Environmental impacts of milk production and processing in the Eastern Alps: A "cradle-to-dairy gate" LCA approach

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ABSTRACT

This study aimed to evaluate the environmental footprint and feed energy conversion ratio of Alpine dairy chains in the Eastern Alps, taking into account both the milk production and dairy processing phases, and to identify farm management features useful for targeting mitigation measures in the production phase. A cradle-to-farm gate Life Cycle Assessment model that included herd and manure management, on-farm feedstuff production and purchased feedstuffs and materials (dairy farm), and production inputs and dairy outputs (dairy processing) was applied to 75 farms (10 dairies). As functional units, we used 1 kg fat- and protein-corrected milk (FPCM) and 1 m^2 of agricultural land, to account for production intensity and land managed by alpine farms, respectively. Impact categories (CML-IA and CED methods, background data from Ecoinvent database) assessed were global warming (GWP), GWP plus land-use change (GWP_LUC), acidification (AP) and eutrophication (EP) potentials, cumulative energy demand (CED) and land occupation (LO). Feed energy conversion ratio (whole diet - ECR; potentially human-edible portion of the diet - HeECR) was computed as the ratio between gross energy in feeds and that in milk. Mean ECR was 6.6 ± 0.5 MJ feed/MJ milk, of which only 8% derived from potentially human-edible feedstuffs. For 1 kg of FPCM at the dairy farm, GWP averaged 1.19 kg CO_2-eq, GWP_LUC 1.31 kg CO_2-eq, AP 17.3 g SO_2-eq and EP 6.0 g PO_4-eq (coefficients of variation, CV, ranged 17–21%), whereas mean CED was 2.7 MJ and LO 2.1 m^2/y (CVs: 40–46%). When dairy processing was included, the impact values for 1 kg of dairy product were from 8 to 13 times greater than those obtained for 1 kg FPCM. Based on the outcomes of a principal component analysis, the farm management features most related to impacts and feed ratios were milk yield (MY, for the impacts per unit of milk and ECR), stocking rate (SR, for the impacts per unit of area), and percentages of concentrates (C, for GWP_LUC and HeECR). Stepwise analysis evidenced that strategies aiming to decrease the environmental footprint referred to milk and managed area at the same time and to improve the feed energy conversion ratios should include MY, SR and C jointly. These issues are particularly important for the sustainability of mountain farming systems, which need to create a virtuous link with local forage resources and the territory.

1. Introduction

The European Union is one of the most important contributors to the global production of dairy milk, with a yield of almost 160 million tons in 2018, about 10% of which is produced in mountain areas (European Commission, 2019). In Italy, the 12,000 dairy farms located in mountain areas account for almost 43% of all dairy farms and 14% of total milk production (ISMEA, 2019). Alpine dairy farms account for nearly 40% of the milk produced in Italian mountain areas (ISMEA, 2019) and often belong to cooperative dairies

producing high-value local and Protected Designation of Origin (PDO) cheeses (Battaglini et al., 2014).

In the last decades, traditional Alpine dairy systems comprising small-scale, grassland-based farms, have experienced a strong decline driven by technical, social and economic factors (Strijker, 2005; Tasser et al., 2007). The Alpine dairy sector is now characterized by a wide variation in farming systems, with small-scale, low-input traditional farms coexisting alongside recently established, large-scale, intensive farms (Sturaro et al., 2009, 2013). At the same time, dairy production chains have to deal with new social and policy demands, such as the increasing awareness of environmental issues characterising consumers' buying patterns (Feldmann and Hamm, 2015), the general concern for global climate change (Feucht and Zander, 2017), and the ongoing implementation of environmental criteria under the EU common agricultural policy (CAP) (Erjavec and Erjavec, 2015). This situation is particularly challenging for mountain dairy systems, which operate under tougher production conditions and run a greater risk of low profitability than lowland dairy systems (Bazin, 1995). Therefore, proactive actions are needed to place them in a favourable position with respect to consumers' opinions, market prices and the CAP. Fundamental requirements to achieve this will be the ability to mitigate their environmental impacts and to better integrate production systems with territorial resources (Ripoll-Bosch et al., 2014; Rivera-Ferre et al., 2016).

Life Cycle Assessment (ISO, 2006) is a commonly used method for evaluating the environmental impacts of a product throughout its life cycle, i.e., from the sourcing of its raw materials to its disposal. Most LCA studies evaluating the environmental footprint of milk production have considered only one impact category, i.e., global warming potential (GWP, expressed as kg CO_2-eq/kg of milk) in lowland intensive farming systems (see Baldini et al., 2017 for a review). These studies agree in recommending increasing milk yield and feed energy conversion ratio (MJ in the feedstuffs needed to produce 1 MJ of milk) to reduce the GWP of dairy farms (e.g., Gerber et al., 2011). Mountain - and in particular Alpine - dairy systems have been less studied (Penati et al., 2013; Guerci et al., 2014; Salvador et al., 2016, 2017; Berton et al., 2020), but they are generally at a disadvantage compared with intensive lowland systems both in terms of GWP per unit of milk and feed energy conversion ratio because of their lower productivity. However, as GWP per unit of product is only one facet of the environmental impact of livestock systems, recent studies have included in their LCAs other impact categories (Penati et al., 2013; Berton et al., 2020) or functional units Ross et al., 2017. Furthermore, only a few studies have used LCA to identify the critical phases of Alpine dairy systems and hence the areas amenable to mitigation, such as using highland pastures during summer (Guerci et al., 2014) or modifying milk yields, stocking rates and feed self-sufficiency rates (Penati et al., 2013). At the same time, improvements in terms of feed energy conversion ratio in ruminant systems have been obtained by increasing the proportion of concentrates in animal diets. However, these improvements worsened ruminant systems' capacity to produce a net positive contribution to the human food balance (Ertl et al., 2015; Wilkinson and Lee, 2018). Moreover, LCA methodology usually failed to include the complex connections in the food system, for instance distinguishing the typology and the quality of the feedstuffs in terms of potential edibility for men (Van Hal et al., 2019). Consequently, the risk may be to propose mitigation strategies appropriate for the specific system but that exacerbate the environmental burdens at a more global level, posing the necessary to include potentially human-edible input-output food balance in the environmental assessment of food production systems (Van Zanten et al., 2018), especially when dealing with grassland-based systems such as small-scaled alpine dairy farms. Moreover,

the integration of different aspects of food sustainability is the centre of the EU Farm-to-Fork strategy (European Commission, 2020).

The overall environmental impact associated with dairy products is determined as the impact of milk production on the farms plus the impact of milk processing in the dairy factories. Different studies have analysed the environmental impacts of various dairy products, such as pasteurised milk, cheese and butter, using varied sets of impact categories (Djekic et al., 2014; Finnegan et al., 2018; Palmieri et al., 2017; Bava et al., 2018). However, to the best of our knowledge, no studies have yet taken a whole-chain (cradle-to-dairy gate) approach to analyse the environmental impact of dairy products produced by mountain supply chains.

This study used a cradle-to-dairy gate LCA model to evaluate the environmental footprint and feed energy conversion ratios of Alpine dairy chains in the Eastern Alps. We examined a large sample of farms located in different regions and included the dairy cooperatives to which they belonged with the aims of assessing the relative importance of the milk production and processing phases and identifying the farm management features that could be the target of mitigation measures in the production phase. To gain a more comprehensive insight into environmental sustainability, we considered different categories of impact using unit of milk and unit of land as the functional units and compared the efficiency of feed conversion into milk in terms of both total and human-edible gross energy.

2. Materials and methods

The LCA model, the data collection and editing followed the ILCD Handbook protocol (European Commission, 2010). The study was conducted in four different regions of the Eastern Alps (Veneto, Friuli Venezia Giulia and South Tyrol in Italy, and Carinthia in Austria). We examined 75 farms (55 in Italy, 20 in Austria) belonging to 10 dairy cooperatives (9 in Italy, 1 in Austria), which were typical of the dairy systems operating in the Eastern Alps, as described in Sturaro et al., 2009 and 2013. The study area is heterogeneous in land morphology conditions, with co-presence of areas with low elevations, gentler slopes and areas with higher elevation and steeper slopes, which determined great levels of land fragmentation and low suitability to crop production (Cocca et al., 2012).

The environmental footprint was assessed for two reference units (see Fig. 1): the farm (cradle-to-farm gate LCA) and the dairy (farm plus dairy processing, cradle-to-dairy gate LCA). The methodological information about the farm unit is reported in sections 2.1, whereas that related to the dairy unit in section 2.2.

2.1. Farm unit

2.1.1. Goal and scope definition

The assessment of the farm unit was based on a cradle-to-farm gate model, with 1 kg of fat- and protein-corrected milk (FPCM, milk corrected to standard contents of 4.0% fat and 3.3% protein; Gerber et al., 2010) as functional unit (FU), following ISO (2006) guidelines, which prescribe that FU has to be related to the function of the production system. However, as Alpine dairy systems are mainly characterized by small-scale farms managing local meadows and pastures (Battaglini et al., 2014), and should be considered as multi-functional systems rather than single-function systems (OECD, 2001), as also targeted by the European CAP policies (European Commission, 2013), we were interested in analysing the environmental footprint using also a land-based perspective. For this reason, we used 1 m^2 of farmland occupation as second FU.
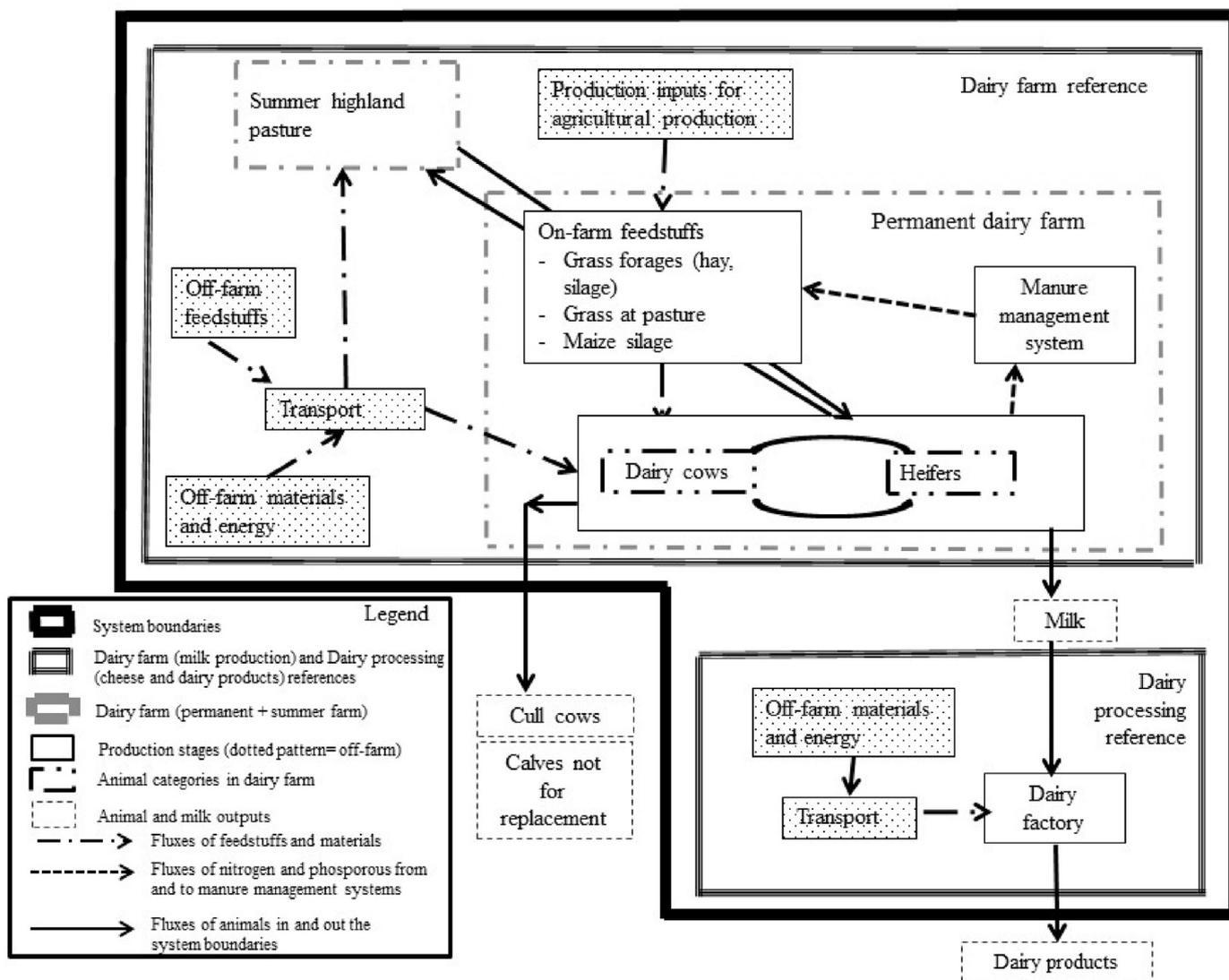
Fig. 1. System boundaries for the cradle-to-dairy-gate Life Cycle Assessment of North-eastern Alps dairy systems (off-farm stages with dotted pattern).

The system boundaries encompassed the processes and phases related to the production of the milk, which were partly "on-farm", i.e., herd and manure management and on-farm production of feedstuffs, and partly "off-farm", i.e., purchased inputs, such as fertilizers, off-farm produced feedstuffs, fuel, electricity and bedding materials, and related transport. Outputs were milk and animals (male and surplus female calves, culled cows). Impacts were allocated to these two co-products using the biophysical method (IDF, 2015). The impact categories assessed were global warming (GWP, kg CO_2-eq), acidification (AP, g SO_2-eq) and eutrophication (EP, g PO_4-eq) potentials, cumulative energy demand (CED, MJ) and land occupation (LO, m^2/y). For the farm unit, two efficiency indicators were also calculated: the feed gross energy (GE) conversion ratio of the total diet (ECR, MJ feed/MJ milk) and the feed GE conversion ratio of the fraction of the diet including potentially human-edible feedstuffs (HeECR, MJ feed/MJ milk), following Berton et al. (2017).

2.1.2. Life cycle inventory

Data were collected over a period of one year. Each farm was visited once by the same trained operator in a given region, each of whom used the same standardised questionnaire and procedure to minimize any operator-associated bias. The data collected to describe farm structure and management regarded housing (tie *vs* loose), manure management (slurry *vs* solid manure), manure storage (covered *vs* uncovered tank), calving management (seasonal *vs* non-seasonal), feeding (total mixed rations (TMR) *vs* traditional, i.e., forages administered *ad libitum* and concentrate supplements or part of forages administered in different amounts to each animal). We also recorded whether or not the farms used lowland pastures and practiced transhumance (i.e., movement of livestock to temporary units at high altitudes in summer to graze on Alpine grasslands), and, where relevant, the length of the grazing period.

We describe below the general procedure, while details of the procedures for editing the raw data and making the intermediate calculations are described in Supplementary Material sections 1.1-1.4. To measure herd sizes and composition, we referred to the monthly milk recordings to obtain the number of cows, the number of lactations, calving intervals, age at first calving and dry period length, and adopted the approach used by Berton et al. (2020) to model herd size on an annual basis. Livestock categories (lactating cows, dry cows, replacement heifers) were standardised as EU livestock units (LU; cattle > 2 years = 1 LU, cattle 6 months to 2 years = 0.6 LU, cattle < 6 months = 0.4 LU). To measure farm output, each farm's milk production was obtained from the records

of the dairy cooperative to which it belonged, while the number of animals sold was obtained from the herd register of each farm.

Data on feeding were collected separately for the winter period on the permanent farm and the grazing period on the permanent farm and/or the summer farm (see Supplementary Tables 1a, 1b, 1c). Feed intake was estimated using the procedure described by Berton et al. (2020) based on the animals' energy requirements (NRC, 2001; IPCC, 2006) and the ingredient composition of the rations, with a distinction made between farms using TMR and those not. Gross energy and NE contents and the chemical composition of the feeds and the grass grazed were obtained from INRA (2007), except for the commercial compounds, where the values were listed on the labels. Nitrogen (N) and phosphorus (P) input-output flows were computed for all livestock categories according to Ketelaars and Van der Meer (1999). N and P intakes were computed as dry matter intake x N and P contents (% dry matter, DM), while their total retentions were computed as the sum of the retentions for milk (crude protein content derived from dairy data x 0.157), growth and pregnancy (retention coefficients per livestock category were derived from Ketelaars and Van der Meer (1999)). Excretion was calculated as intake - retention.

The farms produced part of the feedstuffs fed to their animals (mostly forages: hay, grass silages and grass at pasture from grassland, maize silage from cropland) and purchased the rest (mostly concentrates, but also some forages). The total amounts of each feedstuff used were measured differently according to whether they were on- or off-farm sourced. The total amount of each purchased feedstuff (off-farm) was calculated from records of the diet ingredients and commercial invoices. As the amounts of on-farm produced feedstuffs were not directly calculable and were subject to year-to-year variability, they were estimated on the basis of the size and agronomic management of the farm agricultural area (FAA) given over to producing each feedstuff (see SM section 3).

Stocking rate (LU/ha FAA) was calculated excluding the period spent in summer farms, with the equation used in Sturaro et al. (2013). The other main inputs, such as electricity and fuel consumption and bedding materials (straw and sawdust), were obtained from farm invoices.

2.1.3. Calculation of impacts and efficiency indicators

The impacts of the farm unit were calculated separately for the winter in-house period and the grazing periods (on the permanent farm and/or on the summer farm; see Supplementary Tables 3 and 4). The general framework for emission calculation was taken from the IPCC (2006). Methane (CH_4) due to enteric fermentation was calculated using the equations suggested by Ramin and Huhtanen (2013), CH_4 and nitrous oxide (N_2O) resulting from manure management and fertilizer spreading using IPCC (2006) equations. Moreover, we included carbon dioxide (CO_2) emission associated with land-use change (LUC) due to deforestation in tropical areas which is mainly driven by agricultural expansion for producing soybean or pasture for animals (Morton et al., 2006; Gerber et al., 2013). The connection between the farms sampled here and such deforestation is the import of soybean meal from Brazil, the main source of soybean meal for Europe (FAOSTAT, 2019). For this reason, LUC emission in this study was associated with soybean meal included in the animal rations, using the value proposed by Caro et al. (2018) in a recent analysis.

Acidification potential was calculated on the basis of the emissions of N volatilised as ammonia and of nitrogen oxides during manure storage and the spreading of fertilizers (organic and chemical) on the field. The emission factors for manure storage were obtained from ISPRA (2011) and for fertilizer application from the IPCC (2006). Assessment of the eutrophication potential

included the contributions of the deposition of volatilised N (= N volatilised during manure storage and fertilizer spreading; IPCC 2006), N lost as nitrate through leaching (26% of N input; Bretscher, 2010), and P loss at the field (Nemecek and Kägi, 2007). For the impacts related to the background systems (production of fertilizers, pesticides and seeds for producing on-farm feedstuffs, and production and use of bedding materials, fuel, electricity), we used the impact factors (IFs) in the Ecoinvent database (v3.1, cut-off system model; Ecoinvent Centre, 2014) implemented in Simapro software v8.0.5, apart for the GWP of the use of 1 kg of fuel (EEA, 2013) and the GWP of the production of 1 kWh of electricity (ISPRA, 2011).

2.1.4. Life cycle impact assessment (LCIA)

Within each impact category, the single substances emitted (for GWP, AP and EP) and single contributions (in terms of energy consumed for CED and of occupied land for LO) were standardised to the common unit of the related impact category. Characterization factors for GWP, AP, EP and LO were derived from the CML-IA method (Oers, 2016), whereas the Cumulative Energy Demand method, directly implemented in Simapro software, was used for CED.

2.2. Dairy unit

The dairy unit included the farm unit and the following dairy processing, with different dairy products (yogurt, ricotta, butter and different cheeses) as output. The FU for the dairy unit was 1 kg of dairy product. As data collection, data editing and impact computation regarding the milk production phase have been already described in section 2.1, here the information and methodological aspects strictly related to the dairy processing phase are reported. The dairy processing phase included the processes that take place at the dairy, from the arrival of the milk to the shipping of products to the retail stage, and took into account the milk flows within the plant for producing the various dairy products and the inputs other than milk, such as energy sources (electricity, fuel, methane), water, cleaning agents and packaging materials. The impact categories assessed were equal to those assessed for the farm unit. Each dairy factory was visited once. Inputs were recorded from official registers and invoices and included the amount of milk supplied by each farm as well as the energy sources (fuel, methane gas, electricity), cleaning agents and packaging materials (tetrapak, glass, food wrapping paper, plastic) used. For details of these production input data see SM section 1.4 and Supplementary Table 2. The transport of milk from farm to dairy factory was not included due to a lack of data. Output was recorded as the types and amounts of the various dairy products (i.e., cheese, butter, yogurt). The average yields (kg milk/kg product) of each product were used to allocate the corresponding amounts of milk. Milk-embedded impacts were computed for each dairy cooperative as the mean of the impact values of the member farms, weighted by each farm's share of the total milk collected. If the milk used to produce butter was reused to produce cheese, the total milk processed into cheese was calculated as the butter-residual milk (milk composition after deducting the solids recovered in the butter) plus the milk needed to cover the remaining amount allocated to cheese products. The other production inputs were allocated to each dairy product using the mass-allocation methodology.

The impacts related to the background systems of the dairy unit - the production of the inputs used at the dairy unit - were calculated using IFs from the Ecoinvent database (Ecoinvent Centre, 2014) for energy sources, cleaning agents and packaging materials, except for the GWP of 1 kWh of electricity (ISPRA, 2011). The impacts associated with the production of milk were derived from

the results obtained from the farm unit. The LCIA procedure used in the dairy processing was equal to that use in the farm unit.

2.3. Interpretation and statistical analysis

We used hotspot analysis (European Commission, 2010) to assess the contribution of each phase and production process to the total impact from cradle to dairy gate. Based on the results, further statistical analyses were conducted only for the farm unit. We used principal component analysis (PCA; PROC PRINCOMP, SAS 2013) to identify the associations among a complex set of farm structural and management variables, impact values and efficiency indicators. The link between the features identified with PCA and the indicators of impact categories and energy conversion ratios was then assessed using a step-wise regression model (PROC REG, SAS 2013), adopting a P value of 0.05 as the threshold to retain a variable in the model. A preliminary test for the absence of collinearity (variance inflation factor < 2) between independent variables was carried out.

3. Results

3.1. Characteristics of farms, impacts and efficiency indicators

The main structural and management features of the farms are reported in Table 1. The mean total FAA was about 33 ha, located almost entirely at the permanent farm (86%) and managed as grassland (95%). Herd size averaged 38 LU, with 28 dairy cows (lactating or dry). The stocking rate averaged 1.37 LU/ha.

Table 1
Descriptive statistics of structural and management features of the farms sampled (variables subject to temporal variation are expressed on a per year basis).

Variable	Unit	Mean	SD	Min	Max
Farmland					
FAA[a] grassland permanent farm	ha	26.7	20.1	5.1	100.0
FAA cropland permanent farm	ha	1.9	3.7	0.0	16.3
FAA, permanent farm total	ha	28.6	21.0	5.1	100.0
Pasture area, summer farm	ha	4.5	6.8	0.0	32.5
FAA, total	ha	33.1	22.9	5.1	106.8
Altitude, permanent farm	m a.s.l.	790	281	280	1375
Cropland share	% FAA	5	10	0	48
Herd composition					
Dairy cows	LU[b]	28	19	4	99
Replacement	LU	10	7	1	36
Total	LU	38	25	5	123
Stocking rate	LU/ha	1.37	0.80	0.50	4.40
Farm management (0, absence; 1, presence)					
Loose stall	.	0.56	0.50	0.00	1.00
Total mixed ration	.	0.47	0.50	0.00	1.00
Pasture at permanent farm	.	0.64	0.48	0.00	1.00
Transhumance to summer farm	.	0.59	0.50	0.00	1.00
Energetic input					
Fuel	kg/LU	162	87	46	478
Electricity	kWh/LU	641	391	43	1684
Bedding materials					
Wheat straw	kg/LU	410	617	0	4732
Sawdust	kg/LU	154	387	0	1517
Total bedding	kg/LU	504	516	0	1851
Farm production					
Milk, per LU	kg FPCM	4749	1250	2095	7664
Milk, per dairy cow	kg FPCM	6400	1661	2543	10336
Milk, per ha FAA	kg FPCM	6628	4339	1249	24278
BW[c], per LU	kg BW	153	30	75	222
BW, per dairy cow	kg BW	210	54	89	356
BW, per ha FAA	kg BW	244	148	47	801

[a] FAA: farm agricultural area.
[b] LU: livestock unit.
[c] BW: body weight.

Considerable variability was associated with these features, with coefficients of variation (CV) ranging between 58 and 70%. Loose stall and TMR were almost equally more frequent than tie stalls and traditional feeding. Around 60% of the farms used pasture on the permanent farm and/or the summer farms.

Farm outputs were the milk and the animals sold to market (male and surplus female calves, culled cows). Mean milk yield was 6400 kg FPCM/cow/y (CV: 26%). Milk production intensity was 6630 kg FPCM/ha FAA (CV: 65%), showing a greater variation than in milk yield because of the inherent variability in the stocking rate. The animals sold amounted to a body weight of 153 kg per dairy cow (CV: 19.6%) and 244 kg per ha of FAA (CV: 60.8%).

Consumption of the different feeds and diet characteristics are reported in Table 2. Total feed consumption was nearly 6100 kg DM/LU per year (CV: 14%). Around 70% of the feedstuffs were produced on-farm, mostly hay and grazed grass. Off-farm purchased feeds comprised one-third of concentrates and two-thirds forages (hay, alfalfa hay and wheat straw) and raw materials for silages (grass and maize). Overall, hay represented half the diet and grass at pasture almost a quarter, the rest being silages and concentrates. There was a huge variation in the farms' production, purchase and use of different feeds (SDs always exceeded the mean values). The average diet contained 5.4 MJ of NE per kg DM, 2.1% DM of N and 0.3% DM of P. Understandably, the CVs were low (1–10%).

The average impact values per unit of milk and unit of area as well as feed energy conversion ratios for the farm unit are shown in Table 3. The production of 1 kg FPCM was associated with the emission of nearly 1.2 kg CO_2-eq (+10% when including CO_2 emissions related to land-use change) on average and to the consumption of nearly 3 MJ of CED and 2 m^2/y of LO. Variability was lower for emissions (CVs: 17–21%) than for resource usage (CVs: 40–46%). Since producing 1 kg FPCM needed almost 2 m^2 of land, the management of 1 m^2 of land showed mean values per impact category nearly halved with respect to means per 1 kg FPCM. However, the variation in impact values per unit of land was greater than those expressed per unit of milk, with CVs of 35–42% for emissions (GWP, AP and EP) and 55% for CED. Regarding feed energy conversion ratios, the production of 1 MJ in the milk required on average 6.55 MJ in the feedstuffs (whole diet) fed to the animals (CV: 21%), but only 0.48 MJ in potentially human-edible feedstuffs (CV: 77%).

Table 2
Descriptive statistics of feed intake (kg dry matter/LU/year), diet ingredient composition and chemical composition of the diets in the farms sampled.

Variable	Mean	SD	Min	Max
On-farm feeds intake	4247	1212	1588	7407
Hay	2081	1226	0	5066
Maize silage	294	605	0	2672
Grass silage	600	840	0	3098
Grass at pasture, permanent farm	888	914	0	3308
Grass at pasture, summer farm	384	550	0	2228
Off-farm feeds intake	1855	1443	9	5158
Hay	814	1228	0	4608
Wheat straw	25	97	0	661
Alfalfa hay	211	357	0	1433
Maize silage	130	367	0	1673
Grass silage	9	61	0	513
Maize flour	161	323	0	1753
Soybean	24	111	0	569
Compound feeds	481	602	8	2654
Total Feed intake	6102	835	4111	8225
Chemical composition (on a dry-matter basis)				
Gross energy, MJ/kg	17.9	0.1	17.7	18.1
Net energy, MJ/kg	5.4	0.4	4.6	6.3
Nitrogen, %	2.10	0.19	1.68	2.54
Neutral detergent fibre, %	57.4	5.6	43.5	67.5
Phosphorus, %	0.31	0.03	0.26	0.45

Table 3
Descriptive statistics of impact and feed energy conversion values obtained for the dairy farm reference (cradle-to-farm-gate LCA). Functional units (FU) used were 1 kg of fat- and protein-corrected milk (FPCM) and 1 m^2 of farm agricultural area (FAA).

Variable	Unit	Mean	SD	Min	Max
FU: 1 kg FPCM					
Global warming potential	kg CO$_2$-eq	1.19	0.20	0.69	1.76
Global warming potential + land use change	kg CO$_2$-eq	1.31	0.27	0.69	2.00
Acidification potential	g SO$_2$-eq	17.30	3.15	11.05	25.26
Eutrophication potential	g PO$_4$-eq	6.04	1.06	3.83	8.96
Cumulative energy demand	MJ	2.70	1.08	0.85	5.26
Land occupation	m^2/y	2.08	0.96	0.92	5.71
FU: 1 m^2 FAA					
Global warming potential	kg CO$_2$-eq	0.52	0.18	0.21	1.10
Global warming potential + land use change	kg CO$_2$-eq	0.58	0.22	0.21	1.20
Acidification potential	g SO$_2$-eq	7.76	3.23	2.64	16.59
Eutrophication potential	g PO$_4$-eq	2.67	0.99	1.00	5.44
Cumulative energy demand	MJ	1.19	0.65	0.21	3.59
Energy conversion ratios					
Gross energy conversion ratio	MJ feed/MJ milk	6.55	0.48	4.60	11.28
Potentially human-edible gross energy conversion ratio	MJ feed/MJ milk	0.48	0.36	0.00	1.28

The results of the environmental assessment for the whole system (cradle-to-dairy gate model) are given in Table 4. For every 1 kg of product, the different cheeses (categorised as fresh, medium-ripened, ripened, and "caciotta") evidenced mean impact values nearly 8−9 times (GWP, AP, EP and LO) and 13 times (CED) greater than those related to 1 kg of milk, accordingly to the mean yields of the different dairy products. The variation in impact values related to cheeses was quite low, CVs ranging 2−32% accordingly to the different impact categories. The impact values of ricotta and yogurt were in the ranges, respectively, of 34−50% and 12−16% of those of cheeses. The impacts of butter were 1.2−1.8 times greater than the impacts of cheeses.

3.2. Hotspot analysis and determinants of impacts at the farm unit

The results of the hotspot analysis (Fig. 2) showed that the farm unit accounted for 97−99% of the GWP, AP, EP and LO variations in the whole system, and 75% of the CED variation. Within the farm unit, on-farm stages contributed more than off-farm stages (from 53% for CED to 80% for AP and LO). The main contributors to the impacts were enteric fermentations on GWP (45%) and feedstuff production on AP, EP and LO (19−98%).

Due to the dairy processing unit's marginal contribution to the total impacts, further analyses were focused on the farm unit. The PCA of management indicators and impact values identified two components explaining almost 50% of the variability (Fig. 3). Adopting a threshold of 0.4, the first component correlated positively with stocking rate, milk yield, the proportion of concentrates in the diet, all the impact categories expressed per unit of land and HeECR, and negatively with feed self-sufficiency rate, grazed grass proportion in the diet, LO per unit of milk and ECR. The second
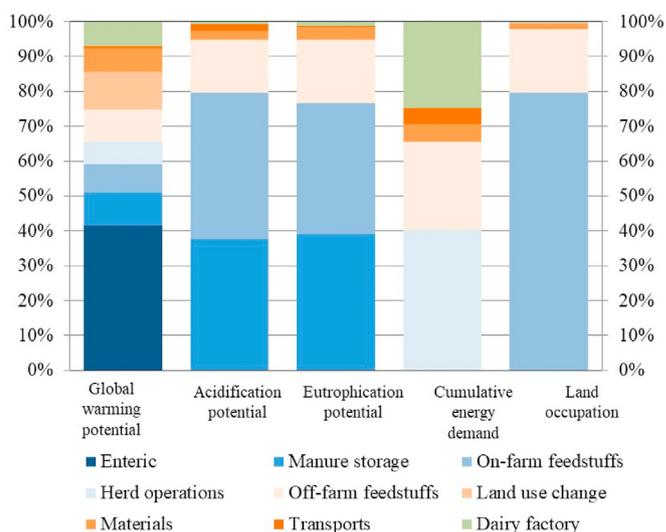
Fig. 2. Hotspot analysis (scale of blue: on-farm production stages in farm unit; scale of orange: off-farm production stages in farm unit; green: dairy processing unit) for the cradle-to-dairy-gate Life Cycle Assessment of North-eastern Alps dairy systems.

component correlated positively with the impact values expressed per unit of milk and ECR, and negatively with milk yield and the proportions of maize and grass silages in the diet.

Based on these results, we retained as indicators of the intensity of land and/or herd management those structural and management variables that met the following criteria: 1) absence of collinearity, 2) possibility to be managed/changed by the farmers. These indicators (stocking rate (SR), milk yield (MY), and proportions of

Table 4
Descriptive statistics of impact values of dairy products taken into account for the whole system (cradle-to-dairy-gate LCA). The functional unit used was 1 kg of dairy product.

	Dairies (N)	Global warming potential, kg CO$_2$-eq/kg		Acidification potential, g SO$_2$-eq/kg		Eutrophication potential, g PO$_4$-eq/kg		Cumulative energy demand, MJ/kg		Land occupation, m^2/kg	
		mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Fresh cheese	6	10.1	0.9	138	20	49.9	5.8	32.9	6.2	17.4	5.5
Mid-ripened cheese	4	10.9	0.9	155	27	55.9	7.3	35.6	7.6	16.3	2.4
Ripened cheese	4	11.7	0.8	166	31	60.2	8.9	38.4	8.7	18.3	2.9
Caciotta	3	9.7	1.0	134	20	47.4	1.0	28.9	2.4	15.5	2.5
Ricotta	5	4.3	0.9	63	8	21.1	3.2	14.9	3.8	8.2	4.2
Butter	6	15.0	2.1	206	18	72.4	8.4	51.6	10.2	25.4	11.3
Yogurt	4	1.5	0.1	21	2	7.5	0.7	4.7	0.4	2.5	0.2
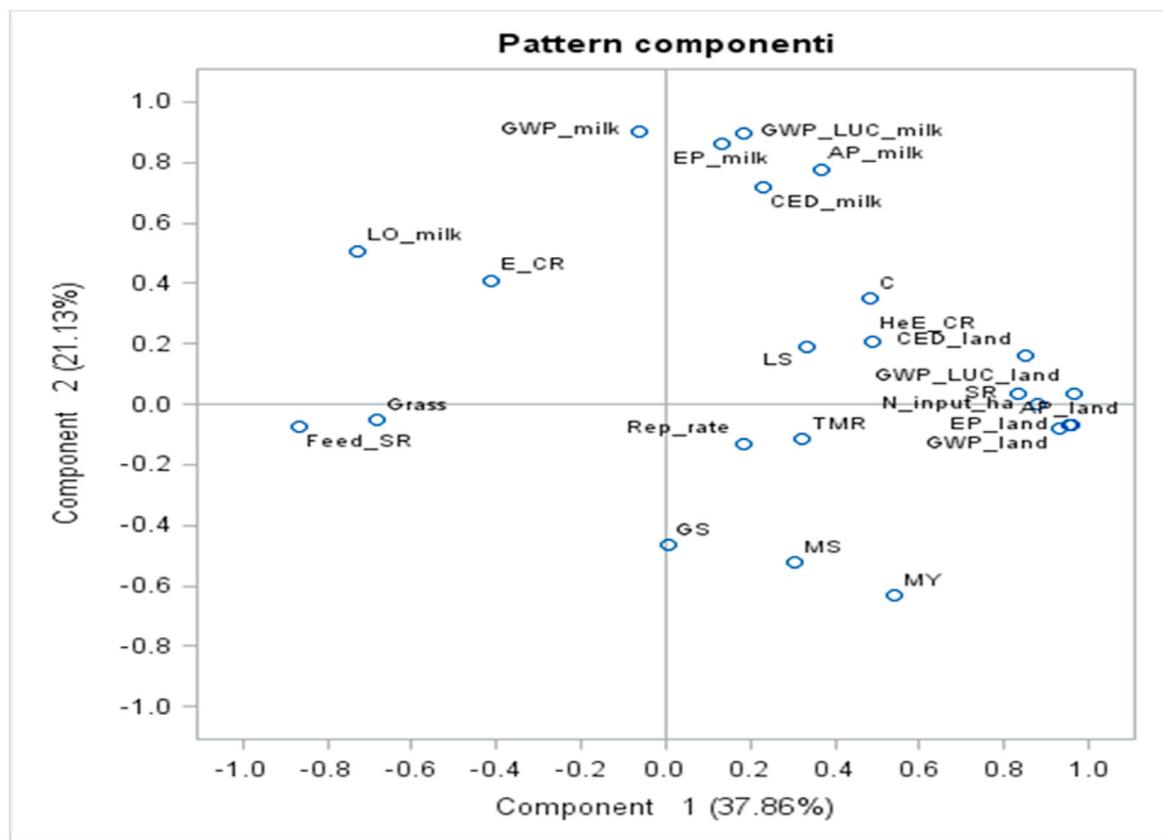
	Unit	Functional Unit	Acronym
Structural and management variables			
Loose *vs* fixed stall	yes/no	--	LS
Milk yield	Kg/cow/year	--	MY
Stocking rate	LU/ha of FAA	--	SR
Feed self sufficiency	% of total diet DM	--	Feed SF
Replacement rate	N of LU heifers / N of LU herd		Rep_rate
Nitrogen input	Kg N / ha farm agricultural area		N_input_ha
Total mixed ration *vs* traditional feeding	Yes/no	--	TMR
Concentrate proportion in diet	% of total diet DM	--	C
Maize silage proportion in diet	% of total diet DM	--	MS
Grass silage proportion in diet	% of total diet DM		GS
Grass at pasture proportion in diet	% of total diet DM		Grass
Emission and resource use variables			
Global warming potential	kg CO_2-eq	1 kg FPCM	GWP milk
Global warming potential	kg CO_2-eq	1 m^2 FAA	GWP land
Global warming potential, land-use change included	kg CO_2-eq	1 kg FPCM	GWP_LUC milk
Global warming potential, land-use change included	kg CO_2-eq	1 m^2 FAA	GWP_LUC land
Acidification potential	g SO_2-eq	1 kg FPCM	AP milk
Acidification potential	g SO_2-eq	1 m^2 FAA	AP land
Eutrophication potential	g PO_4-eq	1 kg FPCM	EP milk
Eutrophication potential	g PO_4-eq	1 m^2 FAA	EP land
Cumulative energy demand	MJ	1 kg FPCM	CED milk
Cumulative energy demand	MJ	1 m^2 FAA	CED land
Land occupation	m^2/y	1 kg FPCM	LO
Energy efficiency variables			
Total energy conversion ratio	GE: MJ feed/MJ milk	1 Kg FPCM	ECR
Human edible energy conversion ratio	GE: MJ feed/MJ milk	1 Kg FPCM	HeECR

Fig. 3. Principal component analysis of the management features, impacts and efficiencies calculated for the farm unit.

concentrates (C), grass silage (GS) and maize silage (MS) in the diet), were used in a step-wise regression model to evaluate their relationships with impacts and feed ratios (Table 5). Clearly, MY has an inherent relationship with impact categories expressed per unit of milk and SR with those expressed per unit of area, but we included them as correction factors with respect to the other management variables and also to assess the strength of their link with (i.e., their power as indicators of) impact and efficiency ratios.

The resulting models for the impact categories expressed per unit of milk and ECR had a lower R^2 (0.32−0.61) than the models for

the impact categories per unit of land and HeECR (0.80−0.90). Milk yield, SR and C were the variables that best explained the variability in the impact categories and feed energy conversion ratios, while GS and MS were retained by few models and made a marginal contribution to R^2. In general, the explained variability was concentrated on the first and second variables entering the models, while the third variables had partial R^2 values of 0.01−0.06.

As expected, MY and SR had notable relationships to the impact categories per unit of milk and unit of land, respectively. Regarding the impacts per unit of milk, GWP was mitigated firstly by an increase in MY (50% of the partial R^2) but also increased at an increasing SR, although with a modest partial R^2 (7%). Interestingly, when the land-use change was also included in the calculation of GWP, MY and C contributed almost equally to the total R^2 (55%), the former having a mitigating effect, the latter an aggravating effect. Around one-third of the variability in AP and EP was explained by the respective models. Acidification potential increased with SR and decreased with MY, with both variables contributing almost equally to the model R^2. Eutrophication potential decreased with MY and increased with C, with MY explaining twice the variability explained by C. Cumulative energy demand was positively related with C and negatively with MY, but the contribution of C was triple that of MY. The land occupation was mitigated by both MY and SR, with MY having a partial R^2 (39%) almost twice that of SR (22%).

Regarding the impacts per unit of land, GWP, GWP + land-use change, AP and EP were greatly increased by SR, which had remarkably high partial R^2 values (60−76%). For GWP, AP and EP the second variable included in the models was MY (partial $R^2 = 6−11\%$), with an aggravating effect. For CED, the first retained variable was instead C, with an aggravating effect and a notable partial R^2 (40%), whereas the second one was SR (partial $R^2 = 28\%$). Regarding the feed energy conversion ratios, ECR improved with an increase in MY (partial $R^2 = 46\%$) and a decrease in C (partial $R^2 = 6\%$), while HeECR improved with a decrease in C (partial $R^2 = 76\%$).

4. Discussion

Life Cycle Assessment is an output-based methodology (Finnveden et al., 2009), since it assesses the environmental footprint of a production system for one unit of output, in our study either milk (farm unit) or dairy product (whole system, dairy farm plus dairy processing unit). We have clearly shown that the industrial phase of processing milk into cheeses and other dairy products made a negligible contribution to the impact of the whole system compared with the agricultural phase of milk production, with the partial exception of CED. These results are in agreement with other studies on lowland intensive (Kim et al., 2013; Bava et al., 2018) and grass-based extensive systems (González-García et al., 2013; Palmieri et al., 2017), and shows that even in small mountain dairy chains, where factories often process small or moderate amounts of milk (see Supplementary Table 2), milk production is the dominant determinant of the environmental footprint of dairy products.

We examined a large group of farms with different structural and management conditions to reflect and represent the wide variation characteristic of current Alpine dairy systems (Sturaro et al., 2009, 2013). As a consequence, the impact values per unit of milk (farm unit) that we observed were also largely variable and covered the range reported by the few studies that have dealt with the GWP (1.0−1.7 kg CO_2-eq), EP (3.0−7.7 g PO_4-eq) and LO (1.4−3.2 m²/y) per 1 kg FPCM of mountain dairy farms. Conversely, our AP (21.0−22.9 g SO_2-eq/kg FPCM) and CED (5.0−5.1 MJ/kg FPCM) values were slightly lower than those reported in other studies (Penati et al., 2013; Guerci et al., 2014; Kiefer et al., 2015; Salvador et al., 2016, 2017; Berton et al., 2020). More generally, the variability in the farms sampled in this study might explain why our mean impact values per unit of milk overlapped only partially with those reported in recently published studies (Supplementary Table 5) for GWP (1.0−1.5 kg CO_2-eq), AP (12−28 g SO_2-eq), EP (6.0−8.5 g PO_4-eq) and CED (2.9−4.1 MJ) per 1 kg FPCM. On the contrary, the mean value of LO per unit of milk found in our study (2.1 m²/y per 1 kg FPCM) was greater than those reported in recent studies (1.2−1.6 m²/y, see Supplementary Table 5), probably due to the presence in our sample of many extensive, grassland-based farms with a low stocking rate and low productivity per unit of land.

Productive land is a limited resource, especially in mountain areas due to their morphological, pedological and climatic conditions, and dairy farms in mountain context are multi-functional

Table 5

Results of the step-wise regression analysis (intercept, beta coefficient, partial R^2 and model R^2) testing the relations of milk yield (MY, kg of fat and protein corrected milk/cow/d), stocking rate (SR, livestock unit/ha), the proportion of concentrate (C, %), grass silage (GS, %) and maize silage (MS, %) with impact categories (functional units (FU) used: 1 kg FPCM and 1 m² of farm agricultural area (FAA)) and feed energy conversion ratios obtained for the dairy farm reference unit.

Variable	Unit	Intercept	1st variable	Beta	Partial R²	2nd variable	Beta	Partial R²	3rd variable	Beta	Partial R²	Model R²
Impacts, FU: 1 kg FPCM												
Global warming potential	kg CO₂-eq	1.70	MY	−0.04	0.50	SR	0.07	0.07	C	0.002	0.02	0.59
Global warming potential + land use change	kg CO₂-eq	1.70	C	0.01	0.28	MY	−0.03	0.27				0.55
Acidification potential	g SO₂-eq	19.66	MY	−0.31	0.16	SR	1.82	0.15	C	0.06	0.04	0.35
Eutrophication potential	g PO₄-eq	7.52	MY	−0.14	0.18	C	0.02	0.09	SR	0.26	0.03	0.30
Cumulative energy demand	MJ	3.38	C	0.06	0.30	MY	−0.07	0.09				0.39
Land occupation	m²/y	4.77	MY	−0.11	0.39	SR	−0.57	0.22				0.61
Impacts, FU: 1 m² FAA												
Global warming potential	kg CO₂-eq	0.10	SR	0.19	0.76	MY	0.01	0.06				0.82
Global warming potential + land use change	kg CO₂-eq	0.03	SR	0.18	0.60	C	0.01	0.17	MY	0.01	0.06	0.83
Acidification potential	g SO₂-eq	−0.48	SR	3.12	0.74	MY	0.21	0.09	C	0.03	0.01	0.84
Eutrophication potential	g PO₄-eq	0.10	SR	0.89	0.67	MY	0.07	0.11	C	0.01	0.02	0.80
Cumulative energy demand	MJ	−0.13	C	0.03	0.40	SR	0.40	0.28	MY	0.03	0.03	0.71
Energy efficiency ratios												
Gross energy conversion ratio	MJ feed/MJ milk	9.96	MY	−0.17	0.46	C	−0.05	0.06	GS	−0.03	0.06	0.58
Potentially human-edible gross energy conversion ratio	MJ feed/MJ milk	0.23	C	0.03	0.76	MS[5]	0.02	0.13	MY	−0.01	0.01	0.90

systems that by managing this land may provide different territorial benefits other than milk (Faccioni et al., 2019). Therefore, the inclusion of an area-based FU adds an important dimension to the assessment of the impacts of mountain, and more generally extensive, dairy systems. As stated by Ross et al. (2017), LCA studies using kg of milk as the sole FU of the dairy farm fail to grasp the complexity of dairy systems, and to do so requires the inclusion also of productive land as an FU. For instance, acidifying and eutrophying emissions are mostly local phenomena, which cannot be indexed by the unit of milk (Potting and Hauschild, 2006). Previous studies on Alpine dairy systems have generally not considered FUs other than 1 kg milk, with the partial exception of Penati et al. (2013), who were able to indirectly calculate the impact per unit of area, and of Berton et al. (2020), who reported the impacts per 1 m^2 of FAA, although they did not take into account the grazing period on the permanent and/or summer farm. Although they used only mass-based FUs, Salvador et al. (2016) adopted a land-based approach taking into account the multi-functionality of mountain dairy farms and attributed the total greenhouse gas emissions not only to milk and meat but also to the ecosystem services provided.

The hotspot analysis results (Fig. 2) showed that the most important impact sources of GWP, AP and EP were on-farm, in line with the findings of Penati et al. (2013), Guerci et al. (2014) and Salvador et al. (2016), thus highlighting the possibility that the farmers may be active agents in mitigating the impacts of their farms. However, most farms sampled in this study would be unable to achieve this mitigation through the options usually recommended, i.e., increasing the proportion of concentrates in the diet and shifting to more specialised breeds (Herrero et al., 2016). Indeed, the medium-small sized farms in the north-eastern Alps are often unable to access financially-onerous investments, while the constraints of climate and land morphology preclude the agricultural productivity gains achievable in lowland areas, which are necessary for exploiting the economies of scale underlying intensification processes (Weersink and Tauer, 1991). Furthermore, our results indicate that increasing the concentrate proportion might actually increase the GWP if the land-use change is considered. In any case, profound changes in structures and management are not an assurance of improvement in environmental performance (Lorenz et al., 2019). In the short to medium term, feasible mountain-specific impact mitigation strategies could be developed on the basis of some existing good practices (Gerber et al., 2013). In this respect, we identified potential indicators through a PCA of a complex set of farm structural and management features and impact categories, and the subsequent step-wise regression analysis identified MY, SR and C as the variables most closely linked with impacts (see Table 5). Milk yield and SR were identified as valuable indicators also by Penati et al. (2013), together with feed self-sufficiency. Although PCA highlighted feed self-sufficiency as a variable associated with impact categories, we retained only SR because of the multi-collinearity criteria, it is easier to calculate and is a parameter well known to farmers.

Beyond the partly-expected indications that increasing MY could mitigate GWP (LUC excluded), AP, EP and LO per unit of milk and improve ECR, and that decreasing SR would mitigate GWP, AP, EP and CED per unit of land, our results showed the consequent mitigations to be also dependent on other variables, such as C and SR, which, in the case of the impacts per unit of milk, also had an opposite effect to MY. Particularly interesting, in our opinion, was the dominant effect of C in increasing GWP per unit of milk when LUC was included, which indicates that there might be a trade-off between global and local mitigation strategies (Schmitz et al., 2012). The role of C as an indicator is remarkable also for its dominant role in increasing CED, whether expressed as per unit of milk or unit of land, and in addressing the feed energy conversion ratios. In this respect, our results indicate that obtaining high yields with diets rich in concentrates improves the total feed gross energy ratio, although this was achieved with greater use of potentially human-edible feeds.

The complex relationship between MY, SR and C that emerged from the results of this study evidences that mitigation strategies aiming to decrease the environmental footprint referred to milk and managed area in the same time should include MY, SR and C jointly, looking to the best combination of these indicators able to minimize the impact values of the farms. In this regards, the farms associated with the lowest impact values (per unit of milk and area) were identified through a non-hierarchical cluster analysis based on MY, SR and C as cluster criteria (4 clusters; FASTCLUS procedure in SAS (2013), number of clusters optimized on the basis of the cubic clustering criterion indicator). The combination of MY, SR and C values in the farms with the lowest impacts showed averaged or good values of MY associated with low values of SR and C (MY value from 13 to 22 kg FPCM/cow/d, with <2.1 LU/ha of SR and <16% of C, data not shown). Farms with MY, SR and C values within these ranges, with respect to farms outside these ranges, showed a decrease in the environmental footprint up to 32%, according to the different impact categories. So, efforts aiming to extend these good practices to all the farms could lead to an important improvement in the environmental footprint of the alpine dairy system, in line with the Food and Agricultural Organization recommendations (FAO, 2013). However, a unique and specific combination of MY, SR and C values to be proposed as target is probably not useful, since the farms sampled in this study are connected to different value chains and agroecosystems. Besides, the level of farm management features could depend also on the goals and objectives of each farmer (Karali et al., 2013) as well as the constraints of the territory where farms are located, such as the presence of protected areas (Piermattei, 2013). Nevertheless, these results can provide useful information to farmers, and to each dairy to which farmers are associated, to plan future management intended to include environmental issues, that have been increasingly including in the CAP policy (Erjavec and Erjavec, 2015).

The farmers' possibility to intervene in the levels of MY, SR and C is quite different. If C is under the control of the farmer and MY is more a response than an input, the modification in terms of SR depends on both the farmer and land availability. Moreover, SR, as a measure of the number of animals managed per unit of farmland, is closely related to how land is managed and the types of relationship holding between livestock systems and their territory. The PCA results revealed that farms with a lower SR made greater use of pastures and less use of concentrates than farms with a higher SR. However, the Alpine dairy systems has shown an opposite pathway, with the (partial) substitution of grazing with off-farm purchases of forages and concentrates (Battaglini et al., 2014). Therefore, a divergence between environmental mitigation outcomes (reduction of SR) and on-going productive trends may arouse. Managing grasslands with a low SR can have different positive effects on soil and water quality (Anzai et al., 2016), by reducing nutrients (N and P) pressure on land determined by external inputs (fertilizers and purchased feedstuffs), biodiversity (Humbert et al., 2016) and conservation of valued landscapes with tourism benefits (Zoderer et al., 2016). On the other hand, grassland-based rations were partially associated with a lower MY (Pearson r = −0.32, P < 0.05), which could make farmers reluctant to adopt this type of management. However, the alternative, i.e., increasing concentrate supplementation, did not have a strong association with MY (r = 0.21, P = 0.08) and had a negative effect on CED, while the consequent off-farm cropland expansion could worsen LUC-related CO$_2$ emissions (Tonini et al., 2016) and reduce biodiversity (e.g., Newbold et al., 2015). The use of maize silage, although effective in

sustaining MY (r = 0.48, P < 0.01), was limited to the farms in the lower valleys. Any on-farm increase in this crop would be restricted by the scarcity of suitable agricultural land; moreover, transforming grasslands into arable crops has negative effects on mountain agroecosystems (Marini et al., 2009).

Besides, as expected, farms with low SR and high feed self-sufficiency were able to produce their own feedstuffs from grass-land that has little or no suitability for arable crops and contributed positively to the potentially human-edible food balance (HeECR<1). Consequently, they would firmly decouple milk production from competitive resources and more efficiently recycle nutrients from non-human-edible resources (Wilkinson, 2011). Feed-food competition is a key issue for the future sustainability of the live-stock sector, and in this regard evaluating the ability of ruminants to convert feed sources or wastes that monogastric livestock and humans are unable to use into high-value protein and energy plays a crucial role (Van Zanten et al., 2018). Additionally, in valuable environments such as the Alpine areas, assessment at a regional scale, beyond farm-scale, could give important insights on sustainability of the production systems (Loiseau et al., 2012), and future studies should investigate the effects of low-SR farms on services provided by the territory (ecosystem services), combining different sustainability assessment methodologies.

5. Conclusion

This study confirms that for all impact categories, with the partial exception of cumulative energy demand, the role of the dairy farm in the environmental footprint of dairy products is predominant. Therefore, the identification of farm management features that could be the target of mitigation measures has a notable importance in the reduction of the environmental footprint of dairy production. When addressing impact mitigation actions in Alpine or, more generally, mountain farming systems, it is neces-sary to take into account their wide diversity in size, structure, milk yields and animal and farmland management. This diversity in turn gives rise to a remarkable variability in terms of impacts (per unit of milk and land) and feed ratios indicators. This study found that milk yield, stocking rate and proportion of concentrates in the diet are the farm traits, when jointly considered, that can explain better impacts and feed ratios variability and that could be a target of mitigation measures. For this purpose, stocking rate and milk yield are simple and easily accessible indicators at the farm scale and could be used as proxies for the impact categories per unit of area in the former case and unit of milk in the latter. It is recommended to include both these functional units in LCA studies; this can help to assess the trade-offs between indicators of production efficiency and sustainable management of grassland, which is particularly important for mountain dairy cattle systems strongly linked to local forages. In this respect, stocking rate was informative of other variables related to farming sustainability, such as feed self-sufficiency and the role of farming practices in maintaining grass-lands and the Alpine landscape in general. Moreover, we found that when we took into account the proportion of concentrates in the diet - another simple indicator of farm management intensity - we were able to better evaluate the global warming potential including land-use change and to address feed-food competition in terms of the energy conversion efficiency of grassland-based farms. From the results obtained in this study, impact minimum was associated with a sufficient but not excessive milk yield (13−22 kg FPCM/cow/d), with a low stocking rate (<2.1 LU/ha) and concentrates pro-portion in the diet (<16%). These data can be used to formulate recommendations for mountain dairy production to favour the reduction of the environmental impact up to one-third. Although the precise combination of the values of these indicators should be assessed taking into account the farm context, this study provides and quantifies the relationships between milk yield, stocking rate and concentrates proportion in the diet with the impact indicators and feed ratios, that could be useful to farmers and dairies to which farmers are associated to plan their management in a more environmental-friendly way. Besides, these results could give a positive contribution in addressing the policymakers' decisions, to address future policies intended to sustain the Alpine dairy system in a more comprehensive perspective that includes productive, environmental and territorial issues. Future research, moreover, should consider other issues, such as ecosystem services, to obtain a more comprehensive evaluation of the sustainability of mountain dairy systems.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127056.

Author statement

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References

Anzai, H., Wang, L., Oishi, K., Irbis, C., Li, K., Kumagai, H., Inamura, T., Hirooka, H., 2016. Estimation of nitrogen and phosphorus flows in livestock production in Dianchi Lake basin, China. Anim. Sci. J. 87 (1), 37−45. https://doi.org/10.1111/asj.12390.

Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of Life Cycle Assessment applied to milk production. J. Clean. Prod. 140, 421−435. https://doi.org/10.1016/j.jclepro.2016.06.078.

Battaglini, L., Bovolenta, S., Gusmeroli, F., Salvador, S., Sturaro, E., 2014. Environ-mental sustainability of Alpine livestock farms. Ital. J. Anim. Sci. 13, 431−443. https://doi.org/10.4081/ijas.2014.3155.

Bava, L., Bacenetti, J., Gislon, G., Pellegrino, L., D'Incecco, P., Sandrucci, A., Tamburini, A., Fiala, M., Zucali, M., 2018. Impact assessment of traditional food manufacturing: the case of Grana Padano cheese. Sci. Total Environ. 626, 1200−1209. https://doi.org/10.1016/j.scitotenv.2018.01.143.

Bazin, G., 1995. In égalités de développement agricole et politiques correctrices dans les zones de montagne et défavorisées communautaires. INRA-Université de Paris ed., Paris, France.

Berton, M., Agabriel, J., Gallo, L., Lherm, M., Ramanzin, M., Sturaro, E., 2017. Envi-ronmental footprint of the integrated France−Italy beef production system assessed through a multi-indicator approach. Agric. Syst. 155, 33−42. https://doi.org/10.1016/j.agsy.2017.04.005, 2017.

Berton, M., Bittante, G., Zendri, F., Ramanzin, M., Schiavon, S., Sturaro, E., 2020. Environmental impact and efficiency of use of resources of different mountain dairy farming systems. Agric. Syst. 181 https://doi.org/10.1016/j.agsy.2020.102806, 102806.

Bretscher, D., 2010. Agricultural CH4 and N2O Emissions Switzerland. Agroscope Reckenholz 400 Tanikon Research Station (ART) DFE (Zurich, Switzerland).

Caro, D., Davis, S.J., Kebreab, E., Mitloehner, F., 2018. Land-use change emissions

from soybean feed embodied in Brazilian pork and poultry meat. J. Clean. Prod. 172, 2646—2654. https://doi.org/10.1016/j.jclepro.2017.11.146.

Cocca, G., Sturaro, E., Gallo, L., Ramanzin, M., 2012. Is the abandonment of traditional livestock farming systems the main driver of mountain landscape change in Alpine areas? Land Use Pol. 29 (4), 878—886. https://doi.org/10.1016/j.landusepol.2012.01.005.

Djekic, I., Miocinovic, J., Tomasevic, I., Smigic, N., Tomic, N., 2014. Environmental life-cycle assessment of various dairy products. J. Clean. Prod. 68, 64—72. https://doi.org/10.1016/j.jclepro.2013.12.054.

Ecoinvent Centre, 2014. Ecoinvent Data v3.1 - Final Report Ecoinvent No 15. Swiss Centre for Life Cycle Inventories. Dübendorf, Switzerland.

Erjavec, K., Erjavec, E., 2015. Greening the CAP' — just a fashionable justification? A discourse analysis of the 2014—2020 CAP reform documents. Food Pol. 51, 53—62. https://doi.org/10.1016/j.foodpol.2014.12.006.

Ertl, P., Klocker, H., Hörtenhuber, S., Knaus, W., Zollitsch, W., 2015. The net contribution of dairy production to human food supply: the case of Austrian dairy farms. Agric. Syst. 137, 119—125. https://doi.org/10.1016/j.agsy.2015.04.004.

European Commission, 2010. International Reference Life Cycle Data System (ILCD) Handbook — General Guide for Life Cycle Assessment — Detailed Guidance. Institute for Environment and Sustainability. European Commission — Joint Research Centre, Publications Office of The European Union, Luxembourg, Luxembourg.

European Commission, 2013. Common Agricultural Policy. EU regulation 1305/2013. Bruxelles, Belgium.

European Commission, 2019. Cows' milk collection and products obtained - annual data. Available at: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_mk_cola&lang=en (seen 10th May 2020).

European Commission, 2020. Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System. COM, p. 381 (European Commission, Bruxelles, Belgium).

European Environmental Agency, 2013. EMEP/EEA Air Pollutant Emission Inventory Guidebook — Technical Report 12/2013. European Environmental Agency, Copenhagen, Denmark.

Faccioni, G., Sturaro, E., Ramanzin, M., Bernués, A., 2019. Socio-economic valuation of abandonment and intensification of Alpine agroecosystems and associated ecosystem services. Land Use Pol. 81, 453—462. https://doi.org/10.1016/j.landusepol.2018.10.044.

Food and agricultural Organization (FAO), 2013. Report of the Expert Consultation on a Good Agricultural Practices (GAP) Approach. FAO, Rome, Italy.

FAOSTAT, 2019. FAOSTAT detailed trade matrix. http://www.fao.org/faostat/en/#data/TM.

Feldmann, C., Hamm, U., 2015. Consumers' perceptions and preferences for local food: a review. Food Qual. Prefer. 40, 152—164. https://doi.org/10.1016/j.foodqual.2014.09.014.

Feucht, Y., Zander, K., 2017. Consumers' willingness to pay for climate-friendly food in European countries. Proceedings in Food System Dynamics 360—377. https://doi.org/10.18461/pfsd.2017.1738.

Finnegan, W., Yan, M., Holden, N.M., Goggins, J., 2018. A review of environmental life cycle assessment studies examining cheese production. Int. J. Life Cycle Assess. 23 (9), 1773—1787. https://doi.org/10.1007/s11367-017-1407-7.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91, 1—21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Gerber, P., Vellinga, T., Opio, C., Henderson, B., Steinfeld, H., 2010. Greenhouse Gas Emissions from the Dairy Sector, A Life Cycle Assessment. Food and Agriculture Organisation, Rome, Italy.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139 (1—2), 100—108. https://doi.org/10.1016/j.livsci.2011.03.012.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change through Livestock — A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

González-García, S., Hospido, A., Moreira, M.T., Feijoo, G., Arroja, L., 2013. Environmental life cycle assessment of a Galician cheese: san Simon da Costa. J. Clean. Prod. 52, 253—262. https://doi.org/10.1016/j.jclepro.2013.03.006.

Guerci, M., Bava, L., Zucali, M., Tamburini, A., Sandrucci, A., 2014. Effect of summer grazing on carbon footprint of milk in Italian Alps: a sensitivity approach. J. Clean. Prod. 73, 236—244. https://doi.org/10.1016/j.jclepro.2013.11.021.

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Butterbach-Bahl, K., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Change 6, 452—461. https://doi.org/10.1038/nclimate2925.

Humbert, J.Y., Dwyer, J.M., Andrey, A., Arlettaz, R., 2016. Impacts of nitrogen addition on plant biodiversity in mountain grasslands depend on dose, application duration and climate: a systematic review. Global Change Biol. 22 (1), 110—120. https://doi.org/10.1111/gcb.12986.

IDF, 2015. Bulletin of the IDF No 479/2015. A Common Carbon Footprint Approach for Dairy Sector. The IDF Guide to Standard Life Cycle Assessment Methodology. International Dairy Federation (IDF), Brussels, Belgium.

Institut de la Recherce Agronomique (INRA), 2007. Tables de Composition and Nutritional Value of Feed Materials. INRA, Paris, France.

Intergovernmental Panel on Climate Change (IPCC), 2006. Guidelines for National Greenhouse Gas Inventories - Volume 4: Agriculture, Forestry and Other Land Use. Geneva, Switzerland.

ISMEA, 2019. In: Rama, D. Osservatorio (Ed.), Il mercato del latte — rapporto 2018, sul mercato dei prodotti zootecnici (Cremona, Italy).

ISO, 2006. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland. ISO 14044.

ISPRA, 2011. Emissioni nazionali in atmosfera dal 1990 al 2009 — rapporto 104/2011, Istituto superiore per la protezione e la ricerca ambientale (Rome, Italy).

Karali, E., Brunner, B., Doherty, R., Hersperger, A.M., Rounsevell, M.D., 2013. The effect of farmer attitudes and objectives on the heterogeneity of farm attributes and management in Switzerland. Hum. Ecol. 41 (6), 915—926. https://doi.org/10.1007/s10745-013-9612-x.

Ketelaars, J.J.M.H., Van der Meer, H.G., 1999. Establishment of Criteria for the Assessment of the Nitrogen Content of Animal Manures. Report 14. Final Report to ERM. Plant Research International, Wageningen, The Netherlands.

Kiefer, L.R., Menzel, F., Bahrs, E., 2015. Integration of ecosystem services into the carbon footprint of milk of South German dairy farms. J. Environ. Manag. 152, 11—18. https://doi.org/10.1016/j.jenvman.2015.01.017.

Kim, D., Thoma, G., Nutter, D., Milani, F., Ulrich, R., Norris, G., 2013. Life cycle assessment of cheese and whey production in the USA. Int. J. Life Cycle Assess. 18, 1019—1035. https://doi.org/10.1007/s11367-013-0553-9.

Loiseau, E., Junqua, G., Roux, P., Bellon-Maurel, V., 2012. Environmental assessment of a territory: an overview of existing tools and methods. J. Environ. Manag. 112, 213—225. https://doi.org/10.1016/j.jenvman.2012.07.024.

Lorenz, H., Reinsch, T., Hess, S., Taube, F., 2019. Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. J. Clean. Prod. 211, 161—170. https://doi.org/10.1016/j.jclepro.2018.11.113.

Marini, L., Fontana, P., Klimek, S., Battisti, A., Gaston, K.J., 2009. Impact of farm size and topography on plant and insect diversity of managed grasslands in the Alps. Biol. Conserv. 142, 394—403. https://doi.org/10.1016/j.biocon.2008.10.034.

Morton, D.S., DeFries, R., Shimabukuro, Y.E., Anderson, L.O., Arai, E., del Bon Espirito-Santo, F., Freitas, R., Morisette, J., 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Proc. Natl. Acad. Sci. U.S.A. 103 https://doi.org/10.1073/pnas.0606377103, 14637e14641.

Nemecek, T., Kägi, T., 2007. Life Cycle Inventories for Swiss and European Agricultural Production System — Final Report Ecoinvent No 15. Agroscope Reckenholz Taenikon Research Station ART. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Newbold, T., Hudson, L.N., Hill, S.L.L., Contu, S., Lysenko, I., Senior, R.A., Purvis, A., 2015. Global effects of land use on local terrestrial biodiversity. Nature 520, 45—50. https://doi.org/10.1038/nature14324.

NRC, 2001. NRC (National Research Council) Nutrient Requirements of Dairy Cattle, 7th rev. Natl. Acad. Press, Washington, DC (United States of America).

OECD, 2001. Multifunctionality: towards an Analytical Framework. Organisation for Economic Co-operation and Development, Paris, France.

Oers, L. van, 2016. CML-IA Database, Characterisation and Normalisation Factors for Midpoint Impact Category Indicators. August 2016. downloaded from, Version 4.8. http://www.cml.leiden.edu/software/data-cmlia.html.

Palmieri, N., Forleo, M.B., Salimei, E., 2017. Environmental impacts of a dairy cheese chain including whey feeding: an Italian case study. J. Clean. Prod. 140, 881—889. https://doi.org/10.1016/j.jclepro.2016.06.185.

Penati, C.A., Tamburini, A., Bava, L., Zucali, M., Sandrucci, A., 2013. Environmental impact of cow milk production in the central Italian Alps using Life Cycle Assessment. Ital. J. Anim. Sci. 12 (4), e96. https://doi.org/10.4081/ijas.2013.e96.

Piermattei, S., 2013. Local farmers vs. environmental universalism: conflicts over nature conservation in the Parco Nazionale dei Monti Sibillini, Italy. Journal of Political Ecology 20 (1), 306—317. https://doi.org/10.2458/v20i1.21769.

Potting, J., Hauschild, M.Z., 2006. Spatial differentiation in life cycle impact assessment - a decade of method development to increase the environmental realism of LCIA. Int. J. LCA 11, 11—13. https://doi.org/10.1065/lca2006.04.005.

Ramin, M., Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. J. Dairy Sci. 96, 2476—2493. https://doi.org/10.3168/jds.2012-6095.

Ripoll-Bosch, R., Joy, M., Bernués, A., 2014. Role of self-sufficiency, productivity and diversification on the economic sustainability of farming systems with autochthonous sheep breeds in less favoured areas in Southern Europe. Animal 8 (8), 1229—1237. https://doi.org/10.1017/S1751731113000529.

Rivera-Ferre, M.G., López-i-Gelats, F., Howden, M., Smith, P., Morton, J.F., Herrero, M., 2016. Re-framing the climate change debate in the livestock sector: mitigation and adaptation options. Wiley Interdisciplinary Reviews: Climate Change 7 (6), 869—892. https://doi.org/10.1002/wcc.421.

Ross, S.A., Topp, C.F.E., Ennos, R.A., Chagunda, M.G.G., 2017. Relative emissions intensity of dairy production systems: employing different functional units in life-cycle assessment. Animal 11 (8), 1—8. https://doi.org/10.1017/S1751731117000052.

Salvador, S., Corazzin, M., Piasentier, E., Bovolenta, S., 2016. Environmental assessment of small-scale dairy farms with multifunctionality in mountain areas. J. Clean. Prod. 124, 94—102. https://doi.org/10.1016/j.jclepro.2016.03.001.

Salvador, S., Corazzin, M., Romanzin, A., Bovolenta, S., 2017. Greenhouse gas balance of mountain dairy farms as affected by grassland carbon sequestration. J. Environ. Manag. 196, 644—650. https://doi.org/10.1016/j.jenvman.2017.03.052.

SAS, 2013. SAS 9.4. SAS Institute Inc, Cary, New York (United States of America).

Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Weindl, I., 2012. Trading more food: implications for land use, greenhouse gas

emissions, and the food system. Global Environ. Change 22 (1), 189–209. https://doi.org/10.1016/j.gloenvcha.2011.09.013.

Strijker, D., 2005. Marginal lands in Europe – causes of decline. Basic Appl. Ecol. 6, 99–106. https://doi.org/10.1016/j.baae.2005.01.001.

Sturaro, E., Cocca, G., Gallo, L., Mrad, M., Ramanzin, M., 2009. Livestock systems and farming styles in Eastern Italian Alps: an on-farm survey. Ital. J. Anim. Sci. 8 (4), 541–554. https://doi.org/10.4081/ijas.2009.541.

Sturaro, E., Marchiori, E., Cocca, G., Penasa, M., Ramanzin, M., Bittante, G., 2013. Dairy systems in mountainous areas: farm animal biodiversity, milk production and destination, and land use. Livest. Sci. 158, 157–168. https://doi.org/10.1016/j.livsci.2013.09.011.

Tasser, E., Walde, J., Tappeiner, U., Teutsch, A., Noggler, W., 2007. Land-use changes and natural reforestation in the eastern central Alps. Agric. Ecosyst. Environ. 118, 115–129. https://doi.org/10.1016/j.agee.2006.05.004.

Tonini, D., Hamelin, L., Astrup, T.F., 2016. Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes. Gcb Bioenergy 8 (4), 690–706. https://doi.org/10.1111/gcbb.12290.

Van Hal, O., De Boer, I.J.M., Muller, A., De Vries, S., Erb, K.H., Schader, C., Van Zanten, H.H.E., 2019. Upcycling food leftovers and grass resources through livestock: impact of livestock system and productivity. J. Clean. Prod. 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329.

Van Zanten, H.H., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C., De Boer, I.J., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biol. 24 (9), 4185–4194. https://doi.org/10.1111/gcb.14321.

Weersink, A., Tauer, L.W., 1991. Causality between dairy farm size and productivity. Am. J. Agric. Econ. 73 (4), 1138–1145. https://doi.org/10.2307/1242442.

Wilkinson, J.M., Lee, M.R.F., 2018. Use of human-edible animal feeds by ruminant livestock. Animal 12 (8), 1735–1743. https://doi.org/10.1017/S175173111700218X.

Wilkinson, J.M., 2011. Re-defining efficiency of feed use by livestock. Animal 5, 1014–1022. https://doi.org/10.1017/S175173111100005X.

Zoderer, B.M., Stanghellini, P.S.L., Tasser, E., Walde, J., Wieser, H., Tappeiner, U., 2016. Exploring socio-cultural values of ecosystem service categories in the Central Alps: the influence of socio-demographic factors and landscape type. Reg. Environ. Change 16 (7), 2033–2044. https://doi.org/10.1007/s10113-015-0922-y.