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Management factors affecting the environmental impact of cereal-based dairy farms

Marco Berton, Enrico Sturaro, Stefano Schiavon, Alessio Cecchinato and Luigi Gallo

Dipartimento di Agronomia, Animali, Alimenti, Risorse naturali e Ambiente, University of Padova, Legnaro, Italy

ABSTRACT

This study aimed to assess the environmental impact (cradle-to-farm gate LCA) of milk production of cereal-based dairy farms in northern Italy and to analyse which traits related to farm management (MAN_F), lactating cows' ration composition (DIET_F), and animal responses (ANI_F) could be identified as main determinants to address specific mitigation strategies. Data originated from 28 dairy farms. The functional unit was 1 kg of fat- and protein-corrected milk (FPCM). Impact categories were global warming (GWP), acidification (AP) and eutrophication (EP) potentials and land occupation (LO). Impact values were analysed with a linear model to test separately the effects of MAN_F, DIET_F and ANI_F variables. One kg FPCM was associated with an average impact of 1.10 kg CO_2-eq (GWP), 17.1 g SO_2-eq (AP), 6.0 g PO_4-eq (EP), and 1.3 m^2/y (LO). Regarding MAN_F, GWP and LO linearly decreased with increasing values of stocking rate and feed self-sufficiency (FSS), whereas minimum EP was found for intermediate FSS values (50% DM). Regarding DIET_F, GWP linearly decreased at increasing levels of dietary inclusion of cereal silages, whereas AP and EP linearly decreased at decreasing dietary crude protein (CP) content values. Among ANI_F, GWP and EP were quadratically associated with milk yield (MY), evidencing the lowest values at intermediate MY (9100 ± 477 kg FPCM/cow per 305d-lactation). The GWP, AP and EP decreased with decreasing age at first calving. These results can contribute at drawing good practices for farmers and consultants to promote more environmentally sustainable dairy production while supporting farm functioning and farmers' income.

HIGHLIGHTS

- Farm and animal determinants of Life Cycle Assessment of cereal-based dairy farms were studied.
- Mitigation effects can be achieved by operating on farm organisation, cow's diet, and animal responses.
- Good practices for farmers and consultants can be proposed for a better dairy production sustainability.

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Introduction

Dairy production is one of the most important livestock sectors in the European Union (EU), with nearly 145 million tons of dairy produced in 2020 (EU-27). The Italian dairy sector represents the fifth largest contributor, with a share of nearly 8.5% (Eurostat 2021). Most of the Italian dairy operations are in Northern Italy (75% of the total production), where the dairy system is characterised by medium–large farms (>150 dairy cows), with milk-specialised cow breeds (mainly Holstein Friesian) that produce 8,000–10,000 kg milk per cow/year, and that are fed total mixed rations, including or not including silages, according to the destination of the milk (ISMEA 2020). This system has faced different challenges in recent years, such as the liberalisation of the EU milk quota, milk price fluctuations (ISMEA 2020), a shift in the priorities of the Common Agricultural Policy towards the environmental sustainability of food production (Pe'er et al. 2019), and the increasing awareness of consumers of the environmental impact of milk (Canavari and Coderoni 2020). Moreover, the EU Farm-to-Fork initiative poses new and ambitious objectives for the European food systems towards 'a

CONTACT Marco Berton marco.berton.1@unipd.it
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neutral or positive environmental impact' (European Commission 2020). Consequently, the necessity to measure the environmental impact (EI) and identify feasible mitigation strategies for these systems is increasing. The assessment of the EI is increasingly based on the life cycle assessment (LCA) methodology (ISO 2006), which is used to assess the impacts associated with the production of one unit of product along its supply chain. Several LCA studies have been published on the impact of milk production (Mazzetto et al. 2022, for a review). Moreover, in some studies, researchers have assessed a number of mitigation options that could be applied at the different stages of dairy farms, from herd management to manure storage structures and/or treatments to feed management (Hristov et al. 2013, for a review). However, these mitigation options were frequently evaluated alone, or in experimental designs that were focussed on one stage of the farm. In addition, the input-related variables (e.g. the amount of concentrate in the diets fed to animals) are usually not separated from the output-related ones (e.g. milk yield – MY, feed efficiency) in the analyses on the impact of the whole farm for possible mitigation strategies. However, farmers can only intervene in input-related variables, whereas the desirable levels of the output-related variables can be set as goals to be achieved. For these reasons, the consideration of the logical flow of the inputs and processes on dairy farms (from the inputs to the processes and stages to the outputs), the effects of each stage on the milk EI, and the effects of the proposed mitigation options on the foreground production stages could provide a coherent framework for the mitigation of the impacts related to milk, and for the possible consequences of these mitigation strategies. Indeed, on dairy farms, the management factors and the diets of lactating cows are established to support milk productivity and reproduction (e.g. fertility and calving intervals). Thus, within the frame of a wider project that is aimed at assessing the environmental sustainability of the regional livestock systems (MITIGACTIONS), in this study we aimed to investigate the following: (i) the EI (cradle-to-farm gate LCA) of the milk production of cereal-based dairy farms located in the Veneto region, which are representative of the typical intensive dairy system of Northern Italy; (ii) the farm traits that could be identified as the main determinants for addressing specific mitigation strategies, following the farm's productive flow, from the farm management to the ration composition for lactating cows to the animal performance.

Materials and methods

Goal and scope definition

We analysed the EI of a group of cereal-based dairy farms in Northern Italy using a cradle-to-farm gate LCA model, considering the contributions due to the herd and manure management, production of the feedstuffs (on-farm and purchased), and production and use of the main materials used for farm and animal management (electricity, fuel, bedding materials). The impact categories that we assessed were global warming (GWP, kg CO_2-eq), acidification (AP, g SO_2-eq) and eutrophication potentials (EP, g PO_4-eq), and land occupation (LO, m^2/y), according to the categories defined by CML (2016). The functional unit was 1 kg of fat- and protein-corrected milk (FPCM). The milk was corrected to a fat content of 4% and a protein content of 3.3%, according to Gerber et al. (2010). Because the dairy farms not only produced milk, but also sold animals to other farms or slaughterhouses, thereby contributing to the beef production, the whole-farm impact was allocated to two co-products (milk and surplus body weight – BW) *via* a biophysical method (IDF 2015).

Data collection and editing

The study involved 28 dairy farms located in the Veneto region. The data collection was based on official sources (official milk recording system, communication for EU Nitrate Directive accounting) and farm interviews. Each farm was visited at least once by the same operator, together with the technicians of the farmers' association which all the farms were associated with. During each visit, the farmer was asked to describe the structure of the farm and to fill a questionnaire, together with the operator, about the herd and agronomical management, animals rationing, the farms outputs and the farm materials consumption. The questionnaire was developed by the researchers together with the technicians of the farmers' association, in order to cover all the relevant inputs, outputs and processes of the farms and to be compliant with the FAO LEAP guidelines (FAO 2020). The time period considered was 1 year (2018), according to FAO LEAP guidelines (2020).

The farm agricultural area (FAA) was recorded during the farm interview as the farm area utilised for producing the on-farm feedstuffs fed to the dairy animals. For each type of on-farm feedstuff, the agronomical inputs (land area, types and quantities of fertilisers and pesticides) and yields were collected to estimate the emissions related to the production of 1 kg of dry matter (DM) of each type of feed. To account for the possible annual variation in terms of crop yields, an average yield in the previous three years was recorded. The manure and other agronomical inputs not utilised for crops destined to cash crops were considered outside of the system boundaries.

For the herd size, composition, and management, the data originated from the official milk recording system as annual means. Holstein Friesian (HF) was by far the most prevalent breed, as 91% of all the cows belonged to this genetic group. However, only 35% of the farms kept only HF cows, whereas the remaining farms also maintained some cows of other breeds (mainly crossbreds of different origins, not better specified in the official milk recording data). Therefore, for each genetic type, the number of dairy cows (lactating and dry cows), age of first calving, calving interval, replacement and culling rates, and dry period length were collected. These data were integrated with those collected during the farm interviews to model the herd compositions (i.e. information on the number of calves born, average weaning age, the use or not of X-sorted and/or beef semen).

The detailed procedure for modelling the herd composition is reported in the Supplementary Materials (Supplementary Tables S1a-b and-S2). This model was independently applied to each genetic type, and the outcomes of the different genetic types maintained on the farms were summed up. Briefly, pregnant heifers were computed as dairy cows × the replacement rate. All the pregnant heifers were assumed to produce one calf, and the number of calves from dairy cows was computed as the difference between the total number of calves and the calves derived from pregnant heifers. For herds with heifers that were inseminated with X-sorted semen, a success rate of 65% and a purity rate of 90% were assumed according to Bittante et al. (2020). The proportion of the cows inseminated with beef semen was acquired from the farmer interviews. A mean weaning mortality rate of 3% for the calves was applied. Consequently, the calves were grouped as follows: purebred female calves, purebred male calves, dairy–beef crossbred female and male calves.

As the number of sold purebred female calves was not available as direct information on most of the farms, we assumed that up to 130% of the purebred female calves born in the year were retained for reproduction, and that the remainder were sold. The total number of calves sold was the sum of the number of purebred female calves not retained for reproduction plus all the purebred male calves and all the dairy–beef crossbred calves, both female and male. Regarding the dairy cows, the number of lactating and dry cows during the year was modelled based on the calving interval and dry period length. The number of culled cows was computed as dairy cows × the culling rate.

The farm output included the milk delivered to the milk retailers and the BWs derived upon the sales of the animals. The data on the amount of milk delivered, with the relative protein and fat content percentages, were recorded during the farm interviews, whereas the total BW of the animals sold was computed as the sum of the animals sold multiplied by the relative BW at the sale, based on regional farmers' association data. Combining the FAA extension and herd size, the dairy cow stocking rate (DSR) was computed as the ratio between the number of dairy cows and the FAA.

The data on the feeding management were collected during the interviews. The rations fed to the different livestock categories (lactating cows, dry cows, heifers, calves) were recorded for each farm. The feed intake was estimated using the procedure adopted by Berton et al. (2020), and by considering the net energy (NE) requirements and NE contents of the rations (MJ/kg DM). The NE requirements were computed according to the NRC (2001) and IPCC (2019) procedures, as the sum of the requirements for maintenance, activity, growth, milk production and pregnancy (see Supplementary Table S3). The NE contents of the rations were computed as the NE values of the individual feedstuffs, weighted by the relative contributions in the rations. The same procedure was adopted to compute the gross (GE) and digestible (DE) energy, as well as the chemical compositions of the rations. The energy and chemical composition values of the individual feedstuffs were derived from Martillotti et al. (1996), Sauvant et al. (2004), and INRA (2019), except for the commercial feed compounds, for which the chemical compositions were listed on the labels and energy values estimations were based on the lists of ingredients, weighted by their relative inclusion. Ketelaars and Van der Meer (1999) procedure was adopted to compute the nitrogen (N) and phosphorus (P) input–output flows for all the livestock categories. The N and P intakes were computed as the DMI × the N and P contents (% DM), while their total retentions were computed as the sum of the retentions for the milk (dietary crude protein content – dietCP_DM – derived from dairy data × 0.157), growth, and pregnancy (retention coefficients per livestock category were derived from Ketelaars and Van der Meer 1999). The excretion was calculated as the intake minus the retention.

The feed self-sufficiency rate (FSS) was computed as the ratio between the DM produced on-farm and the total DM intake.

Emission and resource computation and impact assessment

The impact computation equations are reported in Supplementary Tables 4a–c. The GWP computation included the emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The CH_4 emissions due to enteric fermentation were computed according to Ramin and Huhtanen (2013), based on the feed intakes and chemical compositions of the diets, whereas that due to manure storage was computed according to IPCC (2019). Emissions of N_2O were mainly derived from the manure storage as well as from the manure, and N-based fertilisers used for the feedstuff production. The emissions were estimated according to IPCC (2019) and EEA (2019). The acidification and eutrophication potentials were estimated based on the flows of nutrients (N and P) within the system boundaries. Ammonia (NH_3) and nitrogen oxides were included in the AP computation, with both mainly related to the N-volatilisation events that occur during manure storage and the spreading of manure and fertilisers on the fields. The volatilisation factors were derived from EEA (2019). In cases of the solid/liquid separation of the slurry and anaerobic digestion, the NH_3 emission factors were modified according to Dinuccio et al. (2008) and Holly et al. (2017), respectively. The eutrophic emissions included the deposition on the soil of the N volatilised from manure storage and fertiliser spreading, the N leaching into the soil as nitrate (IPCC 2019), and the P loss during the feedstuff production process (Nemecek and Kägi 2007).

The emissions related to the production, transport, and use of purchased inputs for feedstuff production (e.g. fertilisers and pesticides, seeds, fuel) and for animal handling (off-farm feedstuffs, fuel and bedding materials, such as straw and/or sawdust) were computed according to the impact factors published in the Ecoinvent (Wernet et al. 2016) and Agri-footprint (Blonk Agri-footprint BV 2014) databases (see Supplementary Tables 5a–d).

The conversion of the different emissions to the common unit of the impact categories concerning the GWP, AP and EP was based on the characterisation factors used by Berton et al. (2017), according to the CML (2016) methodology (see Supplementary Table S6).

Sensitivity analysis and data quality check

The FAO LEAP (FAO 2020) and ISO (ISO 2006) guidelines recommend considering the potential effect of the choices made in the LCA computation. For this reason, we performed a sensitivity analysis to assess the effect of two choices operated in the LCA modelling. The first one regarded the method to allocate the whole impact to the different coproducts. To assess the effect of the biophysical method applied, we used also an economic allocation method, with the prices of the milk and surplus animals derived from farm interviews and the Italian stock exchange database (ISMEA 2021). With respect to the reference year, no major changes were reported during the interviews with farmers in the previous year with respect to farm structure and management, agronomical management or farm materials consumption. Moreover, data about herd management and milk production were checked together with farmers and farmers' association technicians for accuracy and time-related consistency. To assess the potential sensitivity of the impact values to the reference year, we computed the LCA model also using the data retrieved from the official milk recording system as 3-year average (years 2017–2019).

Statistical analysis

The contribution of each emission source to the different impact categories was analysed *via* hotspot analysis (European Commission 2010). The impact categories were tested by using three different general linear models (GLM, SAS 2013). The independent variables were grouped under the farm management (MAN_F), ration composition (DIET_F), and animal response (ANI_F) factors (see the complete list of variables and the relative classification criteria in Supplementary Table S7). The effects of each group on the variation of the impact categories were separately analysed. All the factors that belonged to the same group were tested together in the same statistical model, and only those that influenced at least one impact category with $p \leq 0.1$ were retained in the final model. The final farm management model included the DSR (3 classes, <1.5, 1.5–3.0 and >3.0 dairy cows/ha) and FSS (3 classes, based on the mean $\pm$ 0.6 $\times$ standard deviation), with the 305 d fat- and protein-corrected milk yield (FPMY) as the covariate (3 classes, based on the mean ± 0.6 × standard deviation). The final ration composition model included the proportion of whole-cereal silages inclusion (WCS_incl) and dietCP_DM (3 classes, based on the mean ± 0.6 × standard deviation). The final animal response model included the FPMY, replacement rate (3 classes, based on the mean ± 0.6 × standard deviation), and age at first calving (2 classes, <24 months and ≥ 24 months). The MAN_F and DIET_F models were used also to test the effect of the farm management and ration composition on the animal response variables (milk yield, milk protein content, milk fat content, replacement rate, calving interval). Polynomial contrasts (linear and quadratic components) between the least-square means of the significant independent variable classes were estimated to evaluate the trends in the variations of the different impact categories.

Results

The descriptive statistics of the farms characteristics and management traits are reported in Table 1. On average, the number of dairy cows per farm was 120, plus 88 replacement heifers. The FAA destined to produce on-farm feedstuffs averaged 64 ha. The average DSR was nearly 2.6 dairy cows/ha FAA, and the intensity of the milk production/ha FAA averaged 24,000 kg of FPCM. The variabilities in terms of the farm size and production intensity were notable, with the standard deviations almost equal to the mean values. On average, almost half of the DM fed to the animals was produced on-farm, with a coefficient of variation (CV) around 32%. Because the farms produced different feedstuffs, and because the nutrient (N and P) requirements change among crops, the N and P fertilisation rates showed high variability (CV around 40%). On average, manure contributed to the overall fertilisation for nearly 40% of the N and nearly 80% of the P.

We present the descriptive statistics of the performance traits of the dairy cows in Table 2. The mean milk production over a 305-d lactation period was nearly 9100 kg of FPCM/dairy cow (CV: 14%). Regarding the reproduction indicators, the age at first calving averaged 25 months, and calving interval nearly 420 d. Almost one-third of the dairy cows were replaced each year, on average (CV around 25%). Sexed semen was used on most of the farms (22 out of 28, data not shown in tables), producing nearly 14% of the total yearly calves born on the farms (18% when only considering farms that used X-sorted semen). Only one farm did not use beef semen to inseminate the dairy cows for producing crossbred calves to be sold, with Belgian Blue and INRA-95 as the most widespread beef breeds used (data not shown).

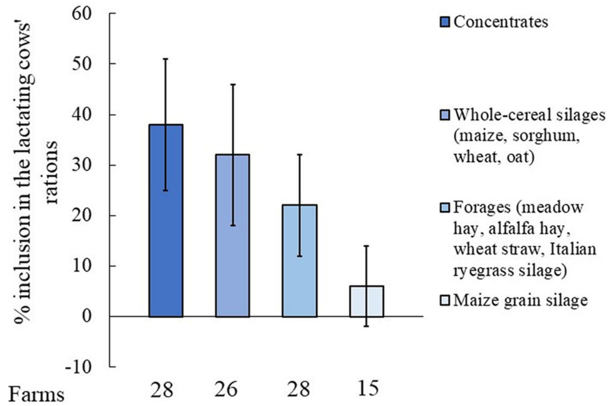
The main constituent types, relative proportions, and chemical compositions of the diets fed to the lactating cows are reported in Figure 1. The complete list of ingredients and their inclusion in the diets of the lactating cows, dry cows and heifers are reported in Supplementary Tables S8-S9. The diets were mainly based on whole-cereal silages and concentrates, which were used on almost all the farms, the average contributions of which were 32 and 38% of the DM of the rations, respectively. Conversely, maize grain silage (mean: 6%) was used as an ingredient in the diets of

Table 2. Descriptive statistics of performance traits of dairy cows ($N = 28$).

Variable	Unit	Media	Std
Milk production, 305-d lactation	kg fat and protein-corrected milk	9092	1235
Milk protein content	%	3.40	0.09
Milk fat content	%	3.86	0.27
Age at first calving	mo	25	2
Calving interval	d	423	25
Replacement rate	%	31.1	7.2
Calves from sexed semen	%	13.9	8.4
Calves from specialised-beef semen	%	26.4	16.7

Table 1. Descriptive statistics of farms characteristics and management traits ($N = 28$).

Variable	Unit	Mean	*SD*
Size			
Farm agricultural area (FAA) dedicated to feed production	ha FAA	64	63
Dairy cows	*n*	120	110
Replacement heifers	*n*	88	98
Intensity			
Stocking rate	dairy cows / ha FAA	2.58	2.35
Milk production	ton fat and protein corrected milk / ha FAA	24.3	22.5
Fertilisation			
Nitrogen fertilisation (total)	kg / ha FAA	308	126
Nitrogen fertilisation, from manure	%	43	12
Phosphorous fertilisation	kg / ha FAA	64	26
Phosphorous fertilisation, from manure	%	81	17
Self-sufficiency			
Feed self-sufficiency	% dry matter intake	50.6	16.2



Variable	Mean	SD
Chemical (% DM) and energy (MJ/kg DM) composition		
Dry matter	53.22	10.68
Crude protein	15.5	1.22
Fat	3.77	0.71
Neutral detergent fiber	34.9	4.21
Ash	7.07	0.94
Phosphorous	0.42	0.07
Net energy	6.6	0.3

Figure 1. Descriptive statistics of main constituents' proportion and chemical composition of diets fed to lactating cows ($N = 28$) (Farms: $n°$ of farms including the feeds category in the farm rations).

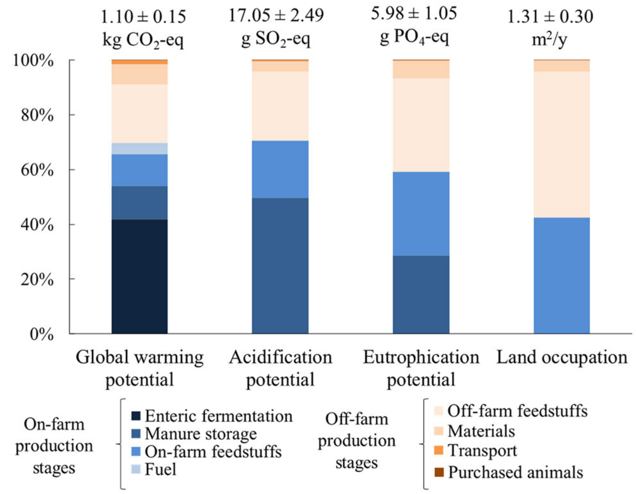


Figure 2. Raw means, standard deviations and hotspot analysis of impact categories per 1 kg fat- and protein-corrected milk (3.3% protein content, 4.0% fat content) for cereal-based dairy farms in Northern Italy ($N = 28$).

lactating cows on nearly half of the farms. Forages (hays plus Italian ryegrass silage) were also used on all the farms, contributing to nearly 20% of the ration composition. All the feedstuff types showed great variability among farms in terms of inclusion in the diets (CVs ranging from 34% to 132%). Regarding the chemical composition of the diets, the DM content was on average equal to 53% of the fresh content. The average content of the dietary CP was equal to 15.5% of DM, and it evidenced little variability among farms (CV: 8%), whereas the dietary P content averaged 0.42% (CV: 17%). The NDF content averaged almost 35% of the diets (CV:12%).

The raw means and standard deviations of the impact categories, as well as the relative contributions of the different production sources to the impact category values are illustrated in Figure 2. The production of 1 kg of FPCM was associated with an average emission of 1.10 kg CO_2-eq (GWP), 17.1 g SO_2-eq (AP), and 6.0 g PO_4-eq (EP), and with an occupation of nearly 1.3 m^2/y (LO). The variation coefficients of the impact categories ranged between 14 and 22%. About the hotspot analysis, the on-farm contributions overcame the off-farm ones in all the considered impact categories. The GWP had enteric fermentation (43%) and the production of the purchased feedstuffs (22%) as the first two contributors, whereas the manure storage, on-farm feedstuff production, and materials made similar contributions (around 10%). In terms of AP, the manure storage contributed to half of the whole impact, whereas both the on-farm and off-farm feedstuff production contributed to around one-quarter of the entire emissions. Feedstuff production was the first contributor to the EP (65%), with similar incidences for on-farm- and off-farm-origin feeds, whereas manure storage was the second contributor (29%). The land occupation was almost totally derived from the land needed to produce the feedstuffs.

The results of the GLMs are reported in Figures 3, 4, and 5 for the farm management (MANF_F), diet composition (DIET_F), and animal response (ANI_F) factors, respectively. Regarding the MAN_F, GWP and LO linearly decreased ($p < 0.10$) with the increasing values of both DSR and FSS. However, the decrease in GWP occurred when the feed self-sufficiency increased until around 50% of DM, whereas a further increase of FSS over 50% did not affect GWP further. Conversely, EP had a quadratic relationship with FSS, and the lowest EP values were associated with the medium-FSS class (around 50% of dietary DM), compared with the low- or high-FSS classes (average dietary DM values of 20% and 70%, respectively).

In terms of the DIET_F (Figure 4), GWP linearly decreased with the increase in WCS_incl. The AP and EP linearly increased with the increasing values of dietCP_DM ($p < 0.05$). Conversely, GWP was quadratically related to dietCP_DM, and it showed lower values at CP dietary concentration close to 15.5% DM compared to those close to 14 or 17%. The LO

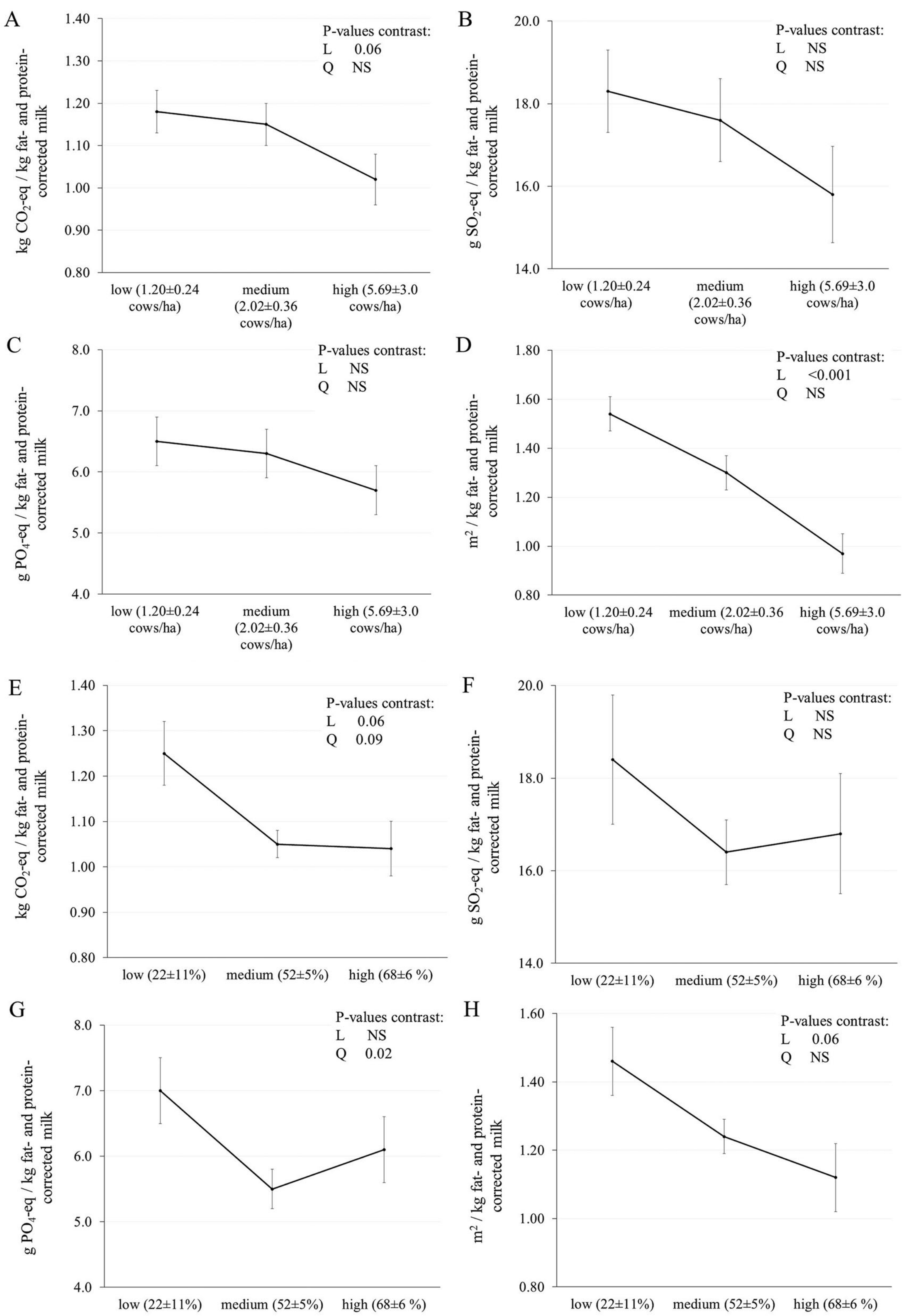


Figure 3. Least squares means and *p*-values of the linear (L) and quadratic (Q) trends of some farm management traits – stocking rate class (dairy cows/ha farm agricultural area) (A–D); feed self-sufficiency rate class (% share of the dry matter feed intake produced on farm) (E–H) – on the impact categories values. Milk corrected to 3.3% protein content and 4.0% fat content.

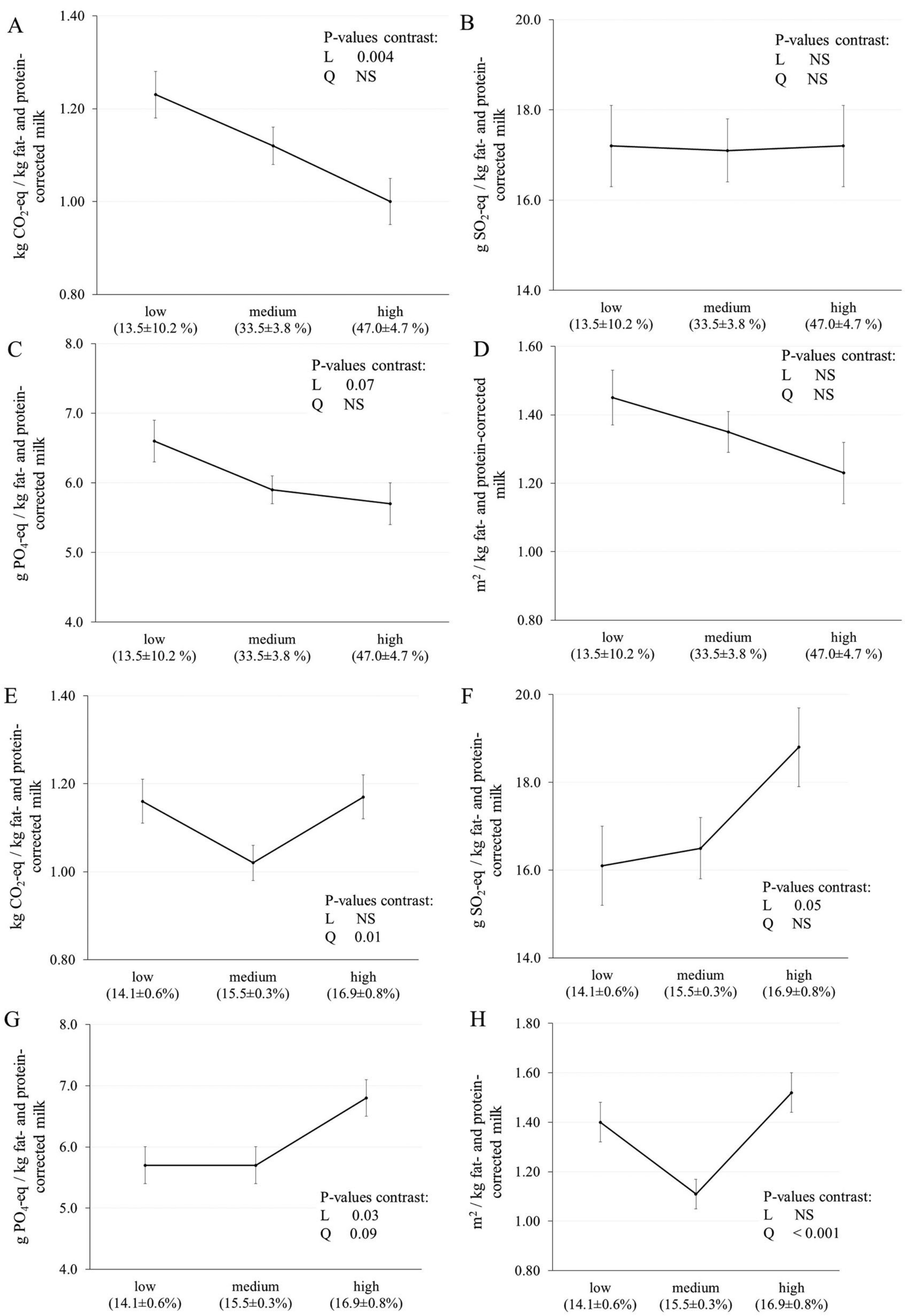


Figure 4. Least squares means and *p*-values of the linear (L) and quadratic (Q) trends of characteristics of rations fed to lactating cows – cereals silages (% dry matter – DM – intake from silages on total DM intake) (A–D); dietary crude protein content (% DM) (E–H) – on the impact categories values. Milk corrected to 3.3% protein content and 4.0% fat content.

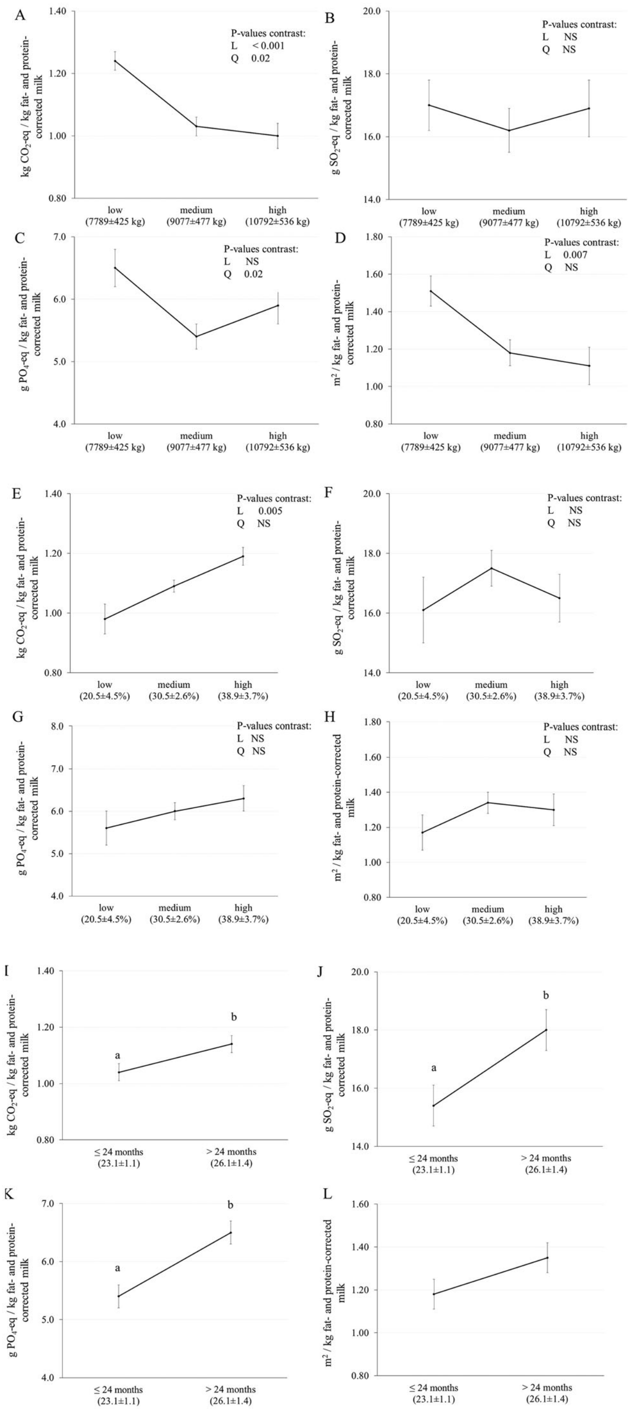


Figure 5. Least squares means and *p*-values of the linear (L) and quadratic (Q) trends of dairy cows response traits – yield of fat- and protein-corrected milk (kg/cow/305-d lactation) (A–D); replacement rate (%) (E–H); age at the first calving (months) (I-L) – on the impact categories values. Milk corrected to 3.3% protein content and 4.0% fat content. LSmeans with different superscripts within row differ significantly (*p* value < 0.05).

category was not affected by WCS_incl, whereas it was quadratically influenced by dietCP_DM, with the lowest values found for the intermediate values of dietCP_DM.

Regarding ANI_F, GWP and EP were significantly influenced by FPMY: they decreased moving from low- to medium-productivity herds (average FPMY values of 7800 and 9100 kg, respectively), whereas further increases in the productivity of herds had only slight effects on the emissions. On the contrary, LO evidenced a linear decrease with increasing values of FPMY. The replacement rate only influenced GWP ($p < 0.01$), with the emissions linearly increasing with the increase in the replacement rate. The age at first calving significantly influenced GWP, AP, and EP, with lower impact values when the first calving occurred at younger ages.

To define the relationships between the management and the dietary factors that were substantially related to one or more impact categories and animal response traits, the least squares of the MAN_F and DIET_F factors on the milk and animal-rearing traits are reported in Figure 6 and 7, respectively. In terms of MAN_F (Figure 6), the replacement rate linearly decreased ($p < 0.05$) with the increasing values of both DSR and FSS, whereas the milk protein content tended to linearly decrease with the increasing of FSS values. In terms of DIET_F (Figure 7), MY was affected by both WCS_incl and dietCP_DM. In particular, MY increased with the increasing WCS_incl ($p < 0.01$), whereas there was a quadratic trend with the increasing dietCP_DM, with the greatest values for the intermediate dietCP_DM class. The WCS_incl had an opposite influence on the milk components: the milk fat content linearly increased with the increasing of WCS_incl ($p < 0.02$), whereas a decrease in the milk CP content was observed, moving from the intermediate (mean value: 33% DM intake) to high (mean value: 47% DM intake) class of WCS_incl.

Sensitivity analysis results

The impact values showed few changes shifting from biophysical to economic allocation method, and Pearson correlations between biophysical-based and economic-based impact categories averaged 0.98. With respect to the time-related consistency of the data retrieved from the official milk recording system, data about number of dairy cows, FPMY, calving interval, age at first calving and dry period did not show evident changes when considering 1-year or 3-year data (Pearson correlation r factors ranged 0.92–1.00).

The replacement rate showed a greater 1-year vs 3-year variation with respect to the previous traits, but the correlation found remained positive and significant (r: 0.80, $p < 0.05$). Moreover, the distribution of the

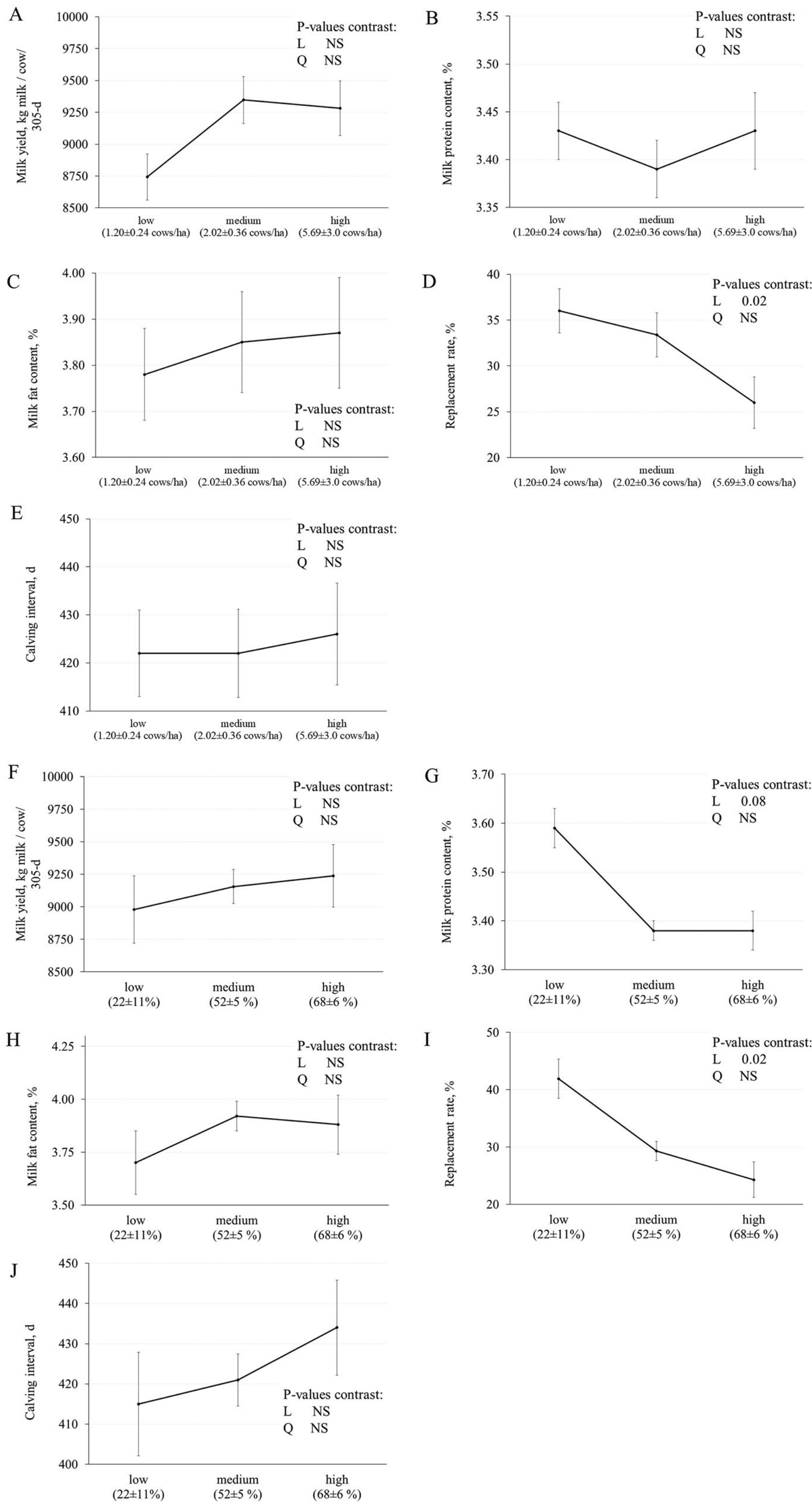


Figure 6. Least squares means and *p*-value of the linear (L) and quadratic (Q) trends of farm management traits (stocking rate class: dairy cows/ha farm agricultural area (A–E); feed self-sufficiency rate class-SELF%: % share of the dry matter intake produced on farm; (F–J)) on performance traits of dairy cows.

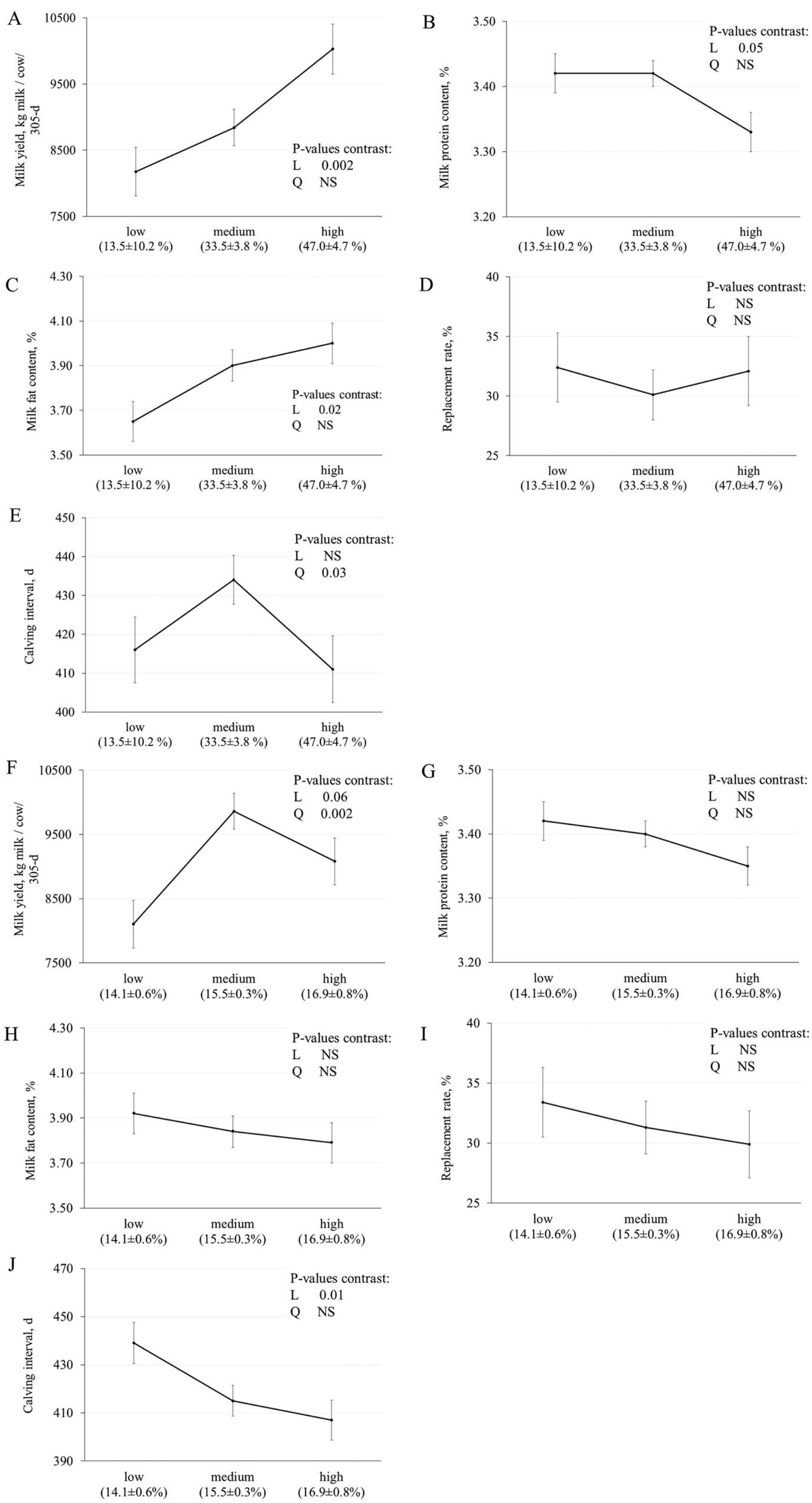


Figure 7. Least squares means and *p*-value of the linear (L) and quadratic (Q) trends of characteristics of rations fed to lactating cows (cereals silages: dry matter – DM – intake from silages on total DM intake, % (A–E); dietary crude protein (CP) content: % DM, (F–J)) on performance traits of dairy cows.

impact values found for the different impact categories when using 1-year or 3-year herd data was very similar (r factors ranging 0.96–0.99, $p < 0.01$). For details, see Supplementary Tables S10–S14.

Discussion

The mean impact values found in this study were generally comparable with those found in previous studies in which the authors assessed the dairy milk production systems in Italy (Bava et al. 2014; Battini et al. 2016; Lovarelli et al. 2019; Pirlo and Lolli 2019) and in other countries (Mazzetto et al. 2022), although the differences in the computation methods limit the comparability between the studies for AP and EP. Moreover, the impact values obtained showed a good time-related consistency between the reference year and a 3-year average.

In this study, we applied a systematic approach to assess how the dairy farm main stages affected the EI of the milk produced on cereal-based dairy farms. The analysis considered both the stages under farmers' control (the management of the farm organisation and composition of the diets of lactating cows) and those related to the outputs (the animal response, such as the milk yield and composition), obtained through farm and animal management settings. This approach can provide farmers with specific information for mitigating the EI of milk while supporting their efforts to maintain well-functioning farms. In fact, the probability that a farmer will adopt a mitigation option depends not only on its efficacy, but also on how it can be included in the present-day farm organisation, its cost, and its consequences on the farm performance (Vellinga et al. 2011).

The results of this study show that some traits concerning the farm organisation/management and diet formulation/composition, together with some animal response traits, which can be regarded as typical 'target' traits, such as the average production level, reproductive efficiency of the dairy cows, and so on, could play a role in mitigating the EI associated with dairy milk production, and they also evidenced complex reciprocal interactions. Regarding those modifiable by farmers, DSR and FSS (farm organisation/management), WCS_incl and dietCP_DM (diet of lactating cows) had associations with the impact values.

The mitigating effect of the increase in DSR values on LO was expected due to the DSR computation method (animal per on-farm area) and the notable importance of the on-farm land area (42 ± 18%) on the LO value. However, the associations between DSR and other impact categories (GWP, AP, EP) are less easy to explain. Although all the impact categories showed a declining trend with the increase in DSR, only GWP was substantially affected, probably because of the greater intraclass variability in AP and EP than in GWP. The stocking rate is a well-studied indicator, as it is a measure of the agricultural production intensity. However, the intensification of dairy production may have variable effects on the impact values (Gerssen-Gondelach et al. 2017). In fact, in different studies on the intensive dairy system in Northern Italy, researchers have found different results. Guerci et al. (2013) identified the mitigating effect of DSR on AP and EP categories, but not on GWP. Bava et al. (2014) did not observe any effects, whereas Battini et al. (2016) observed a mitigating effect on GWP. These differences could be related to the possibility that different FAA management options were observed on farms with similar DSR values (Tabacco et al. 2018), as greater crop yields could potentially sustain greater FSS values with the same DSR level.

The land management could affect the feed self-sufficiency as well. According to our results, FSS had a mitigating effect on GWP, EP, and LO, which was probably related to the fact that the increasing FSS values were associated with the replacement of high-impact feeds imported from outside with feeds produced on-farm and characterised by a lower EI (e.g. mean GWP per 1 kg of DM: 0.55 ± 0.12 kg CO_2-eq and 0.29 ± 0.10 kg CO_2-eq for off- and on-farm feedstuffs, respectively). Similar outcomes were found by Battini et al. (2016) with respect to GWP. However, the null effect on GWP and EP of a further increasing FSS when the self-sufficiency exceeded 50% of the diets (as DM) evidenced that this positive substitution rate had a decreasing trend with the increase in FSS values. Therefore, farms that are already characterised by high FSS levels should focus their attention on issues other than further increasing the FSS, such as practices to reduce the EI of crop production (e.g. Snyder et al. 2009). Moreover, the FSS could have other positive effects on the farm management and environmental aspects, such as the increase in the farm economic stability through the reduction in external feeds and relative price fluctuations (Lebacq et al. 2015), and the increase in the recirculation of the nutrients on farms (van der Wiel et al. 2020).

The main on-farm feedstuff type produced on the cereal-based dairy farms of Northern Italy was whole-cereal silages, which was the variable retained in the DIET_F model, together with dietCP_DM. The increase in WCS_incl in the diets of lactating cows had a double-mitigation effect: first, cereal silages are typically produced on-farm; thus, they contribute to FSS and its abovementioned capacity to reduce the milk EI. Second, we found a substantial and positive effect of WCS_incl on MY (see Figure 7). These effects were observed for the GWP and EP categories, but not for AP and LO. The LO only nominally decreased with the increasing values of WCS_incl. A possible reason explaining why these differences did not reach the statistical significance could be related to the intra-variability of LO within each class of this effect. The AP did not show any trend with the variation in the level of WCS_incl, probably because this impact category was more related to manure storage, a production stage not directly associated with feed production or diet formulation.

However, whole-cereal silages are characterised by low CP contents (7.8–9.3% DM; Martillotti et al. 1996; INRA 2019), and diets based on this ingredient need to be supplemented with protein. At present, the most utilised protein-rich feed is soybean meal, which is widely imported from South America (FAOSTAT 2019) and is loaded with CO_2-related emissions due to land-use change (Caro et al. 2018). Consequently, increasing WCS_incl in the rations of lactating cows risks also to increase the use of soybean meal in order to maintain dietCP_DM in the animal diets, which contrasts with the observed mitigating effects of WCS_incl on GWP. The use of other protein-rich feeds apart from imported soybean meal should be considered as an alternative solution to avoid this trade-off that should be assessed.

Moreover, dietCP_DM evidenced a substantial association with the EI of dairy milk production. Remarkably, it was the sole explored mitigating variable that significantly affected the values of all the impact categories. The positive effects of decreasing diet CP_DM on the AP and EP values were related to the reduction in the N intake, which consequently decreased the pool from which N could be volatilised during manure storage, but also to the reduction in the intake of protein-rich feeds, avoiding the impacts associated with their production. Furthermore, the quadratic trend observed for the GWP and LO categories at increasing dietCP_DM values was probably due to the comparable effects exerted on MY when dietCP_DM was progressively increased (Figure 7). Considering all the impact categories, the lowest impact values were observed at intermediate values of dietCP_DM, which, in this sample of dairy herds, corresponded to an amount of 150–160 g CP/kg of DM. This suggests that CP values lower or greater than this range had negative effects on both the EI numerator (the impact amount), when exceeding dietCP_DM increased the polluting N pool and the impact related to the feed production, and on the denominator (milk production), when dietCP_DM limiting availability harmed MY (e.g. Lee et al. 2012). The role of dietCP_DM as a driver of the livestock EI has been previously observed (Bittman et al. 2014), also in livestock systems other than dairy ones (Schiavon et al. 2015; Berton et al. 2018). However, according to the results of this study, actions that involve changes in dietCP_DM of dairy cow diets can be effective at mitigating a variable set of impact categories at the same time. Moreover, by combining the emerging good practices concerning diets composition and dietCP_DM, and by considering their relationships with MY (Figure 7), it is possible for farmers to obtain win–win results in terms of reducing their environmental impacts while sustaining the milk production and, consequently, the incomes of their farms.

Regarding the animal response, the increase in FPMY had general mitigating effects on the impact category values, which was expected, as the milk was the denominator of the impact/product ratio. This mitigation effect was not observed for AP, whereas the lowest EP value was found at the intermediate FPMY level. These results could be related to the notable importance of the manure storage source for EP and especially AP categories (see Figure 2), whose structure for storage and management (i.e. whether the manure is covered during the storage or not or whether the manure is treated) is mostly independent from FPMY. Moreover, the results obtained in this study evidenced an increase of emissions related to AP and EP with increasing dietCP_DM, which in turn was quadratically associated with milk yield, resulting in a correspondent increase in the potential pool for N volatilisation and a decrease in FPMY (see Figures 4 and 7).

Moreover, the small improvements in terms of GWP and LO, as well as the EP increase, which were associated in this study with the further increase in FPMY over an average yield comprised between 8500 and 9500 kg of FPCM per 305-d lactation, suggests that the exclusive focus on incrementing MY has many limits with respect to the mitigation of dairy milk EI at the greater yield level (Moallem 2016). From a broader point of view, the sole attention on the increase in MY risks creating an environmental ‘rebound’ effect if this increase is accompanied by a decrease in the provision of beef originating from dairy herds and a correspondent increase in suckler-cow-derived beef characterised by large impact values (Styles et al. 2018). This risk could be managed by enhancing the dairy-bred beef provision *via* crossbreeding with the semen of specialised beef breeds (Bittante et al. 2020) or by improving cull cow traits through rotational crossbreeding program for dairy cows (Piazza et al. 2023). The practice of using beef breeds semen had already been adopted by most of the farms involved (Table 1), and it can exert positive effects on the EI of beef production (De Vries et al. 2015).

Together with milk yield, good performances in terms of dairy cow reproduction and heifer management could mitigate dairy milk EI (Hristov et al. 2013). In this study, we found that the reduction in the replacement rate, which indirectly means increases in the longevity and milk careers of cows, and the reduction in the age at first calving, had mitigating effects on the EI of the milk, probably because both actions allow for reducing the size of and the time spent by cows as non-productive heifers. These goals can be pursued through management strategies able to increase the productive lifetimes of dairy cows, and to anticipate the time at which heifers can be inseminated for the first time (Lucy 2001). Last, the management factors associated with the EI of the dairy herds had insubstantial influences on the animal response traits (the milk yield and composition, replacement rate, and so on, Figure 6), which suggests that decreases in the environmental impact categories can be obtained without jeopardising the performance levels of dairy farms.

Conclusion

In this study, we analysed the EI of a cereal-based dairy milk production system that is typical of Northern Italy, and we identified a set of determinants related to the farm organisation, diets of lactating cows, and animal response traits associated with the environmental burden generated by this production system, and that are therefore potentially able to act as mitigation factors of dairy herds. According to the results of this study, each impact category (GWP, AP, EP, and LO) was associated with the abovementioned traits in a unique and complex way, evidencing the necessity of having a whole-farm vision to mitigate the environmental impact of dairy milk in an effective way without harming the farm functioning. In particular, the increases in the stocking rate and feed self-sufficiency (farm organisation), proportion of cereal silages in the diets (diets of lactating cows), and milk yields (animal response), as well as the decreases in dietary CP (diets of lactating cows), replacement rate, and age at first calving (animal response), demonstrated mitigating effects. However, the quadratic trends observed for the feed self-sufficiency, dietary CP content, and milk yield with respect to the different impact categories, as well as the complex relationships between the farm organisation and the diet composition and animal response are evidence of the need for a strict monitoring of the interventions aimed at mitigating the dairy milk environmental burden. In perspective, these results contribute to the establishment of good practices for farmers and consultants for the promotion of more environmentally sustainable dairy production while supporting farm functioning and farmers' incomes.

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Ethical statement

All research reported in this research has been conducted in an ethical and responsible manner, and is in full compliance with all relevant codes of experimentation and legislation.

Disclosure statement

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

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ORCID

Marco Berton http://orcid.org/0000-0002-2351-3090
Enrico Sturaro http://orcid.org/0000-0001-9508-5622
Stefano Schiavon http://orcid.org/0000-0002-5539-8947
Alessio Cecchinato http://orcid.org/0000-0003-3518-720X
Luigi Gallo http://orcid.org/0000-0002-8908-5105

Data availability statement

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

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