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Consequential-based life cycle assessment of reducing the concentrates supply level in the diet fed to lactating cows in the alpine dairy farming system

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ABSTRACT

This study aimed to assess the consequences of reducing the concentrates supply level (CSL) in the lactating cows' diet on Alpine dairy system's GHG emissions. Consequential-based Life Cycle Assessment (cLCA) was adopted to assess the consequences within the 'dairy_system' (farm plus milk processing) and outside ('expanded_system'). The functional unit was 1 kg of protein and fat (ProtFat). Data (1-year average) originated from 40 dairy farms in the Alps, collected through farm questionnaires during farm visits. Emissions were evaluated without (GWP) and with land-based emissions (crop- (GWP_LULUC_cb) or global-based (GWP_LULUC_gb) method). The feed conversion ratio was computed in terms of potentially human-edible gross energy (HeECR, MJ feed/MJ milk). Three scenarios were explored: 100% (t_0), 75% ($t_1$75), and 50% ($t_1$50) of the initial CSL. Impact values for both systems were analysed with a mixed model to test the effect of the scenarios. At 'dairy_system', 1 kg ProtFat caused 19.0 (GWP), 22.9 (GWP_LULUC_cb) and 23.4 kg CO_2-eq (GWP_LULUC_gb) at t_0 and HeECR resulted in 0.71 MJ feed/MJ milk. The CSL reduction from t_0 to $t_1$75 and $t_1$50 significantly increased impact values (2–11%) and decreased HeECR (from −10 to −23%). Considering 'expanded_system', CSL reduction significantly increased GWP (4%) and GWP_LULUC_gb (3%) but decreased GWP_LULUC_cb (up to −4%). In conclusion, cLCA-based approach evidenced that CSL reductions implied diversified effects on GHG emissions, at Alpine dairy system and at food supply level, giving new insights into the challenge of reducing GHG emissions while favouring the decoupling of milk production from the use of human-edible resources.

HIGHLIGHTS

- Consequential Life Cycle Assessment of reducing concentrates supply (CSL) to lactating cows on the GHG emission of Alpine dairy products was analysed
- GHGs per protein plus fat in the product increased with decreasing CSL (75% and 50% of initial CSL) but can decrease considering land-use change GHG
- Decoupling Alpine dairy production from concentrates could be environmentally challenging but feasible

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Alpine dairy farms; consequential life cycle assessment; concentrate supply level; global warming potential

Introduction

In recent years, the need to reduce anthropogenic emissions of greenhouse gases (GHG) has become increasingly urgent. Food production has been associated with nearly one-third of total GHG emissions, livestock production being one of the main contributors (IPCC 2022). Over the last two decades, the European livestock industry has reduced its GHG emissions (EEA 2021), driven mainly by an increase in animal productivity while consumption of animal products has remained stable (Eurostat 2021). However, these improvements have been sustained mainly through increasing the dietary content of concentrate feeds, especially for ruminants (Wilkinson and Lee 2018). Since concentrates are mainly comprised of potentially human-edible foods, this strategy has increased the competition between the use of such foods for animal nutrition and their direct use for human nutrition (Mottet et al. 2017).

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A similar development was experienced by the small-scale dairy farms in the Alps. These farms have traditionally exploited local meadows and pastures – human-inedible feed resources grown in areas with little or no suitability for agriculture – to produce high-quality products. In recent decades, this production system has undergone a process characterised by the abandonment of marginal areas and intensification of the more favourable valley bottoms, which has led to a greater use of purchased concentrates and the adoption of breeding, structural and management practices typical of lowland dairy systems, and made Alpine dairy farms more reliant on potentially human-edible food resources (Sturaro et al. 2013; Battaglini et al. 2014).

Life cycle assessment (LCA; ISO 2006) has emerged as the standard method to evaluate the GHG emissions associated with food and livestock production. The most common approach is the attributional LCA (aLCA), which is an estimation of the emissions attributable to a given product (Finnveden et al. 2009). The main limit of aLCA is its poor ability to assess the consequences in the environmental burdens due to changes in production systems. For this, a consequential approach (cLCA; UNEP-SETAC 2011) is needed, as it considers the direct and indirect effects of the changes in a production system. Various studies have used cLCA to assess the potential impacts of the production changes in livestock systems (e.g. Nguyen et al. 2013, Chobtang et al. 2017). These studies have generally shown that the results in terms of modifications in the environmental footprint due to a change can be different when considering only the single system or the wider production context, thus affecting the capacity of that change to produce a real reduction in the environmental burden.

In this regard, the link between animal-sourced food provision and the use of potentially human-edible concentrates to sustain animal production efficiency has been explored (Van Hal et al. 2019), including with respect to milk yield in small-scale Alpine dairy farms (Ertl et al. 2014; Horn et al. 2014), but little consideration has been given to the potential environmental consequences (Röös et al. 2017). This is a crucial issue, given the emergence of environmental-based demands from consumers, the shift in the European Union Common Agricultural Policy towards environmentally-friendly production criteria (Pe'er et al. 2019) and proposals for new result-based carbon farming schemes (COWI, Ecologic Institute, IEEP 2021). Consequently, livestock systems are called upon to produce sustainable food with low levels of competition in the use of edible resources. In this regard, the Alpine dairy system, where concentrates are not widely produced and must be purchased, has a great interest in increasing low-concentrate dairy production but at the same time in remaining capable of meeting the demands of consumers and policymakers.

In this study, we analysed how a reduction in the use of concentrate feeds in Alpine dairy systems would impact its environmental footprint and production efficiency in terms of the conversion of potentially human-edible foods. For this purpose, we used a cradle-to-dairy gate, consequential-based LCA model, in which we considered not only the Alpine dairy system but also the external systems that may be affected by the initial change.

Material and methods

Goal and scope definition

The base scenario (t_0) was taken from Berton et al. (2021), who analysed 75 farms representative of Alpine dairy systems supplying milk to 10 cooperative dairies producing mostly PDO cheeses and other dairy products (nearly 90% of the milk) and a small quantity of fluid milk (nearly 10%). The Alpine dairy system is characterised by small-medium farms (farm agricultural area (FAA) 33.1 ± 22.9 ha, >90% managed as grassland, 28 ± 19 dairy cows). The animals spend the winter season indoors, with rations consisting of (mainly self-produced) forages and purchased concentrates, while in the summer the majority of the farms graze their animals on pastures located either on the permanent farms or on summer farms (i.e. temporary livestock farms that supplement the forage budget of the permanent farms). For the consequential-based assessment, we selected from these 75 dairy farms a subset of farms whose rations fed to lactating cows contained >1 kg DM of concentrates/head per day, on an annual basis, as the analysis would have been unfeasible with values less than this threshold. Forty farms were retained (88% of the farms in Italy – 53% in Veneto Region, 35% in Friuli Venezia Giulia - and 12% in Austria). The farm sizes, breed composition, management practices, and production levels of these farms at t_0 are reported in Tables 1 and 2.

Based on the results reported by Horn et al. (2014), we tested two different scenarios in which the concentrate supply level (CSL) in the lactating cows' rations was reduced to 75% ($t_1$75) and to 50% ($t_1$50) of the initial value. As a decision (i.e. reduction in CSL) is implied and it could have a series of effects not

Table 1. Descriptive statistics of farm area, herd composition (as livestock units -LU – with cattle >2 years: 1 LU, cattle 6 months to 2 years: 0.6 LU, cattle <6 months: 0.4 LU), and productive traits at the base scenario (t_0), before the reduction in the concentrate supply level ($N = 40$).

Variable	Unit	Mean	SD	Min	Max
Farm agricultural area (FAA)					
FAA, permanent farm	ha	31	25	5	100
FAA, summer farm	ha	5	8	0	27
FAA, total	ha	36	27	5	107
Cropland	% FAA	3	7	0	28
Herd size					
LU[1] dairy cows	N	31	21	5	99
LU lactating cows	N	27	18	4	86
LU replacement heifers	N	10	8	1	36
Stocking rate	LU/FAA	1.4	0.8	0.5	4.4
Productivity					
Milk yield (fat and protein-corrected milk)	kg/dairy cow	6408	1632	3242	10336
Animal sold body weight (BW)	kg BW/LU	145	23	76	189
Concentrate supply level (CSL) as dry matter (DM)					
Lactating cows	kg DM/head per day	4.5	2.8	1.1	11.3
Soybean meal, on CSL	% DM	17	13	0	50
Dry cows	kg DM/head per day	1.2	1.3	0.0	5.1
Soybean meal, on CSL	% DM	8	13	0	54
Replacement heifers	kg DM/head per day	0.6	0.4	0.1	1.6
Soybean meal, on CSL	% DM	9	18	0	100
Farm materials					
Fuel	kg/LU	166	86	44	478
Electricity	kWh/LU	536	331	43	1648
Bedding (straw + sawdust)	kg/LU	504	534	0	1871

Table 2. Descriptive statistics of farms' breeding composition and management traits ($N = 40$).

Variable		Percentage of farms
Breed composition	Simmental	50
	Mixed (different breeds and crossbreds)	18
	Holstein Friesian	17
	Brown Swiss	15
Housing	Stall loose	55
	Tie stall	45
Feeding administration	Total mixed ration	50
	Traditional feeding	50
Use of pasture, permanent farm	yes	65
	no	35
Use of pasture, permanent farm, by lactating cows	yes	48
	no	52
Use of pasture, summer farm	yes	48
	no	52
Use of pasture, summer farm, by lactating cows	yes	28
	no	72

only within the Alpine dairy system but also outside, as CSL can affect the milk yield (MY) of lactating cows (e.g. Mayne and Gordon 1984) and consequently the dairy provisioning level, we adopted a consequential-based LCA model for evaluating the net effect associated with the two scenarios ($t_1$75 and $t_1$50) with respect to the base scenario (t_0), in accordance with Schaubroeck et al. (2021). The impact category was the global warming potential, without and with considering the emissions related to land use and land-use change (GWP, kg CO_2-eq and GWP_LULUC, kg CO_2-eq, respectively).

Two reference units were considered. The first ('dairy_system') included the Alpine dairy farm and the dairy factory processing the milk supplied by the dairy farm, whereas the second one ('expanded_system') included 'dairy_system' plus the external food systems whose production level would be affected by the initial decision (i.e. reducing CSL). Our modelling of the consequences related to the 'dairy_system' is reported in subsection Modelling the consequences for the dairy system of the reduction in CSL, and that related to the 'expanded_system' in subsection Modelling the consequences of the 'expanded_system'. As protein and fat contents in the milk were the most important output of the 'dairy_system', the functional unit was set at 1 kg of protein plus fat in the product (ProtFat) for both the 'dairy_system' and 'expanded_system'. Moreover, since the dairy farms are multifunctional, producing surplus animals (quantified as body weight at sale, BWS) as well as milk, we applied an expansion of the system (ISO, 2006) to solve the multifunctionality, assuming the northern Italian intensive system (Berton et al. 2017) as the alternative system production.

Modelling the consequences for the dairy system of the reduction in CSL

The inventories of the dairy farm (farm area, herd size, milk production, herd management, manure management, on-farm feedstuff production, purchase of off-farm feedstuffs and materials), and dairy processing (dairy factory inputs and outputs) stages at t_0 were derived from Berton et al. (2021) for the retained 40 farms. Briefly, about the dairy farm, the feed intakes of the lactating cows, dry cows and replacement heifers were calculated on the animals' net energy (NE) requirements (IPCC 2019) and the NE content per kg of dry matter (DM) of the animal diet (NE_DM). The NE_DM and the chemical composition of the various feedstuffs were obtained from INRA (2019), except for the commercial compound feeds, where they were obtained from the product labels. The amount of purchased feedstuffs, as well as of on-farm maize silage, was calculated on the basis of the composition of the rations, whereas the on-farm forage production was based on the manure-derived N fertilisation rate (Scotton et al. 2005). In the case of on-farm hay production was not sufficient to cover the hay consumption, this gap was assumed to be covered by purchased hay. About the outputs of the dairy farm, annual milk production and milk composition data (fat and protein content, weight/weight, as 1-year average) were obtained from the registers of the cooperative dairies to which each farm belonged, whereas farms' herd register was used for collecting data about animals' sale. The ProtFat delivered by each farm was computed by multiplying the milk production by the fat plus protein content of the milk. To consider the milk processing phase, the ProtFat leaving the 'dairy_system' was computed by multiplying the dairy-farm ProtFat by the fat plus protein processing yield (ProtFat_yield, i.e. the ratio between the amount of fat plus protein leaving and that entering the dairy factory) of the cooperative dairy to which the farm belonged. The ProtFat_yield was computed on the data collected in each cooperative dairy, in particular the annual amounts (with relative composition) of the milk entering the dairy factory and those of cheese, other dairy products and fluid milk leaving the dairy factory.

At $t_1$75 and $t_1$50 scenarios, we maintained the same inventory modelling used for t_0 scenario but including the estimated MY associated with the CSL of each scenario. The estimation of MY, as kg of fat and protein corrected milk (FPCM, at 3.3% protein and 4.0% fat, based on Gerber et al. (2010))/lactating cow per day, at $t_1$75 and $t_1$50 for the 40 farms retained was based on modelling the relationship between MY and the composition of the diet with a multi-regression model (PROC REG; SAS 2013) with MY as the dependent variable and the amounts of each ingredient in the diet (kg DM/d, on an annual basis) as independent variables. This yielded the following equation (MY_model, $N = 40$, $R^2 = 0.92$, RMSE: 1.6 kg FPCM/lactating cow per day): MY= $-8.177 + 1.182$*hay + 0.762*wheat straw + 1.526*alfalfa hay + 1.996*maize silage + 1.264*grass silage + 2.068*concentrates + 1.402*grass at pasture. We also tested the MY_model for quadratic instead of linear relationships between feed ingredients and MY but found no differences between the models (see Supplementary Table S1). Milk yield at t_1 was computed using the MY_model by reducing CSL to 75% ($t_1$75) or 50% ($t_1$50) of the level at t_0 and by considering the provision of additional quantities of hay to the lactating cows to replace the concentrates removed, assuming a hay:concentrate substitution rate of 0.45:1, computed according to INRA (2019).

About the dairy processing stage, the inputs consisted of the milk delivered by the farms associated to the dairy, energy carriers (electricity, fuel, methane), water, cleaning agents and packaging materials; transport of the milk from the farm to the dairy factory was not included. The outputs consisted of the various dairy products (cheeses and other processed food products) and fluid milk delivered to the market quantified in terms of ProtFat. At $t_1$75 and $t_1$50, no structural changes in dairy processing were expected, so the quantities of the inputs per 1 kg ProtFat were assumed to be constant. However, since the main end-use of Alpine milk is dairy products rather than fluid milk, we assumed that all the milk produced at t_1 was destined primarily for the production of dairy products and would be sufficient to cover the production level at t_0. Where the milk produced at t_1 was not sufficient to cover the production level at t_0, the deficit was uncovered, meaning that the dairy product output at t_1 was lower than at t_0. We made this assumption because the farms analysed are associated with cooperative dairies that collect and process the milk into highly locally-distinct dairy products subject to product specifications, and therefore do not buy milk externally for processing.

Modelling the consequences of the 'expanded_system'

The 'expanded_system' considered not only the consequences within the 'dairy_system' of reducing CSL, but also outside. As stated in Section Goal and scope definition, the reduction in CSL potentially affects the total production level of the Alpine dairy system. The new production of food items in response to a potential deficit in Alpine dairy products (DPdef) and fluid milk (FMdef) production as a result of the reduction in CSL was modelled as shown in Figure 1 and Supplementary Table S2. Regarding the Alpine dairy products category, we assumed that the demand for dairy products in Italy was constant (Russo 2020) and so the potential DPdef would be covered by the provision of greater quantities of dairy products by the Italian lowland dairy system. However, the consumption of dairy fluid milk has slowly decreased in recent years, along with a corresponding increase in the consumption of plant-based substitutes (Russo 2020). We therefore tested two different assumptions: that FMdef would be covered either by increasing the production of fluid milk by the Italian lowland dairy system ($milk_{100}$) or by increasing the production of soy drink (soy_{100}), the most widely consumed fluid milk substitute in Italy (Russo 2020). As the uses of fluid milk from Italian lowland dairy system or soy drink would be similar to those of Alpine fluid milk, we supposed a 1:1 substitution rate. The potential deficit in terms of fat, being dairy milk (as FPCM) richer in fat than soy drink (4.0% *vs* 1.9%, respectively) was not considered because of a lack of information about the possible consumer behaviour in compensating deficits in single nutrients.

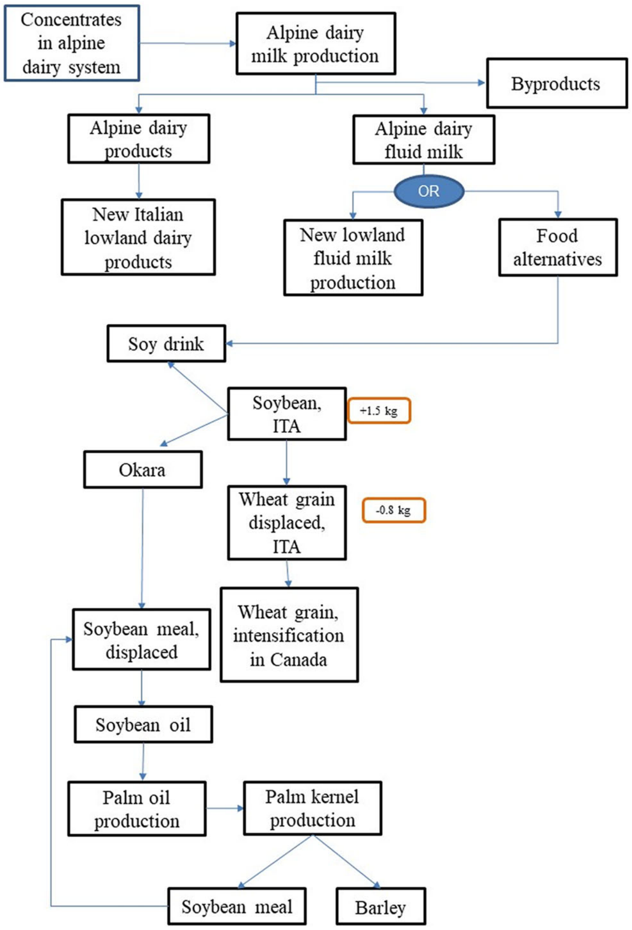

Figure 1. Scheme for the 'expanded_system', covering the deficit in dairy products and fluid milk from the Alpine dairy system at t_1 (after the reduction in the concentrates supply level in the lactating cows' rations) with respect to t_0 (base scenario).

The production of soy drink requires additional soybean production. These soybeans were assumed to be produced in Italy, where the soybean harvested area has increased in recent years. As Italy's total harvested area is quite stable, the increase in the soybean harvested area would come at the expense of wheat, identified as the marginal displaced crop, given its declining harvested area (FAOSTAT 2020). The supplementary wheat production - to produce the displaced one - was assumed to come from the intensification of wheat production in Canada, the primary source of wheat imported to Italy. Soy drink production is multifunctional, since the residue of the process (i.e. okara, composed of the insoluble portion of the soybean) is mainly used as a livestock feedstuff (Zang et al. 2021). We assumed that this marginal okara production displaced an equivalent amount of soybean meal produced in South America (1 kg CP from okara replaced 1 kg CP from soybean meal). The deficiency in soybean meal production implied a corresponding deficiency in soybean oil production, which, following Dalgaard et al. (2008), was covered by a new production of palm oil, and the co-produced palm kernel meal replaced a combined barley and soybean meal.

Computing the impact

Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions were included in the computation of the GWP impact category. Emissions regarding 'dairy_system' were computed using the same equation framework as that used by Berton et al. (2021). Briefly, we used the IPCC framework (IPCC 2019) to calculate the emissions from manure management and fertilisation of the agricultural area, the equation proposed by Ramin and Huhtanen (2013) to calculate enteric CH_4 emissions, and the emission factors obtained from the Ecoinvent database (Wernet et al. 2016) to calculate the emissions related to the external inputs to the farm and dairy factory.

The total impact of the emissions related to the 'expanded_system' was calculated as the sum of the impact due to the 'dairy_system' plus the impact due to the production of lowland dairy products, lowland dairy fluid milk and soy drink. The emission factors were obtained from the Ecoinvent database (Wernet et al. 2016), taking consequential emission factors into account where possible, expect for the production and processing of dairy milk by the Italian lowland dairy system, for which we used an average emission factor from scientific literature and for soy drink processing (Coluccia, 2022). Emissions from transport in the expanded system were not included because of a lack of information. The complete set of equations and emission factors are presented in Supplementary Tables S3-S5.

Regarding LULUC, emissions due to agricultural intensification and land-use change were included. The former was calculated on the basis of the emission factor given by de Bikuña et al. (2018), the latter according to two different methods. The first was a crop-based method (GWP_LULUC_cb), in which the emissions were attributed to the crop driving the change in land use. Emission factors were obtained from Caro et al. (2018) for soybean meal (whose main sources for Europe have been Brazil and Argentina, where soybean growing has expanded at the expense of forestland; EC 2021) and from Wernet et al. (2016) for palm oil (the main source being south-east Asia; FAOSTAT 2020). The second was a global-based method (GWP_LULUC_gb), in which it is assumed that all agricultural area is responsible for land-use change, directly or indirectly. The global-based LULUC was calculated according to FAO (2016).

Potentially human-edible gross energy conversion ratio

Production efficiency was calculated from the potentially human-edible gross energy conversion ratio (HeECR), which was calculated according to Berton et al. (2021) as the ratio gross energy in the potentially human-edible portion of the animal rations at the farm level divided by the gross energy in the milk. Computation of the potentially human-edible portion of the animal rations was based on the factors published by Ertl et al. (2015; see Supplementary Table S6).

Statistical analysis

The impact categories (GWP, GWP_LULUC_cb and GWP_LULUC_gb), calculated with respect to the 'dairy_system' and the 'expanded_system', and the HeECR were analysed with a repeated-measures mixed model (PROC MIXED; SAS 2013). We used this model to test the effect of CSL (t_0, $t_1$75, and $t_1$50), included as the fixed effect, with the dairy farm as the repeated measured factor. Differences between the least square means were tested with Bonferroni adjustment.

Results

Table 3 reports the LSmeans and P values of the lactating cows' MY, feed intake and diet composition (1-year average) at t_0, $t_1$75 and $t_1$50. At t_0, MY averaged 21 kg FPCM/cow per day and dry matter intake 19.6 kg DM/cow per day. The lactating cows' diet had a mean NE content of 5.5 MJ/kg DM and was mainly composed of dry forages (nearly 47% in dry matter), concentrates (23%) and grass at pasture (20%). The reduction in CSL in the $t_1$75 and $t_1$50 scenarios compared with the t_0 scenario affected MY ($p < 0.001$),

Table 3. LSmeans and *p*-values of milk yield and diet composition for lactating cows at t_0, $t_1$75, and $t_1$50 (before and after reducing the proportion of concentrates in lactating cows' diet, -25% in $t_1$75 and -50% in $t_1$50), per one lactating cow ($N = 40$). LSmeans with different superscripts (^{a,b,c}) within row differ significantly ($p < 0.05$).

	Unit	t_0	$t_1$75	$t_1$50	*p* Value
Milk yield (fat- and protein-corrected milk, FPCM)	kg FPCM/d	21.0^a	19.1^b	17.4^c	<0.001
Dry matter (DM) intake	kg DM/d	19.6^c	19.2^b	18.7^a	<0.001
Net energy	MJ/kg DM	5.50^c	5.37^b	5.20^a	<0.001
Diet composition	kg DM/d				
Hay		8.33^a	8.95^b	9.65^c	<0.001
Straw		0.09	0.09	0.09	0.32
Alfalfa hay		0.78	0.79	0.81	0.06
Grass silage		0.92	0.95	0.98	0.14
Maize silage		1.15	1.18	1.20	0.06
Concentrates		4.48^c	3.40^b	2.30^a	<0.001
Grass at pasture		3.89	3.83	3.82	0.06
Forage: concentrate ratio	.	$75{:}25^a$	$79{:}21^b$	$84{:}16^c$	<0.001
Diet self-sufficiency	%	67.9^a	70.3^b	73.1^c	<0.001

which was nearly 9% lower at $t_1$75 and 17% lower at $t_1$50. Since feed intake was estimated on the basis of the animals' NE requirements, including the NE needed for milk production, a reduction (-2% in $t_1$75 and −5% in $t_1$50; $p < 0.001$) was expected, although it was much less than the reduction in MY since the dietary NE content also decreased. As expected, the concentrate content of the diet significantly decreased and the hay content increased ($p < 0.001$), with a mean of +0.59 kg/cow per day at $t_1$75 and +1.27 kg/cow per day at $t_1$50. There were no significant changes in the other dietary ingredients (wheat straw, alfalfa hay, grass silage, maize silage and grass at pasture). As a result of the changes in the composition of the diet, the forage:concentrate ratio significantly increased by +6% ($t_1$75) and +13% ($t_1$50) above the average value of 75:25 observed at t_0. Regarding the diet self-sufficiency rate, nearly 68% of the ration (expressed as dry matter) consisted of feedstuffs produced on the farm at t_0, and this increased significantly to 70% between t_0 and $t_1$75 and to 73% between t_0 and $t_1$50.

The LSmeans and *P* values for the impact categories and HeECR with respect to the 'dairy_system' are reported in Figure 2. In the base scenario (t_0), the GWP associated with the production of 1 kg ProtFat leaving the dairy processing plant was 19 kg CO_2-eq (excluding land-use change), whereas when LULUC was also considered the emission was 22.9 (GWP_LULUC_cb) and 23.4 (GWP_LULUC_gb) kg CO_2-eq. From t_0 to $t_1$75 and to $t_1$50, CSL significantly affected GWP ($p < 0.001$), with an increase of nearly 1 kg CO_2-eq for each 25% reduction in CSL. When LULUC was included, there was an increase in GHG emissions per 1 kg ProtFat at t_1 compared with t_0 with both methods, but was significant only with the global-based method ($p < 0.001$). The HeECR, which averaged 0.71 MJ/MJ at t_0, was affected by the reduction in CSL ($p < 0.001$), decreasing by 10% at $t_1$75 and by 23% at $t_1$50.

Figure 3 reports the values for the individual gases contributing to the impact with respect to the 'dairy_system' in terms of CO_2-eq per 1 kg ProtFat and the credits due to the averted emissions associated with the sale of surplus animals. At t_0, methane was the main contributor to GWP (56%, without considering the credit), whereas CO_2 had a value nearly half that of CH_4 and N_2O made the smallest contribution (nearly 15%). The credits offset nearly 7 kg CO_2-eq/kg ProtFat. All contributions were affected by the reduction in CSL ($p < 0.001$). Methane increased by nearly 10% at $t_1$75 and 20% at $t_1$50 compared with t_0, whereas N_2O increased at just under half the rate of CH_4. Moreover, the increase in CO_2 emission was lower than 7% in both t_1 scenarios. Emissions due to LULUC averaged 3.9 (crop-based) and 4.4 kg/kg ProtFat (global-based) at t_0, and these decreased significantly at $t_1$75 (-0.6 kg CO_2/kg ProtFat) and at $t_1$50 (-1.5 kg CO_2/kg ProtFat) with the crop-based method ($p < 0.001$), but increased significantly at $t_1$50 ($p < 0.01$) and had an intermediate value at $t_1$75 with the global-based method.

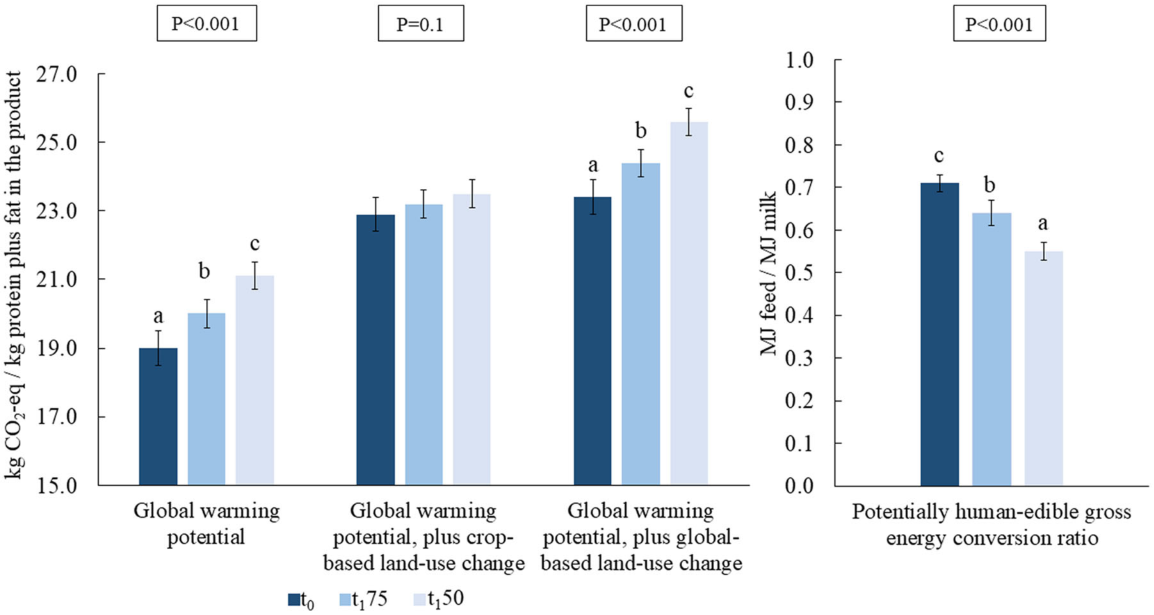

Figure 2. LSmeans and *p*-value of the impact categories and potentially human-edible energy conversion ratio, computed for the dairy farms plus dairy processing system and ($N = 40$). Three scenarios tested: 100% (t_0), 75% ($t_1$75) and 50% ($t_1$50) of the initial concentrate supply level in the rations fed to the lactating cows.

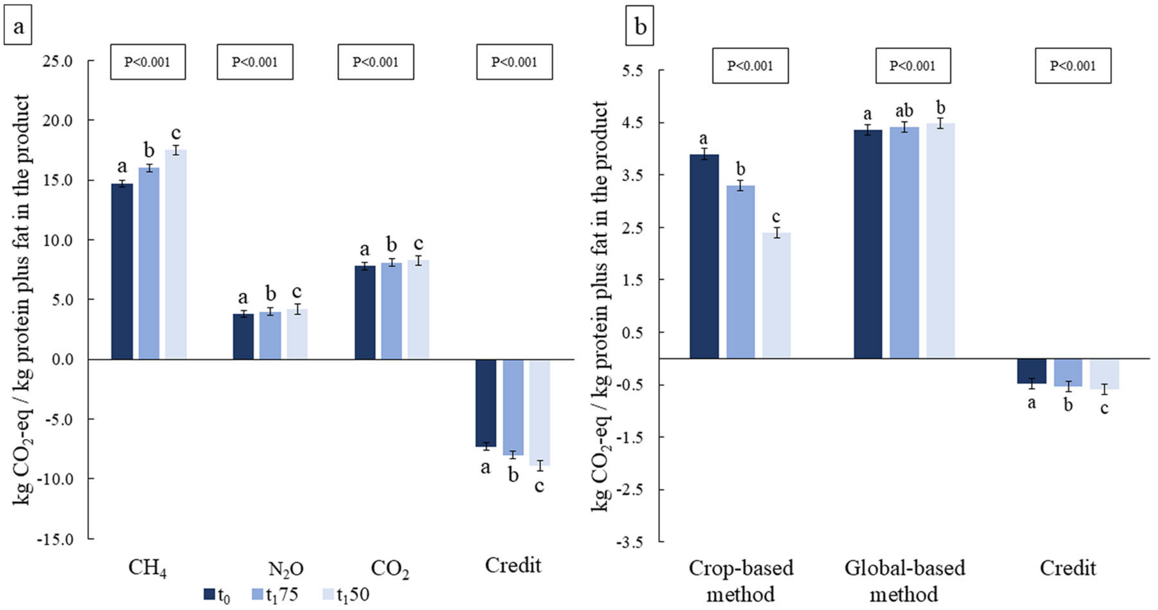

Figure 3. LSmeans and *p*-value of the single gases contribution (a) and land-based CO_2 (b) contributing to the global warming potential for dairy farms plus dairy processing system ($N = 40$). Three scenarios tested: 100% (t_0), 75% ($t_1$75) and 50% ($t_1$50) of the initial concentrate supply level in the rations fed to the lactating cows. Credit due to body weight sold and avoided production of mineral fertilisers.

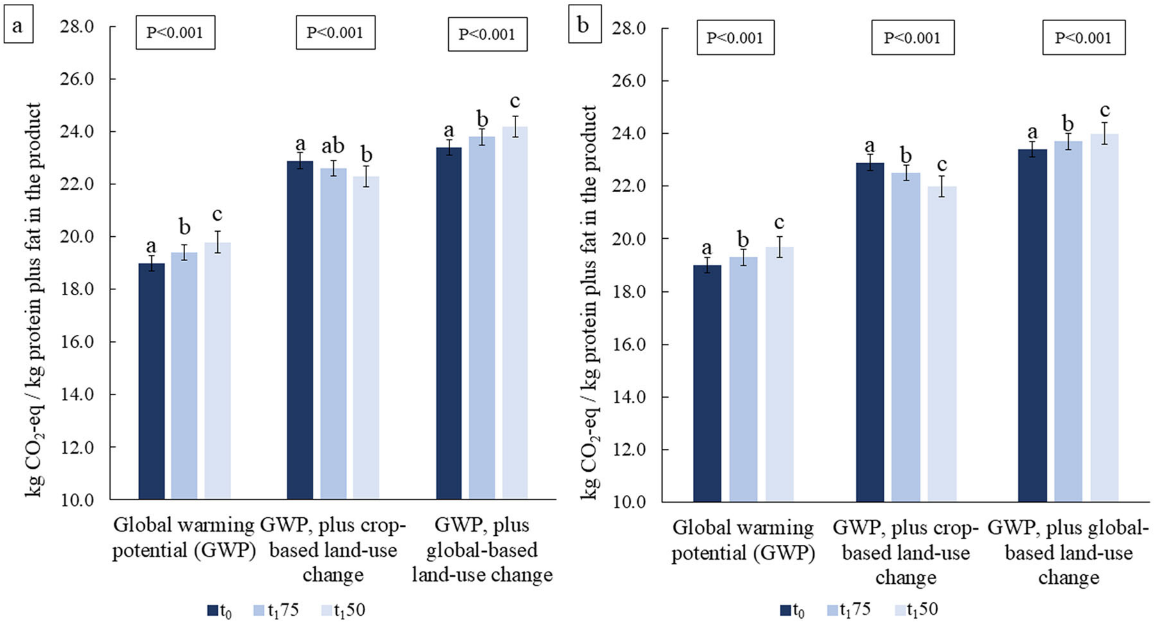

Figure 4. LSmeans and *p*-value of the impact values, the system expanded to cover the product deficit in the Alpine dairy system ($N = 40$), covering based on Italian lowland fluid milk (a) or soy drink (b). Results were reported for the three tested scenarios: 100% (t_0), 75% ($t_1$75) and 50% ($t_1$50) of the initial concentrate supply level in the rations fed to the lactating cows.

With regard to the 'expanded_system', the CO_2-eq emissions associated with the provision of 1 kg ProtFat (by the Alpine dairy system exclusively at t_0 and by this and the alternative food system at t_1) are shown in Figure 4. At t_0, GWP and GWP_LULUC values were the same as those reported in Figure 3. The production of 1 kg ProtFat was significantly affected by the reduction in CSL with respect to all the impact categories, irrespective of the sub-scenario ($milk_{100}$, soy_{100}). The trend in the LSmeans from t_0 to $t_1$75 and to $t_1$50 depended on the method used to compute GHG emissions. In particular, GWP and GWP_LULUC_gb increased ($p < 0.001$), whereas GWP_LULUC_cb significantly decreased in association with the reduction in

CSL (between −0.5 and −0.3 kg CO_2-eq for each 25% reduction in CSL, depending on the impact category and sub-scenario, $p < 0.001$). Differences between $milk_{100}$ and soy_{100} sub-scenarios were minimal (0.1–0.3 kg CO_2-eq per 1 kg ProtFat).

Discussion

The diversion of potentially human-edible food resources to feed animals instead of humans is giving rise to increasing misgivings (Mottet et al. 2017). At the same time, livestock systems are being urged to reduce their carbon footprint (IPCC 2022). This double challenge puts pressure on livestock systems, where improvements in recent years have come about by increasing the levels of potentially human-edible feeds in animal diets (Wilkinson and Lee 2018). Farmers and policymakers, therefore, need new information on the productive and environmental consequences of modifying current production systems to deal with these challenges, particularly small-scale, marginal EU livestock systems, such as the Alpine dairy system, which are constrained by adverse environmental conditions and the low agricultural suitability of their land.

Consequential LCA results for the alpine dairy system

Reducing the proportion of concentrates in the feed of lactating cows to 75% or 50% of their initial levels led to a higher forage:concentrate ratio in the diet. The initial level at t_0 (75:25 for lactating cows) was in line with that found in other studies assessing the Alpine dairy system (e.g. Salvador et al. 2016). At t_1, the higher forage:concentrate ratio meant a more voluminous, fibre-rich diet, with potentially negative effects on digestibility and the ability to cover the peak requirements of lactating cows (Coppock et al. 1974). We therefore recommend monitoring the animals' response in terms of body condition while reducing the level of concentrates in the diet, as modelled in this study.

Since the Alpine dairy farms in our study did not produce concentrates, the reduction in CSL also implied a corresponding reduction in the farms' dependence on external, potentially human-edible energy feed. This was reflected in the farms' increased feed self-sufficiency and the lower HeECR (see Table 3 and Figure 2). Greater feed self-sufficiency could increase the farms' resilience to market fluctuations (Bernués et al. 2011) and create a stronger link between production (milk) and the land (locally available feeds). This could have positive consequences with regard to land pressure, i.e. fewer imported inputs, which can cause the local release of pollutants (Anzai et al. 2016).

Greenhouse gases emissions associated with the production of 1 kg ProtFat increased as a result of the reduction in CSL (Figure 2). This is probably related to the greater reduction in MY than in GHG emissions per lactating cow (-10% and −4% at $t_1$75 and −17% and −9% at $t_1$50, respectively). Changes in the impacts per unit of product are, of course, expected when MY is modified (Gerber et al. 2011), and this also applies to the Alpine system (Berton et al. 2021). Most of the increase in GHG intensity can be attributed to CH_4 (see Figure 3) and linked to a less efficient production-*vs*-maintenance energy requirements partition (Hristov et al. 2013). The detrimental effect of reducing CSL on GHG emissions intensity at 'dairy_system' could harm the market position of Alpine dairy products, as environmental impact, which is usually reported per unit of product (e.g. in the Environmental Product Declaration), plays an increasing role in consumer choices (Canavari and Coderoni 2020). There are, however, several points of interest to note in this regard. Although both GWP and GWP_LULUC (crop- or global-based) increased at $t_1$75 and $t_1$50 compared with t_0, the LULUC contribution decreased (see Figure 3). The greater reduction observed with the crop-based than with the global-based computation was due to the methodology, as in the former soybean meal underwent the same reduction shown by whole concentrates, whereas in the latter the Alpine dairy farms' FAA (80% of total land area for global-based LULUC) remained constant in all the scenarios. Nevertheless, this relieved the pressure on the natural ecosystem due to land-use change, with wide-ranging, positive effects in terms of biodiversity (Newbold et al. 2015). Moreover, although milk production at $t_1$75 and $t_1$50 was lower than at t_0, the milk was associated with fewer potentially human-edible resources (as observable by HeECR results, Figure 2). Together with the decrease in absolute GHG emissions (GWP, −5% at $t_1$75 and −10% at $t_1$50, compared to t_0), this meant an increase in the net production of human-edible gross energy per kg of CO_2-eq generated by the Alpine dairy system.

Adoption of this practice (i.e. reducing CSL) by farmers could be constrained by the expected decrease in MY and consequently in the farmers' income, which depends primarily on the production of milk and dairy products. The financial cost, among other issues, has been found to be an important factor in whether or not farmers adopt new sustainable farming practices (Dessart et al. 2019). Farmers would be more likely to reduce the CSL if well-designed, result-based carbon farming schemes (COWI, Ecologic Institute, IEEP 2021), focussed not only on reducing carbon intensity but also absolute emissions, would be introduced.

Expanded system

The production of dairy products and fluid milk from the Alpine dairy system at t_1, characterised by a reduced competition in the use of potentially human-edible resources, resulted in a lower production level with respect to the present-day situation (t_0). This difference was compensated for by the increase in the production of alternative products. Expanding the system to include the indirect effects of the reduction in CSL can have a notable effect on the environmental footprint that would emerge if the focus were only on the system analysed and at the same time it avoids shifting the burden from the system analysed to other systems (Finnveden et al. 2009). The results obtained in this study show that, compared with the t_0 scenario, the reduction in CSL at $t_1$75 and $t_1$50 determined an increase in GWP, whereas GWP_LULUC exhibited different trends depending on the method used to calculate land-based CO_2 emissions. This underscores the importance of how the LCA model is set up with respect to the sources of GHG emissions (Flysjö et al. 2012). Moreover, although the changes in the GWP and GWP_LULUC values between scenarios were statistically significant, the absolute increase/decrease was always less than 4%, making CSL reduction in the Alpine dairy system potentially achievable without negative effects on GHG intensity. The two sub-scenarios ($milk_{100}$ and soy_{100}) differed very little in their impact values (see Figure 4). This is probably related to Alpine fluid milk accounting for a small part of the total output of the Alpine dairy system (almost 10%). Consequently, alternative food substitutes were hardly likely to make a great difference to GHG emissions when considering the entire 'expanded_system'.

Consequential-based life cycle assessment modelling

Consequential-based LCA requires a series of assumptions to model the complex consequences arising within and outside the system analysed, since it includes temporal, dynamic and socio-economic factors in the evaluation. For this reason, these assumptions need to be founded on as solid a basis as possible and potential areas of uncertainty considered.

We assumed that the response to CSL reduction on Alpine dairy farms was linear and wholly attributable to MY. When we tested for quadratic instead of linear relationships between feed ingredients and MY (see Materials and Methods section) we found no differences between the two methods. Attributing all the consequences of reducing CSL to MY is a simplification of the situation, as these consequences could also be seen in terms of deterioration in reproductive performance, e.g. calving interval (Sehested et al. 2003), or in body condition score (Bovolenta et al. 2008). However, quantitative modelling of these other consequences would be very complex and would depend on many variables related to the animals, such as genetic type (Kennedy et al. 2003). This study, then, represents a first attempt to model the environmental consequences of modifying the dairy feeding strategy and further studies that model such schemes with additional features are needed.

Furthermore, the model we used did not include any strategies to minimise the deficit in milk in the Alpine dairy farms at t_1, such as increasing the number of dairy cows (see, e.g. Nguyen et al. 2013). However, this would mean expanding the farm facilities to rear the additional animals and increasing FAA to feed them and spread their manure. Given that the most productive areas in the Alpine region have already been exploited, land expansion would have to be into more marginal areas that are now covered by forests as a result of decades of land abandonment (Battaglini et al. 2014). Nevertheless, some efforts could be made by farmers to recover the reduction in MY, such as improving forage quality and/or feed management, although modelling such a scenario would be challenging, as each farm has its own particular structures and management. This would be an important area for future research.

The expanded system also showed some uncertainties that had to be managed. In this regard, the main constraint lies in the difficulty of precisely modelling consumer response to an alteration in food provision. As an example, the dynamics of plant-based alternatives to animal products have shown a diversified trend in recent years, with soy drink being the main alternative to dairy milk in terms of quantities sold, but with other plant-based beverages (e.g. almond drink) gaining a greater market share (Russo 2020). Given the wide variety of plant-based alternatives and changing patterns of consumption, modelling could be a very complex affair. However, soy drink (in soy$_{100}$ sub-scenario) contributed up to 10% of the ProtFat provided (considering individual farms), and therefore a different plant-based milk alternative would not alter our results by much. Nevertheless, these potential new dynamics in food provision and consumer preferences should be considered in perspective.

Conclusion

The demand for more sustainable animal-source food that is, at the same time, less competitive in the use of potentially human-edible resources is creating a multi-facets challenge to the livestock systems, in particular to those limited by harsher territories and lower possibility of economy of scales such as the Alpine dairy system. This study shows that decoupling dairy production from the use of potentially human-edible resources, reducing up to 50% the CSL in diets fed to lactating cows on dairy farms in the Alps, had a generally negative effect in terms of GHG emissions, which increased per unit of protein plus fat in the product. However, when considering not only the dairy system but also the external food system, as well as the sources of land-based CO_2 emissions, the effect was unclear, highlighting the importance of considering the effects external to the production system analysed. Moreover, the reduction in the supply of concentrates improved the ability of the Alpine dairy system to make a net positive contribution to the food supply, with a positive effect on the net amount of gross energy provided per unit of GHG emitted. Furthermore, as the reduction led to a significant drop in the milk yield of these farms, the potential negative effects on farm profitability should be considered. In the future, consequential modelling should be further developed to assess the broader potential consequences of actions aimed at minimising the environmental footprint of food production.

Ethical approval

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

The authors report there are no competing interests to declare.

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Data availability statement

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

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