle

Introduction

Societal expectations of dairy products are constantly changing through growing demand for product quality and the environmental impact of the farming system (Lebacq et al. 2013; Farruggia et al. 2014; European Union 2020). The dairy sector needs to position the products in relation to these expectations (Prache et al. 2022). This explains the growing interest in the development of multi-criteria assessment methodologies (Lairez et al. 2015) of the quality of dairy products (Müller-Lindenlauf et al. 2010; Zucali et al. 2016; Prache et al. 2022) and/or the environmental impacts of their manufacture (Müller-Lindenlauf et al. 2010; Botreau et al.2018; Prache et al. 2022).

However, most of the studies listed are not exhaustive in terms of assessing the environmental impacts and/or intrinsic milk quality. Global studies are rare due to several difficulties: the multidisciplinary nature of the issues addressed, the high cost of analysing certain milk compounds, and the time required to collect descriptive data at farm level to implement the indicators. This is why the correlations between all

CONTACT Mathieu Lepoivre mathieu.lepoivre@uca.fr Université Clermont Auvergne, INRAE, Aurillac, France.

the environmental and milk quality dimensions remain poorly studied: research is often limited to certain aspects of quality or the environment (particularly the carbon footprint; Lambotte et al. 2021). However, some authors have highlighted the lack of correlations between the overall intrinsic milk quality scores and the overall environmental impact scores of a system of farms (Penati et al. 2009; Bava et al. 2014; Botreau et al. 2018).

The aim of our work was to study the relationship between milk quality and farm's environmental impacts in grass-based mountain systems. Beforehand, the methodology proposed by Botreau et al. (2018) and Rey-Cadilhac et al. (2021) was adapted to a routine use. To achieve this goal, environmental impact was measured using a life cycle analysis approach by CAP'2ER® software (Moreau et al. 2016) and rapid milk analyses based on spectroscopy.

Materials and methods

Intrinsic milk quality evaluation methodology

The intrinsic milk quality assessment (noted quality assessment thereafter) is an adaptation of the one proposed by Rey-Cadilhac et al. (2021): a participatory construction method for the overall assessment of intrinsic milk quality based on indicators obtained from raw bulk tank milk analyses. The overall quality had to be defined in several dimensions or qualities, then subdivided into principles and criteria (and sub-criteria if needed) that itemised the principles into more concrete categories. Criteria were assessed by indicators that were measurable (=raw data) (Lairez et al. 2015).

The modifications concern 3 points:

1. Selection of indicators that can be only obtained by medium infra-red spectroscopy (MIR) or by fluorescence and that are systematically analysed by French laboratories,
2. Transformation of quantitative data into qualitative data for 5 indicators (C18:*cis*9/C16:0 ratio and C4:0, C17:0, ALA and PUFA concentrations, highlighted in grey in Figure 1) for which the reliability of spectroscopic prediction models was not considered equivalent to the reference method in the literature. For this, we applied the value class approach developed by Coppa et al. (2017),
3. Use of weighted averages to aggregate indicators into criteria, which in turn are aggregated into principles, which in turn are aggregated into dimensions.

All these modifications were obtained through a series of technical committees, with the conciliation of scientific experts (the authors of this article).

The obtained quality assessment was based on 4 dimensions, 7 principles, 16 criteria and 26 indicators (Figure 1). For each of these indicators, favourable and unfavourable thresholds were established according to the methodology of Rey-Cadilhac et al. (2021), which, in the case of quantitative indicators, allowed a score to be assigned between 0 (lowest quality) and 10 (highest quality) by linearly transforming the quantitative values between the two thresholds. For qualitative indicators, the best and worst classes had a value of 10 and 0 respectively. The intermediate classes had fractional values of 10/n-1, where n is the number of classes. It should be noted that for the ratio C18:1cis 9/C16:0, a score of 10 was obtained for an optimal value of 0.9 according to Rey-Cadilhac et al. (2021), so it was decided to give the value of 10 to the class containing this value. The 2 adjacent classes were assigned a value of 5.

Environmental impacts evaluation methodology

The environmental impact assessment (noted the environmental assessment thereafter) is an adaptation of the one proposed by Botreau et al. (2018): a multi-criteria assessment methodology combining environmental performance assessment and milk quality assessment. The modifications concern 2 points: 1/the exclusive use of the indicators present in the CAP'2ER® tool, 2/the use of the weighted average to aggregate the indicators, criteria and dimensions.

Following agreement between the authors in a series of technical committees, the environmental assessment is the made up of 5 dimensions, 6 criteria, and 6 indicators (Figure 2). All indicators are expressed per 1000 kg of milk produced, except for biodiversity, where the functional unit is the equivalent hectare per hectare of useful agricultural area (UAA): each agroecological element (for example: linear metre of hedge, isolated tree) is converted into a biodiversity surface area equivalent, expressed per hectare of UAA (Vilain et al. 2008). The favourable and unfavourable thresholds were established as for quality assessment: each indicator can be scored on a scale ranging from 0 (the highest environmental impact and therefore the lowest score) to 10 (the lowest environmental impact therefore the highest score). As with the quality assessment, the technical committees and consultation of the scientific literature made it possible to adjust

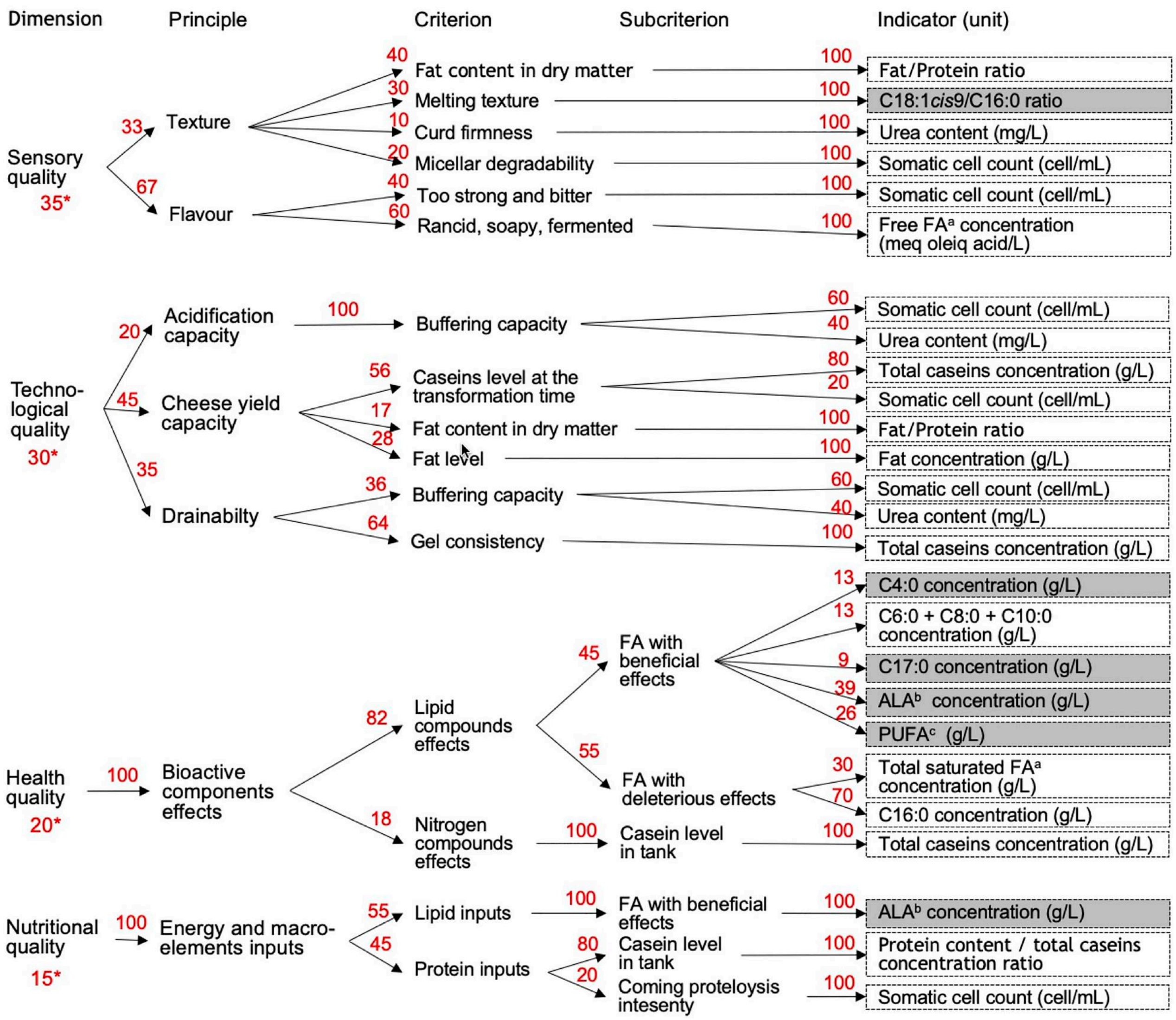

Figure 1. Structure of the multicriteria assessment of the cow milk intrinsic quality for raw milk-cheese production per dimension: sensory, technological, health and nutritional quality. *ponderation of the dimension to the global quality score; $\xrightarrow{100}$ ponderation of the observation (indicators, subcriteria, criteria or principles) to the upper scale one (subcriteria, criteria, principles and dimensions, respectively); [a]FA: Fatty acids; [b]ALA: a-linolenic acid (C18:3n-3); [c]PUFA: polyunsaturated fatty acid; the gray boxes correspond to the indicators evaluated by class.

the weighting of each indicator in the criteria and the criteria in the dimensions to arrive at the final score.

On farm survey and milk sampling

Fifteen farms, located in the mountainous area of the Massif Central, France, were selected to correspond to three types of farming system adaptation, representative of the territorial context: (i) fairly intensive, with an indoor season diet including maize silage, and a high proportion of concentrates in cow's diet throughout the year (called HMC system, for: Herbage + Maize + Concentrates; $n = 5$); (ii) increasing hay production, in large proportion in the diet all year round, with a low annual milk production per cow (HF system: Herbage + Hay; $n = 3$); (iii) maximising grazing, with low concentrate proportion in dairy cow diet all year round and low milk yield (HP system: Herbage + Pasture grazing; $n = 7$). Farms were allocated a priori to the farming systems on the base of brief description (maize silage and concentrate level in diet, supplementation with conserved forage during grazing and milked yield) given by farms' consultants. For the selected farms, 5 milk samples were collected during one year: 2 samples during the indoor period and 3 samples during the grazing season analysed by MIR and fluorescence. The results of these analyses were used to calculate the 15 milk indicators included in the quality assessment. At the same time, a detailed on-farm survey was performed to collect data used to calculate the indicators of the environmental assessment by life cycle

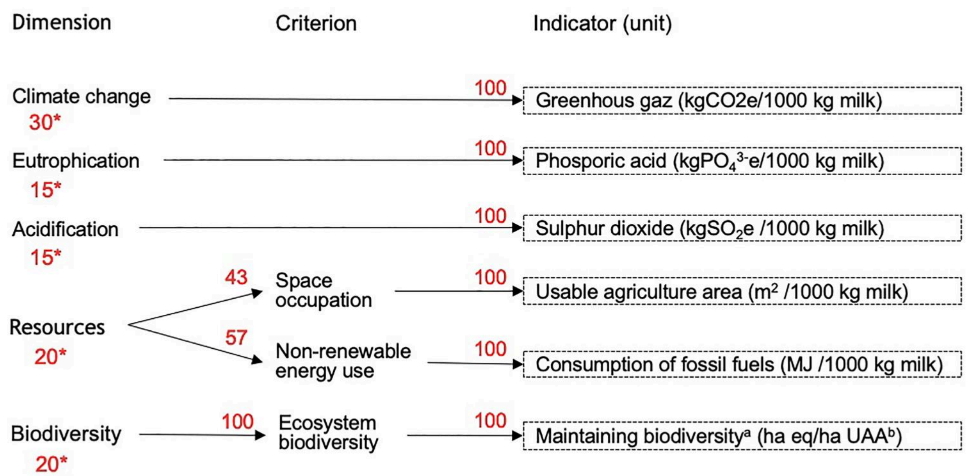

Figure 2. Structure of the multicriteria environmental assessment of dairy farms for raw milk-cheese production by dimension: climate change, eutrophication, acidification, resources and biodiversity impacts. *ponderation of the dimension to the global quality score; →100 ponderation of the observation (indicators) to the upper scale one (criteria and dimensions, respectively); [a]Maintaining biodiversity: Contribution to maintaining biodiversity at the farm level; [b]UAA: Usable agriculture area.

assessment CAP'2ER® software. The questionnaire constructed in accordance with the software instructions (Moreau et al. 2016) covered farm land use, agricultural practices, crop rotation, livestock and their management, animal feed, effluent management, fuel and electricity consumptions. In this way, the environmental impact indicators we needed could be calculated by the CAP'2ER® tool: greenhouse gas emissions (from all farm processes that emit CO2, CH4 and N2O), eutrophication (from processes generating losses of nitrogen and phosphorus to water), air acidification (from processes linked to losses of acidifying substances NH3, NO and SO2), the consumption of space and non-renewable energy (based on the direct energy used on the farm and the indirect energy used to manufacture and transport inputs) and the biodiversity of ecosystems (based on an inventory of agro-ecological elements).

Calculations and statistical analysis

Data analysis and calculation of the quality score were carried out by season and by year. The values of the indicators during the grazing season and during the indoor season were obtained by averaging the values of the 3 milk samples collected from April to October (depending on the farm), and the 2 milk samples collected from November to March, respectively. The annual data were calculated as the average of these mean values per season, weighted by the respective duration of these 2 periods.

The data required for the calculation of the environmental assessment were obtained from the CAP'2ER® software directly for the whole year.

Statistical analysis and graphics were performed using R packages (R Core Team 2020). Correlations between overall environmental scores and overall quality scores were defined using the correlation function (cor function of the statistics package).

A principal component analysis (PCA from FactoMineR package, Husson et al. 2016) was run to determine the main structural trends of these data and to assess the capacity of the method to discriminate situations. The active variables were the scores for each dimension of milk quality and environmental impacts, and the non-active explanatory variables described agricultural practices (number of dairy cows, permanent pastures, age at first calving, time spent grazing, renewal rate, rate of grass kept in the diet, proportion of grazed grass in the diet, proportion of concentrates in the diet, proportion of maize in the diet, rate of high productivity breeds in the herd, milk production, stocking rate, forage area).

Finally, we used an ANOVA procedure, considering the farming system variable as a fixed factor, to determine whether environmental impact and milk quality ratings differed between farming systems.

The entire procedure is detailed in an associated GitHub repository (https://github.com/pmgrollemund/qualenvic_plus/).

Results

Characteristics of farms

Herd size varied between 22 and 67 dairy cows, milk production between 79 864 about and 409 999 L/year and per farm, usable agriculture area (UAA) between

Table 1. Characteristics of the 15 surveyed dairy cattle farms and composition of their milk.

Item	Mean	Median	Minimum	Maximum	SD
Farm characteristics					
Dairy cows (n)	42	40	22	67	14
Utilisable agricultural area (ha)	66	63	30	118	27
Stocking rate (LSU/ha of forage area)	1.0	0.9	0.7	1.6	0.3
Milk production (L/year)	228 671	240 408	79 864	409 999	91 127
Milk yield (L/DC/year)	5 308	5 520	3 571	7 071	1 003
Main forage area (ha)	64	55	30	118	27
Grazing period (d/year)	157	161	98	190	24
Milk composition					
Milk fat content (g/L)	39.87	39.61	36.99	44.59	2.27
Milk protein content (g/L)	32.81	32.75	30.93	35.03	1.43
Somatic cell count (n x 1000/mL)	269	254	128	467	121

30 to 118 ha and grazing period between 98 to 190 days per year (Table 1). Average milk fat content and milk protein content ranged from 37.0 g/L to 44.6 g/L and from 30.9 g/L to 35.0 g/L, respectively.

The HP system had a lower part of permanent grassland in the UAA than the HF or HMC system (-45% on UAA and −48% on UAA respectively; Table 2), and a lower milk yield than HMC (-1422 L/dairy cow.year^{-1}). The HMC system had a lower protein self-sufficiency (-22%), and numerically lower concentrate self-sufficiency (-29%, even if not significant) than HP system. N mineral fertilisation on grassland was numerically higher for HMC system than for the other systems (7 kg N/ha instead of 0 for other systems). During the indoor season, the preserved herbage proportion in dairy cow diet was significantly higher in the HP system than in the HMC system (+32%), as well numerically the hay proportion on total preserved herbage (+80%) whereas the proportion of concentrates was numerically lower (-22%) as well as the fermented herbage proportion (-14%). During the grazing season, the proportion of fresh herbage in the diet of dairy cows was higher in the HP system than in the HF system (+39%), but the HF system had a higher proportion of preserved herbage (+33%). During this same period, the proportion of concentrates in the diet of dairy cows was higher in the HMC system than in the HP system (+17%) whereas the total forages proportion was lower (−17%).

Intrinsic milk quality scores

The annual average of the quality scores obtained in the 15 farms was 5.2 and the averages by dimension were 5.9, 5.4, 4.6 and 4.2 for the sensory, technological, health and nutritional dimension, respectively (Table 3). The annual score ranged from 3.4 to 6.8. Sensory dimension scores had the highest range of variation over all periods compared to other dimensions (SEM always maximum): from 1.2 to 8.2 over the year. On the contrary, the health dimension presented the narrowest range: from 3.4 to 5.6 over the year.

Most of the annual quality scores did not differ significantly between systems (Table 4). Only the annual average health quality was significantly lower for HP system compared to the HMC system (-1.1; $p = 0.022$). The average annual sensory dimension was lower in trend ($p = 0.091$) for HF system than for HMC system (-2.8).

Environmental impacts scores

The average global environmental score in the 15 farms studied was 6.8 and the averages by dimension were 9.7, 7.6, 7.2, 5.8 and 4.0 for eutrophication in water, climate change, resources, air acidification and biodiversity dimension, respectively (Table 5). The global environmental score ranged from 4.9 to 7.6. The ecosystem biodiversity scores presented a huge range of variation, from 0.8 to 9.7. On the contrary, the eutrophication scores ranged only from 7.1 to 10.0.

There were no differences between the farming systems in the dimensions of environmental impacts scores (Table 6) except that the acidification score was lower in trend ($p = 0.064$) between the HF system and the HP system (-1.7).

Relationship between milk intrinsic quality and environmental impact scores

There was no significant linear correlation between the global environmental score and the annual quality score ($p = 0.04$; Figure 3).

The correlation matrix between environmental and quality scores (Table 7) showed positive correlations between eutrophication and health scores ($r = 0.56$) and between resource and sensory scores ($r = 0.46$). Resource and nutritional scores are negatively related ($r = -0.51$), and similarly for acidification and

Table 2. Characteristics of the 15 audited cattle dairy farm from the analysis of variance on the 3 systems: size of the farm, number of livestock, composition of the herd, milk production, cultural practices, composition of the feed diet during indoor season, during grazing season and for the year.

	System[1] of farms				
Characteristics	HP	HF	HMC	SEM	p value
DC (nb)	38	56	40	13	0.183
Average age at first calving (months)	34	35	34	2	0.712
Holstein breed (% on the herd)	71	33	40	48	0.417
Return rate (%)	19	10	23	10	0.201
Days on pasture per year for DC	192	170	192	18	0.215
Utilisable agricultural area (ha)	54	92	68	24	0.107
Grassland area (ha)	18 a	87 b	59 ab	27	0.008
Permanent grasslands (% on UAA)	58 a	96 ab	99 b	23	0.009
Protein self-sufficiency (%)	91 a	81 ab	69 b	8	0.003
Concentrate self-sufficiency (%)	32	8	3	22	0.124
N mineral fertilisation on grasslands (kg N/ha)	0	0	7	10	0.489
Stocking rate (LSU/ha UAA)	1,06	0,80	0,94	0.28	0.408
Milk yield (L/DC/year)	4837 a	4822 a	6259 b	781	0.020
Milk production (L/year)	197 798	270 481	246 933	92 482	0.473
Fuels consumption (L/an)	3436	3890	4218	1956	0.791
Composition of the indoor season diet: (% on diet DM)					
Total preserved herbage (TPH)	88 a	82 ab	56 b	18	0.027
Hay (% on TPH)	83	86	73	28	0.762
Fermented herbage (% on TPH)	8	10	22	24	0.584
Other preserved herbage[2] (% on TPH)	9	4	5	15	0.851
Maize silage	3	0	14	13	0.322
Total forages	91 a	82 ab	69 b	14	0.053
Concentrates	9 a	18 ab	31 b	14	0.053
Composition of the grazing season diet: (% on diet DM)					
Fresh herbage	96 a	57 b	72 ab	20	0.034
Preserved herbage	3 a	36 b	9 ab	15	0.021
Concentrate	2 a	7 ab	19 b	9	0.017
Total forages	98 a	93 ab	81 b	9	0.017

The letters a and b mean that the values obtained are significantly different ($p < 0.05$).
[1]HP system = the most pasture, few concentrates, low milk production per cow ($n = 7$), HF system = production of hay, low annual milk production per cow ($n = 3$), HMC system = quite intensive, maize silage in diet during indoor season, concentrates in a significant way all the year ($n = 5$).
[2]Other preserved herbage: maize silage, legume hay, legume silage, grass hay.
Abbreviations: DC = dairy cow, UAA = Utilisable Agricultural Area, LSU = livestock unit (equivalent to 1 dairy cow over a whole year), DM: dry-matter, TPH: total preserved herbage.

Table 3. Overall results for the 15 cattle dairy farms audited for the 4 dimensions and the global milk intrinsic quality scores, by season and for the whole year.

Quality dimension[1]	Mean	Median	Minimum	Maximum	SEM
Quality during indoor season					
Sensory dimension	6.5	7.6	1.8	8.9	2.1
Technological dimension	4.5	4.4	1.9	8.0	1.7
Health dimension	6.7	6.8	4.7	7.7	0.9
Nutritional dimension	4.3	4.5	2.1	6.2	1.4
Global quality	5.6	6.1	3.8	7.1	1.2
Quality during grazing season					
Sensory dimension	5.3	6.2	0.3	8.6	2.6
Technological dimension	6.3	6.4	3.7	8.6	1.4
Health dimension	2.4	2.5	1.2	4.2	0.9
Nutritional dimension	4.1	4.0	1.6	6.4	1.4
Global quality	4.8	4.9	2.6	6.5	1.1
Quality during the year					
Sensory dimension	5.9	6.7	1.2	8.2	2.0
Technological dimension	5.4	5.2	3.9	7.3	1.0
Health dimension	4.6	4.9	3.4	5.6	0.7
Nutritional dimension	4.2	4.1	2.4	5.7	1.1
Global quality	5.2	5.3	3.4	6.8	0.9

[1]Score ranged between 0 and 10, where 0 was the worst possible quality score, and 10 was the best possible quality score.

technological scores (r=-0.50), climate change and technological scores (r=-0,47), and eutrophication and technological scores (r=-0.44).

Table 4. Effects of the 3 systems of cattle dairy farm studied on intrinsic milk quality scores.

	System[2] of farms				
Quality dimension[1]	HP	HF	HMC	SEM	p value
Annual average					
Sensory dimension	5.5	4.5	7.3	1.7	0.091
Technological dimension	5.3	5.3	5.5	1.1	0.973
Health dimension	4.2 a	4.4 ab	5.3 b	0.6	0.022
Nutritional dimension	4.1	4.2	4.4	1.1	0.889
Global quality	5.0	4.7	5.9	0.8	0.109

The letters a and b mean that the values obtained are significantly different ($p < 0.05$).
[1]Score ranged between 0 and 10, where 0 was the worst possible quality score, and 10 was the best possible quality score.
[2]HP system = the most pasture, few concentrates, low milk production per cow ($n = 7$), HF system = production of hay, low annual milk production per cow ($n = 3$), HMC system = quite intensive, maize silage in diet during indoor season, concentrates in a significant way all the year ($n = 5$).

On the PCA performed on the environmental and annual quality scores (Figure 4(a)), eutrophication and health dimensions scores are positively correlated with the principal component (PC) 1 (29.6% of variance explained), whereas the resource, technological and

Table 5. Overall results for the 15 cattle dairy farms audited for the 5 dimensions and the global environment scores.

Environmental dimension[1]	Mean	Median	Minimum	Maximum	SEM
Climate change	7.6	7.8	4.6	9.9	1.3
Eutrophication	9.7	10.0	7.1	10.0	0.8
Acidification	5.8	6.0	0.0	7.9	2.0
Resources (space and energy)	7.2	7.0	5.6	9.4	1.3
Ecosystem biodiversity	4.0	3.4	0.8	9.7	2.3
Global environmental score	6.8	7.0	4.9	7.6	0.7

[1]Score ranged between 0 and 10, where 0 was the worst possible quality score, and 10 was the best possible quality score.

Table 6. Effects of the 3 systems of cattle dairy farm studied on environmental impact scores.

	System[2] of farms				
Environmental dimension[1]	HP	HF	HMC	SEM	*p* value
Climate change	7.8	6.4	8.1	1.2	0.166
Eutrophication	9.4	9.8	10.0	0.8	0.461
Acidification	6,9	4.0	5.2	1.7	0.064
Resources (space and energy)	7.2	6.2	7.5	1.3	0.431
Ecosystem biodiversity	3.0	4.7	5.0	2.2	0.267
Global environmental score	6.8	6.2	7.2	0.7	0.174

[1]Score ranged between 0 and 10, where 0 was the worst possible quality score, and 10 was the best possible quality score.
[2]HP system = the most pasture, few concentrates, low milk production per cow ($n = 7$), HF system = production of hay, low annual milk production per cow ($n = 3$), HMC system = quite intensive, maize silage in diet during indoor season, concentrates in a significant way all the year ($n = 5$).

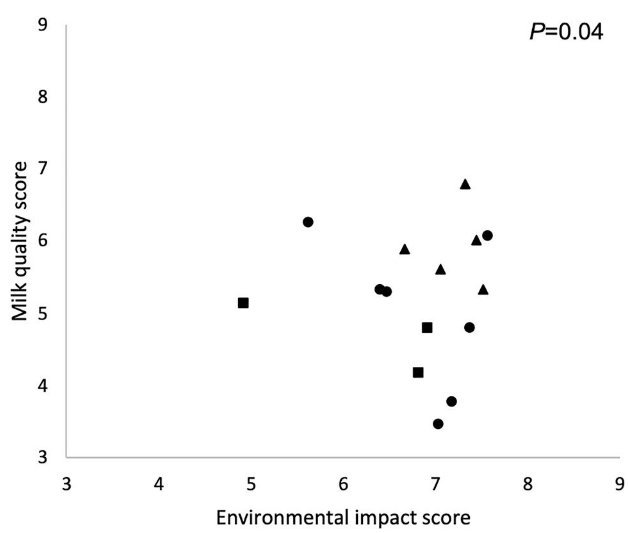

Figure 3. Relationship between the global environmental impact score and the annual average milk quality score in the 15 farms in the sample: HP system (the most pasture, few concentrates, low milk production per cow) represented by a circle, HF system (production of hay, low annual milk production per cow) = square and HMC system (quite intensive, maize silage in diet during indoor season, concentrates in a significant way all the year) = triangle.

sensory dimensions were negatively correlated to PC1. The technological dimension was positively correlated to PC2 (26.2% of variance explained) while the climate change and acidification dimensions were negatively correlated to PC2. Finally, the technological, nutritional and biodiversity dimensions were positively correlated to PC3 (16.7% of variance explained). Farms were quite evenly distributed over the plane defined by PC1 and PC2 (Figure 4(b)), they are positioned from −3.9 to 2.5 on PC1, from −2.8 to 3.1 on PC2 and from −1.8 to 2.1 on PC3.

The total area of permanent grassland on the farm, the age at first calving and the duration of the grazing season were the main explanatory variables correlated with PC1. The parameters most correlated to PC2 were the proportion of high-yielding dairy breeds in the herd, the preserved forage proportion in dairy cow's diet, the proportions of pasture and concentrates in dairy cow's diet.

Discussion

Consequences of adaptations concerning milk intrinsic quality and environment assessments

The quality scores we obtained for all the features, whether yearly or seasonally calculated, were higher than those obtained by the Rey-Cadilhac et al. (2021) assessment carried out on similar group of farm, except for the annual health dimension (4.6 ± 0.7 vs 5.6 ± 0.5), the health dimension during grazing season (2.4 ± 0.9 vs 6.6 ± 0.7) and the nutritional dimension during indoor season (4.3 ± 1.4 vs 5.4 ± 1.5). Likewise, compared to the scores obtained on a similar group of farms by Botreau et al. (2018) assessment, higher scores but lower standard deviation were observed for all the environment features, except for biodiversity: 4.0 ± 2.3 vs 5.5 ± 2.1.

The PCA shows a large scattering of the farms on the plane defined by the first two principal component, demonstrating the sensitiveness of the scores of most of the dimensions studied to changes in agricultural practices. The sensitiveness of the adapted quality assessment was higher than that proposed by the Rey-Cadilhac et al. (2021) assessment (scores ranging from 3.4 – 6.8, vs 2.1 – 4.7, respectively). Conversely, the range of our environmental assessment scores was narrower than that obtained in the Botreau et al. (2018) assessment (ranging from 4.9–7.6 vs 1.5–7.4).

Several reasons could explain these differences, all related to the adaptation of the assessments: the dismissing of several indicators, the modification of the calculation method of certain indicators or of the tool leading to the value of the indicator, and the simplification of the aggregation method. In fact, our methodology used simple weighting, making it

Table 7. Relationship between the scores of the 4 intrinsic dimensions of milk quality and those of the 5 environmental dimensions in the 15 audited dairy farms.

Dimension	Climate change	Eutrophication	Acidification	Resources	Ecosystem biodiversity	Global score
Sensory	0.10	−0.32	−0.19	**0.46**	0.01	0.09
p value	0.719	0.237	0.499	**0.086**	0.986	0.757
Technological	**−0.47**	**−0.44**	**−0.50**	0.01	−0.08	−0.56
p value	**0.080**	**0.097**	**0.057**	0.980	0.762	0.030
Health	0.33	**0.56**	0.09	−0.22	0.43	0.47
p value	0.235	**0.028**	0.750	0.422	0.114	0.076
Nutritional	−0.33	0.42	0.08	**−0.51**	0.44	0.02
p value	0.223	0.115	0.766	**0.051**	0.104	0.953
Global score	−0.08	−0.22	−0.27	0.22	0.12	0.04
p value	0.770	0.424	0.325	0.438	0.681	0.884

Bold: Pearson's correlations with *p* value < 0.10.

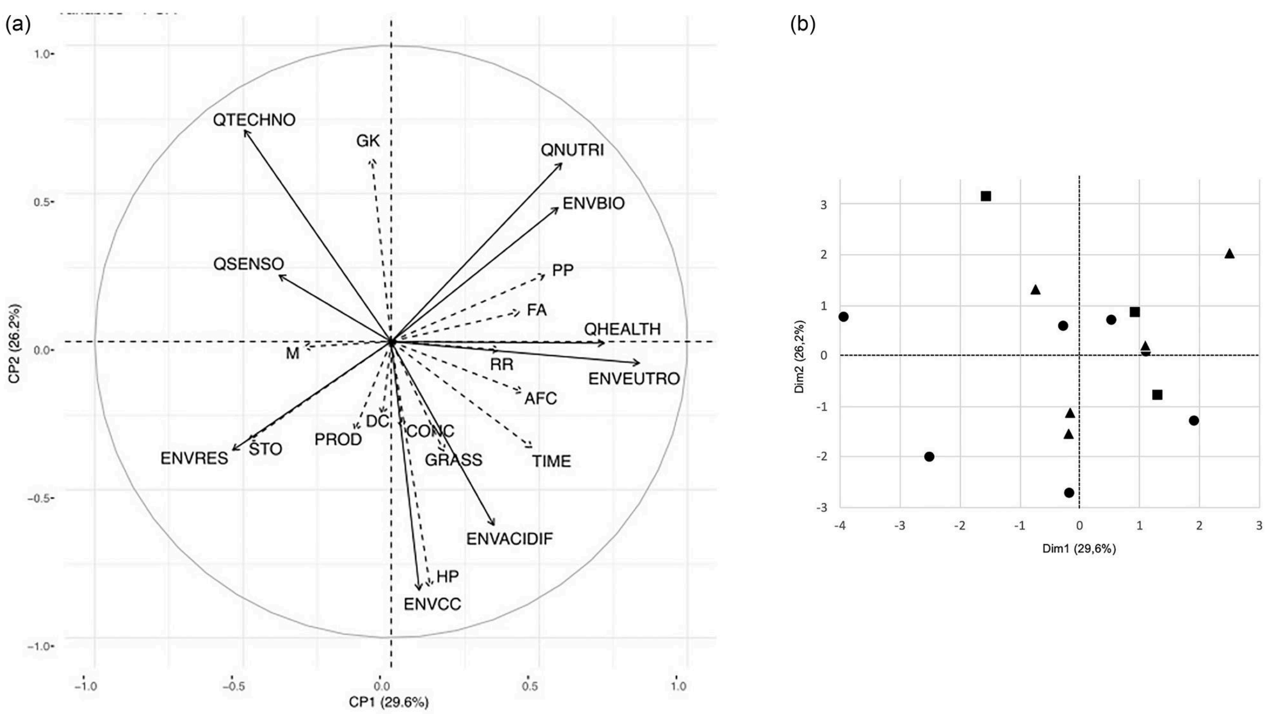

Figure 4. Principal component analysis (PCA) carried out on the 4 milk quality scores and the 5 environmental quality dimensions. (a) Plot of active variable distribution (solid arrows) and of the main explicative non-active variables (dotted arrows) describing the farming practices. QTECHNO: score for technological dimension of milk intrinsic quality, QSENSO: score for sensory dimension of milk intrinsic quality, QHEALTH: score for health dimension of milk intrinsic quality, QNUTRI: score for nutritional dimension of milk intrinsic quality, ENVEUTRO: eutrophication score, ENVRES: resources score, ENVCC: climate change score, ENVACIDIF: air acidification score, ENVBIOD: score biodiversity, DC: number of dairy cows, PP: areas of permanent pasture, AFC: age at first calving, TIME: time spent grazing, RR: renewal rate, GK: rate of grass kept in the diet, GRASS: proportion of pasture in the diet, CONC: proportion of concentrates in the diet, M: proportion of maize in the diet, HP: rate of high productive breeds in the herd, PROD: milk production, STO: stocking rate, FA: forage area. (b) Plot of the distribution of the 15 studied farms by system projected on the two principal components (PC1 and PC2): HP system (the most pasture, few concentrates, low milk production per cow) represented by a circle, HF system (production of hay, low annual milk production per cow) = square and HMC system (quite intensive, maize silage in diet during indoor season, concentrates in a significant way all the year) = triangle.
We add below an overview intended to help the reviewer identify without doubt the number and order of each figure.

possible to compensate for a poor score somewhere with a good score elsewhere, leading to higher aggregated scores than the method used in Botreau et al. (2018) and Rey-Cadilhac et al. (2021) which used a complex qualitative aggregation tool to limit compensation.

Effects of farming system on the intrinsic milk quality and environmental impact scores

Differences among farming system for intrinsic milk quality and environmental impact scores were less than expected. This could be due to the variability of agricultural practices within each farming system that generated a partial overlapping between farming systems. Anyway, some differences among systems were still present.

The significant difference in the annual score of the health dimension, 1.1 points higher for the HMC system than for the HP system (with scores of 5.3 and 4.2, respectively), seems to be explained by a combination of factors which weigh favourably (casein, ALA and PUFA content) or unfavourably (C16:0 content) in the score. Thus, the C16:0 concentration in milk (31.5% of the weight of the health dimension score) was lower in the HMC system in summer than in winter, the casein content (17.5%) was higher in the HMC system in winter but lower in summer, the ALA content (14.3%) was lower in the HMC system in winter, and the PUFA content (9.6%) higher in the HMC system in summer. These differences in milk composition are also explained by some antagonistic mechanisms. For example, a diet richer in maize (rich in starch), distributed to cows as silage or concentrate (as in the HMC system) is known to increase the concentration of C16:0 in milk (Coppa et al. 2013; Kliem et al. 2008). However, cow diets on HMC system farms remain grass-based (56% and 81% of DM intake in winter and summer, respectively), intake of which leads to lower C16:0 concentration in milk (Coppa et al. 2015; Cabiddu et al. 2022) that counterbalances the effect of maize part in the diet on C16:0 content. Nevertheless, herbage intake remains lower in HMC than HP system (Table 2). Fresh or conserved herbage quality could be at the origin of this apparent contradiction: grazing herbage at an early phenological stage induce a lower concentration of C16:0 in milk compared to mature herbage (Coppa et al. 2015). Grazing herbage at an early phenological is common for intensively managed grazing system, even in mountain area, as suggested by a numerically higher grassland N fertilisation observed in HMC system. Similarly, preserving herbage through fermentation instead of drying allows to harvest herbage at an earlier phenological stage. Thus, the numerically higher proportion of fermented herbage in HMC system diet during winter season compared to HP system could explain the lower C16:0 concentration in milk (Borreani et al. 2013). Furthermore, feeding maize silage and starch rich diet increase the concentration in milk of C18:2n-6, one of the main PUFA in milk in disfavour of C18:3n-3, explaining why the PUFA content in HMC is high (Coppa et al. 2015; Cabiddu et al. 2022).

The difference in trend in the annual sensory dimension, 2.8 points higher for the HMC system than for the HF system (with scores of 7.3 and 4.5, respectively), is mainly related to differences during the summer season in milk free FA concentration (40.0% of the weight of the sensory quality score), the somatic cell count (SCC) in milk (26.6%), the fat to protein ratio (FPR) in milk (13.4%) and the C18:1c9/C16:0 ratio (10.0%). Scientific work has proven this relationship: the diet rich in pasture (as in the HMC system) is associated with a low level of free fatty acid concentration in milk (Chilliard et al. 2007) and FRP value in milk close to 1.15 which was set as our ideal threshold (Collomb et al. 2008). Such a diet rich in pasture also decreases the de novo synthesis of saturated fatty acids (SFA) in the udder, which leads to low concentrations of SFA, and partly of C16:0, in milk (Shingfield et al. 2013; Coppa et al. 2015; Cabiddu et al. 2022).

Concerning the environmental impact, the difference in the evolution of the acidification score, 3.0 points higher for the HP system than for the HF system (with scores of 6.9 and 4.0 respectively), seems linked to the differences in herd management between these two systems, particularly regarding feeding during the grazing season. The difference between the two systems is significant regarding the proportion of preserved herbs in the diet (HF: 36%, HP: 3%) and the proportion of fresh herbs in the diet (HF: 57%, HP: 96%) during the grazing period. This feed management in the HF system could be responsible for a greater amount of effluent excreted in buildings during the grazing period (due to the grouping of animals at distribution points), increasing atmospheric ammonia emissions and nitric oxide (Martin et al. 2013; Smith et al. 2021). Other factors seem to be able to influence the higher acidifying losses in the air in the HF system farms than in the HP system farms: the mechanical works necessary for the production of the preserved grass given to the cows during the grazing period and the associated sulphur dioxide (SO2) emissions, the spreading of slurry more frequently because after each hay cut, and on a few farms in the HF system the longer storage time of the slurry before spreading.

The lack of differences for the other quality feature and environmental scores between each farm type was an important and unexpected result. The farms are well distributed on the graphical maps derived from the PCA results, and the correlations between the PC and the farming practices as explanatory variables suggests the sensitivity of the methods to the variability in farming conditions. However, farms are not grouped by system (Figure 4(b)). The farming systems were defined on the basis of crop rotation criteria (usable agriculture area, main forage area) and animal performance (number of dairy cows, milk production per dairy cow), while the explanatory variables mainly correlated with the PC axes were related to cow diet composition (the proportion of pasture in the diet, the time spent grazing, the percentage of grass kept in the diet), and animal breed and reproduction (the age at first calving, rate of highly productive breeds in the herd). These characteristics were only partially implicated in the a priori classification of farms and their variability was therefore transversal to the 3 systems.

Farming system-independent relationship between intrinsic milk quality and environmental impact scores

The absence of a clear relationship between the global environmental score and the average annual quality score in our study agrees with the result of previous multi-criteria studies. Botreau et al. (2018) obtained comparable results with full assessments. Bava et al. (2014) had concluded in their study on the relationship between agricultural intensity and environmental performance that, from a product perspective, the most ecological way of producing milk was not clearly identifiable. Guerci et al. (2013a) found no relationship between environmental impact and milk production per cow or farm stocking rate on the sampled farms.

On the contrary, high correlations were found between the scores of some quality and environmental dimensions. The most innovative result is about the positive and significant relationship between eutrophication and health dimensions scores. A high eutrophication score reflects the low negative impact of nitrogen and phosphorus losses on water quality, therefore the low risk of promoting eutrophication, by reducing the concentrations of nitric oxide (NO), ammonia (NH3), nitrogen trioxide (NO3), phosphorus pentoxide (P2O5) and phosphate ion (PO43-) in the natural environment. By construction, a high score on the health dimension is associated to low concentrations of nitrogen compounds (caseins), C16:0 total and total saturated fatty acids (SFA), and high concentrations of several FA (C4:0, total content of C6:0 + C8:0 + C10:0, C17:0, ALA and PUFA). Independently of the farming system, our methodological work and the analyses of the obtained scores make it possible to associate this low casein content and these specific FA compositions with some characteristics of the farms: a large share of permanent pasture surfaces on UAA, a long time spent grazing all year round, a low stocking rates, a late age at first calving and a large share of forage area on UAA. It has been shown that overall grazing leads to a decrease in SFAs including C16:0 and an increase in PUFAs including ALA (Couvreur et al. 2006; Legarto et al. 2014). Grass ingestion also leads to an overall decrease of the protein content (Hurtaud et al. 2005; Kliem et al. 2008), and Hurtaud et al. (2005) and Couvreur et al. (2007) demonstrated a decrease in casein content.

The negative correlation (in trend) between the acidification and technological dimensions scores means that the risk of air acidification is lower in conditions where the milk has a lower technological dimension score. This technological dimension score decreases when the level of somatic cells and urea in the milk is high. We observed low technological dimension score in farms where the proportion of high-yielding cows in the herd and the proportion of concentrates in the ration were high. These results agree with those of Agabriel et al. (2004) and Coppa et al. (2019) showing that such production conditions (high yielding cows and a high proportion of concentrate in the feed) are often accompanied by a higher somatic cell count. Our results are consistent with what is considered in Botreau et al. (2014) who observed high acidification scores (therefore a lower risk of acidification) in farms of highly productive breeds. The presence of nitrogen concentrates in food seems to have combined effects. A negative effect on the technological dimension score in relation to the increase in the level of urea in milk (Baeza-Campone et al. 2020), and also, a negative effect on the acidification score in relation to NH3 losses. Indeed, these nitrogen concentrates in the feed lead to a stronger NH3 release process during the storage of effluents (Guerci et al. 2013b; Baeza-Campone et al. 2020). The negative correlation observed between the acidification score and the technological dimension score suggests that the effect of nitrogen concentrates on the increase in the urea rate takes precedence over the effect linked to NH3 losses.

The negative and almost significant correlation between the resources dimension score and the nutritional dimension score implied that a better nutritional quality went with a greater consumption of resources (which includes the consumption of space in UAA 1000 kg-1 of milk and fossil fuels in MJ 1000 kg-1 of milk). This could be explained by the fact that extensive systems, with regard to the functional unit chosen in our study (per 1000 kg of milk), have a strong impact on resources since they have a low milk production (Salou et al. 2017). In addition, they often have a lower level of somatic cells in milk, a factor that promotes high nutritional dimension score of milk. The nutritional dimension score was also associated, by construction, with the ALA concentration and the protein content/total caseins concentration ratio of raw milk. The high concentration of ALA in milk in extensive farms is explained in particular by the high diversity of the pasture botanical composition (Renna et al. 2020). Indeed, extensive grazing systems are based on natural grasslands, known for the importance of dicotyledonous plants, rich in secondary metabolites (Cabiddu et al. 2022). These compounds in grass allow higher transfer of ALA to milk due to their ability to partially inhibit ruminal biohydrogenation of herbage PUFA (Leiber et al. 2005; Chilliard et al. 2007). All of these mechanisms are therefore consistent with the negative correlation between the resource impact score and the nutritional feature.

Conclusion

This study is the first to be based on an operational method on field and allowing to deepen the knowledge of the relationship between the quality of milk for the production of raw milk cheeses and the environmental impacts of the farm producing the milk. Our work resulted in the provision of an evaluation method, potentially applicable in routine, based on two evaluation trees of milk quality and environmental impacts of the farm.

The lack of correlation we confirmed between a global milk quality score and impact environmental scores underlines the presence of both synergic and antagonistic effects of certain practices between some quality and environmental features (e.g. extensive grazing consumes space but allows high milk nutritional dimension). Consequently, it would be necessary to define specific priority objectives, farm by farm or system by system depending in particular on the territorial context and economic and social issues, in order to drive changes in farming practices. We have already observed that certain farms obtain good scores both in milk quality and in the environment.

Anyway, the proposed methodological adaptation and the related results should be validated on a larger territorial scale and in different and more diversified farming contexts.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethical approval

All research reported in this study has been conducted in an ethical and responsible manner.

Data availability statement

The data presented in this study are available on request from the corresponding author upon reasonable request.

References

Agabriel C, Martin B, Sibra C, Bonnefoy J-C, Montel M-C, Didienne R, Hulin S. 2004. Effect of dairy production systems on the sensory characteristics of Cantal cheeses: a plant-scale study. Anim Res. 53(3):221–234. doi: 10.1051/animres:2004013.

Baeza-Campone E, Prache S, Cliquart A, Feidt C, Gautron J, Guiller L, Lebret B, Lefèvre F, Martin B. 2020. in Prache, S., Santé-Lhoutelier, V. (Eds.) Qualité des aliments d'origine animale, conditions de production et de transformation. Rapport de l'expertise Scientifique Collective. INRAE (France), p. 183–532. https://www.inrae.fr/actualites/qualite-aliments-dorigine-animale-conditions-production-transformation.

Bava L, Sandrucci A, Zucali M, Guerci M, Tamburini A. 2014. How can farming intensification affect the environmental impact of milk production. J Dairy Sci. 97(7):4579–4593. doi: 10.3168/jds.2013-7530.

Borreani G, Coppa M, Revello-Chion A, Comino L, Giaccone D, Ferlay A, Tabacco E. 2013. Effect of different feeding strategies in intensive dairy farming systems on milk fatty acid profiles, and implications on feeding costs in Italy. J Dairy Sci. 96(11):6840–6855. doi: 10.3168/jds.2013-6710.

Botreau R, Beauchet S, Laurent C, Hulin S, Hérisset R, Thiollet-Scholtus M, Kanyarushoki C, Boucault P, Renaud-Gentié C, Jourjon F. 2018. Une méthode pour évaluer conjointement performance environnementale et qualité globale des produits – Application aux filières vin et lait. Innovations Agronomiques [A method for jointly evaluating environmental performance and overall product quality – application to the wine and milk sectors]. 63:23–42. https://www.scopus.com/record/display.uri?eid=2-s2.0-85107725969&origin=inward&featureToggles=FEATURE_NEW_DOC_DETAILS_EXPORT:1.

Botreau R, Farruggia A, Martin B, Pomiès D, Dumont B. 2014. Towards an agroecological assessment of dairy systems: proposal for a set of criteria suited to mountain farming. Animal. 8(8):1349–1360. doi: 10.1017/S1751731114000925.

Cabiddu C, Peratoner G, Valenti B, Monteils V, Martin B, Coppa M. 2022. A quantitative review of on-farm feeding practices to enhance the quality of grassland-based ruminant dairy and meat products. Animal. 16 Suppl 1(1): 100375. doi: 10.1016/j.animal.2021.100375.

Chilliard Y, Glasser F, Ferlay A, Bernard L, Rouel J, Doreau M. 2007. Diet, rumen biohydrogenation and nutritional quality of cow and goat milk fat. Euro J Lipid Sci Tech. 109(8): 828–855. doi: 10.1002/ejlt.200700080.

Collomb M, Bisig W, Bütikofer U, Sieber R, Bregy M, Etter L. 2008. Fatty acid composition of mountain milk from Switzerland: comparison of organic and integrated farming systems. Int Dairy J. 18(10–11):976–982. doi: 10.1016/j.idairyj.2008.05.010.

Coppa M, Chassaing C, Sibra C, Cornu A, Verbič J, Golecký J, Engel E, Ratel J, Boudon A, Ferlay A, et al. 2019. Forage system is the key driver of mountain milk specificity. J Dairy Sci. 102(11):10483–10499. doi: 10.3168/jds.2019-16726.

Coppa M, Ferlay A, Borreani G, Revello-Chion A, Tabacco E, Tornambé G, Pradel P, Martin B. 2015. Effect of phenological stage and proportion of fresh herbage in cow diets on milk fatty acid composition. Anim Feed Sci Technol. 208:66–78. doi: 10.1016/j.anifeedsci.2015.07.006.

Coppa M, Ferlay A, Chassaing C, Agabriel C, Glasser F, Chilliard Y, Borreani G, Barcarolo R, Baars T, Kusche D, et al. 2013. Prediction of bulk milk fatty acid composition based on farming practices collected through on-farm surveys. J Dairy Sci. 96(7):4197–4211. doi: 10.3168/jds.2012-6379.

Coppa M, Revello-Chion A, Giaccone D, Tabacco E, Borreani G. 2017. Could predicting fatty acid profile by mid-infrared reflectance spectroscopy be used as a method to increase the value added by milk production chains? J Dairy Sci. 100(11):8705–8721. doi: 10.3168/jds.2016-12382.

Couvreur S, Hurtaud C, Lopez C, Delaby L, Peyraud JL. 2006. The linear relationship between the proportion of fresh grass in the cow diet, milk fatty acid composition, and butter properties. J Dairy Sci. 89(6):1956–1969. doi: 10.3168/jds.s0022-0302(06)72263-9.

Couvreur S, Hurtaud C, Marnet P, Faverdin P, Peyraud J. 2007. Composition of milk fat from cows selected for milk fat globule size and offered either fresh pasture or a corn silage-based diet. J Dairy Sci. 90(1):392–403. doi: 10.3168/jds.S0022-0302(07)72640-1.

European Union. 2020. A farm to fork strategy for a fair, healthy and environmentally-friendly food system. Europ Commission. 1:13–14. https://food.ec.europa.eu/document/download/472acca8-7f7b-4171-98b0-ed76720d68d3_en?filename=f2f_action-plan_2020_strategy-info_en.pdf.

Farruggia A, Pomiès D, Coppa M, Ferlay A, Verdier-Metz I, Le Morvan A, Bethier A, Pompanon F, Troquier O, Martin B. 2014. Animal performances, pasture biodiversity and dairy product quality: how it works in contrasted mountain grazing systems. Agricult Ecosyst Environ. 185:231–244. doi: 10.1016/j.agee.2014.01.001.

Guerci M, Bava L, Zucali M, Sandrucci A, Penati C, Tamburini A. 2013b. Effect of farming strategies on environmental impact of intensive dairy farms in Italy. J Dairy Res. 80(3):300–308. doi: 10.1017/S0022029913000277.

Guerci M, Knudsen M-T, Bava L, Zucali M, Schönbach P, Kristensen T. 2013a. Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. J Clean Prod. 54:133–141. doi: 10.1016/j.jclepro.2013.04.035.

Hurtaud C, Richoux R, Couvreur S, Delaby L, Peyraud J-L. 2005. Régimes Alimentaires et Taille Des Globules Gras Des Vaches Laitières. 3R:371–374. https://www.researchgate.net/publication/341962758_Regimes_alimentaires_et_taille_des_globules_gras_des_vaches_laitieres_effet_sur_la_production_laitiere_l'aptitude_fromagere_et_les_proprietes _thermofonctionnelles_des_emmentals.

Husson F, Josse J, Le S, Mazet J, Husson M-F. 2016. Package 'factominer'. An R Package. 96:698.

Kliem K-E, Morgan R, Humphries D-J, Shingfield K-J, Givens D-I. 2008. Effect of replacing grass silage with maize silage in the diet on bovine milk fatty acid composition. Animal. 2(12):1850–1858. doi: 10.1017/S1751731108003078.

Lairez J, Feschet P, Aubin J, Bockstaller C, Bouvarel I. 2015. Agriculture et développement durable. Guide pour l'évaluation multicritère, Paris, France: Éditions Quae. http://refhub.elsevier.com/S1751-7311(21)00106-3/h0125.

Lambotte M, De Cara S, Brocas C, Bellassen V. 2021. Carbon footprint and economic performance of dairy farms: the case of protected designation of origin farms in France. Agric Syst. 186:102979. doi: 10.1016/j.agsy.2020.102979.

Lebacq T, Baret P-V, Stilmant D. 2013. Sustainability indicators for livestock farming. A review. Agron Sustain Dev. 33(2):311–327. http://refhub.elsevier.com/S1751-7311(21)00106-3/h0130. doi: 10.1007/s13593-012-0121-x.

Legarto J, Gelé M, Ferlay A, Hurtaud C, Lagriffoul G, Palhière I, Peyraud JL, Rouillé B, Brunschwig P. 2014. Effets des conduites d'élevage sur la production de lait, les taux butyreux et protéique et la composition en acides gras du lait de vache [Effects of breeding practices on milk production, butter and protein levels and the fatty acid composition of cow's milk.]. Paris. INRA Prod Anim. 27(4):269–282. doi: 10.20870/productions-animales.2014.27.4.3073.

Leiber F, Kreuzer M, Nigg D, Wettstein H-R, Scheeder M-R-L. 2005. A study on the causes for the elevated n-3 fatty acids in cows' milk of Alpine origin. Lipids. 40(2):191–202. doi: 10.1007/s11745-005-1375-3.

Martin E, Mathias E, Guingand N, Lorinquer E. 2013. Analyse du potentiel de 10 actions de réduction des émissions d'ammoniac des élevages français aux horizons 2020 et 2030. Synthèse [Analysis of the potential of 10 actions to reduce ammonia emissions from French livestock farming by 2020 and 2030. Summary]. Angers. Ed ADEME. France.14p. https://www.researchgate.net/publication/260134119_Analyse_du_potentiel_de_10_actions_de_reduction_des_emissions_d'ammoniac_des_elevages_francais_aux_horizons_2020_et_2030_-_Synthese_Etude_Prospective_-Synthese.

Moreau S, Brocas C, Dollé J-B. 2016. CAP'2ER®, the environmental footprint calculator and decision making for ruminants production systems. LCA Food 2016. Dublin, Ireland, 19–21 October 2016. https://www.idele.fr/?eID=cmis_download&oID=workspace:/SpacesStore/421d4912-5a7f-46bc-9b01-21f52d9754db.

Müller-Lindenlauf M, Deittert C, Köpke U. 2010. Assessment of environmental effects, animal welfare and milk quality among organic dairy farms. Livestock Sci. 128(1–3):140–148. doi: 10.1016/j.livsci.2009.11.013.

Penati C, Tamburini A, Timini M, Sandrucci A. 2009. Milk production, feeding systems and environmental impact of dairy cattle farming in Alpine areas: results of a field study. Ital J Anim Sci. 8(sup2):316–318. doi: 10.4081/ijas.2009.s2.316.

Prache S, Adamiec C, Astruc T, Baéza-Campone E, Bouillot P-E, Clinquart A, Feidt C, Fourat E, Gautron J, Girard A, et al. 2022. Quality of animal-source foods. Animal. 16 Suppl 1(1):100376. doi: 10.1016/j.animal.2021.100376.

R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing.

Vienna, Austria: The R Foundation. https://www.R-project.org.

Renna M, Ferlay A, Lussiana C, Bany D, Graulet B, Wyss U, Enri SR, Battaglini LM, Coppa M. 2020. Relative hierarchy of farming practices affecting the fatty acid composition of permanent grasslands and of the derived bulk milk. Anim. Feed Sci Technol. 267:114561. doi: 10.1016/j.anifeedsci.2020.114561.

Rey-Cadilhac L, Botreau R, Ferlay A, Hulin S, Hurtaud C, Lardy R, Martin B, Laurent C. 2021. Co-construction of a method for evaluating the intrinsic quality of bovine milk in relation to its fate. Animal. 15(7):100264. doi: 10.1016/j.animal.2021.100264.

Salou T, Le Mouël C, Van der Werf H-M-G. 2017. Environmental impacts of dairy system intensification: the functional unit matters!. J Clean Prod. 140:445–454. doi: 10.1016/j.jclepro.2016.05.019.

Shingfield J, Bonnet M, Scollan N-D. 2013. Recent developments in altering the fatty acid composition of ruminant-derived foods. Animal. 7 Suppl 1(1):132–162. volume doi: 10.1017/S1751731112001681.

Smith A, Christie K, Harrison M, Eckard R. 2021. Ammonia volatilisation from grazed, pasture based dairy farming systems. Agric Syst. 190:103119. doi: 10.1016/j.agsy.2021.103119.

Vilain L, Boisset K, Girardin P, Mouchet C, Viaux P, Zahm F. 2008. La méthode IDEA Indicateurs de durabilité des exploitations agricoles, 3e édition [The IDEA method Farm sustainability indicators, 3rd ed. Dijon: Educagri. France; p. 64–66.

Zucali M, Battelli G, Battini M, Bava L, Decimo M, Mattiello S, Povolo M, Brasca M. 2016. Multi-dimensional assessment and scoring system for dairy farms. Ital J Anim Sci. 15(3):492–503. doi: 10.1080/1828051X.2016.1218304.