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Feed-food and land use competition of lowland and mountain dairy cow farms

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ABSTRACT

Dairy cows and other ruminants contribute to human nutrition as they are able to convert feed components containing human inedible fibre concentrations (e.g. roughage and by-products from the food processing industry) into valuable animal-sourced food. A number of crops often fed to dairy cows (e.g. soy or cereals) are however potentially edible by humans too. Additionally, land used to grow dairy cattle feed may compete with crop production for human consumption. Two different methods to assess the competition between feed consumption of dairy cows and human food supply were thus refined and tested on 25 Swiss dairy farms. With respect to the potential human edibility of the feeds used in dairy production, the human-edible feed conversion ratio (**eFCR**) was applied. The land use ratio (**LUR**) was used to relate the food production potential, per area of land utilised, with the dairy production output. Low to medium eFCR, with values ranging from 0.02 to 0.68 were found, as an average proportion of 0.74 of total DM intake consisted of roughage. In contrast, we found relatively high LUR (0.69–5.93) for most farms. If the land area used to produce feed for cows was used for crop production (applying a crop rotation), 23 of the 25 farms could have produced more edible protein and all farms more human-edible energy. Indicator values strongly depend on the underlying scenarios, such as the human-edible proportion of feeds or the suitability of land and climate for crop production. Reducing the amount of human-edible feeds in dairy farming by feeding by-products from the food processing industry and improving forage quality may be suitable strategies to reduce eFCR, but relying on low-opportunity cost feeds may restrict milk performance level per cow. On farm level, improving overall efficiency and therefore using less land (especially area suitable for crop production) per kg product decreases LUR. However, the most promising strategy to mitigate land use competition may be to localise dairy production to land areas not suitable for crop production. Both methods (eFCR and LUR) should be used in parallel. They offer an opportunity to holistically evaluate the net contribution of dairy production to the human food supply under different environmental conditions and stress the importance of production systems well suited to specific farm site characteristics.

Implications

Feed-food and land-use competition can be assessed on farm level and the presented methods may serve as indicators to express the extent to which feeding dairy cows competes with human food supply. Grassland-based production systems may be a suitable strategy to reduce feed-food competition but only if land not suited for crop production (e.g. mountainous areas) is used for feeding. The indicators could be used as resource efficiency indicators alongside with life cycle assessments or incorporated into the functional unit. The two concepts may also be adopted for other livestock categories. Our findings aim to support farmers and policy makers to efficiently allocate scarce resources to optimise net human food production.

Introduction

Facing a continuously growing world population and scarce natural resources (i.e. land and water), future food systems will be required to efficiently allocate resources to nourish the world's population while still providing sufficient ecosystem services

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(Godfray et al., 2010). Ruminants and other herbivores play a key role in accessing marginal resources (such as non-arable land or by-products from the food processing industry) for human food supply, as these animals can convert fibrous plant components not digestible by humans into valuable animal-sourced food (**ASF**) (Schader et al., 2015; Mottet et al., 2017). However, fibrous feed components in dairy cow rations may decrease as milk production levels increase. This can be explained biophysically as the daily feed amount ingested per cow is limited. Therefore, the elevated nutrient requirements for maintenance and production are often met by larger proportions of concentrated and digestible feeds in the ration, such as cereals (Dijkstra et al., 2013). When feeding less overall but more concentrated feed per kg of milk, the feed conversion ratio (**FCR**) decreases. Decreasing the FCR may be economically beneficial for farmers, as feed costs amount to about half of total production costs (Bozic et al., 2012). Aside from economic aspects as potential drivers for shifting dairy cattle diets, decreasing the FCR is a suitable strategy to reduce the negative environmental impacts of livestock production such as the emission of greenhouse gases per kg of product (Hristov et al., 2013). Globally, a productivity gain in livestock production systems may indeed be required to improve eco-efficiency (meaning environmental impact or land use per amount of product) and generate enough food for all (Mottet et al., 2017). Feeding concentrate feed to animals may, however, challenge their function of upcycling fibrous plants into food and thus reduce the contribution to the human food supply on a food system level (Van Zanten et al., 2018).

In fact, there is increasing concern about the role of livestock feeding in global food security, as most concentrate feeds could be used as human food as well (Mottet et al., 2017). Even more so, as competition between feeding animals and producing food arises not only in the barn but begins on the fields. Net food production could be increased if arable land used for feed production would instead be used for crop production for direct human consumption (Vandehaar, 1998). The feeding of roughage does not directly compete with human food supply. However, it may still compete indirectly if the roughage was produced on land suitable for food crop production. Arguably, methods that assess productivity and eco-efficiency of agricultural production without considering the "opportunity costs" (alternative use) of inputs (e.g. feed and land) fail to fully acknowledge the contribution of production systems to human food supply (van Zanten et al., 2022). Mountainous areas are often characterised by soil quality or climatic constraints that do not allow crop production and could thus be considered of low value for direct human food supply. Traditionally, grassland-based ruminant production systems have dominated mountainous regions and in Switzerland. Ruminant production in the alps is mainly characterised by dairy cows (Zorn and Zimmert, 2022).

However, in past decades, dairy production systems all over Europe, including mountain regions, have been intensified (Berton et al., 2020) and thus may not rely on "low-opportunity cost" feeds alone. Therefore, the present paper aims to refine two different calculation methods to assess feed-food competition on farm level, illustrating different production systems in lowland and mountain regions. To our knowledge, there are limited studies combining the concepts of the human-edible feed conversion ratio (**eFCR**) applied for instance by Wilkinson (2011)) and the land use ratio (**LUR**, van Zanten et al., 2016). Hennessy et al. (2021) have applied both concepts for Irish livestock systems. Particularly for the land use ratio, there have, however, been very few applications on actual farms. We therefore applied and tested the two slightly refined methods on 25 commercial dairy farms in Switzerland under differing environmental and feeding conditions. To date, the LUR was mainly applied regarding protein, as ASF contributes more importantly to human protein than energy supply (van Zanten et al., 2016; Hennessy et al., 2021). To bridge this knowledge gap, the present study also calculates the LUR with regard to edible energy supply. Furthermore, as the computation of the eFCR and LUR indicators rely on a significant amount of off-farm data and assumptions, we examined whether the two concepts show redundancy (also with respect from a protein and energy perspective) or if they could be proxied with existing and more readily available on-farm efficiency parameters.

Material and methods

Production zones, farm model and system boundaries

To test the methods for different farm types and production zones, 25 Swiss dairy farms that belong to the Swiss Milk Producers association were assessed. The selected farms do not represent average Swiss production standards but were chosen to demonstrate a variety of Swiss dairy production systems with respect to the type of land used (e.g. 15 mixed farms with crop production and ten farms with grassland only), milk yield (13 farms where cows yield >8 000 kg milk per year and 12 farms yielding <8 000 kg milk per year) and differing environmental conditions. Farms located in the hill and mountain zone are generally characterised by higher altitudes, steeper slopes, colder climatic conditions and less arable land. Thus, 14 farms in the lowland zone, seven in the hill zone and four in the mountain zone were selected to reflect different topographic and climatic conditions based on Swiss land cadastres (FOAG, 2021). Milk yield was standardised to energy-corrected milk (**ECM**) with 40 g fat, 32 g protein and 48 g lactose per kg (Jans et al., 2015). Farm interviews were conducted in 2018 to collect farm-specific data. Monthly feed rations and the average bodyweight of cows were supplied by the farmers and daily DM intake was computed according to Swiss feeding recommendations for primi-, multiparous and dry cows (Jans et al., 2015). The DM intake was increased or reduced depending on the net energy for lactation (**NEL**) concentration in the ration, the annual milk yield (kg ECM/year per cow) and average BW (kg). The plausibility of the obtained rations was checked by employing an energy balance, where requirements for milk production, maintenance and conceptus were compared to NEL intake. No more than 10% difference in intake (MJ) and requirements were accepted, if so DM intake was manually adjusted. Nutritional values for feedstuffs were obtained from the Swiss feed database, considering utilisation stage and botanical composition when feedstuffs were derived from grasslands (Agroscope, 2016). All feeds with a crude fibre concentration below 120 g/kg DM are, based on expert opinion, referred to as concentrate feeds, whereas all other feeds are referred to as roughage.

"Cradle to farm-gate" was chosen as the system boundary. This means that all feedstuffs used to feed the dairy cows and replacement stock, as well as the land associated to produce the feed, were included in the calculations. The number of cows culled yearly was supplied by the farmers and used to compute the number of replacement animals required. Calves not used for replacement were considered surplus calves and meat output before the fattening (75 kg LW). The feed used for fattening stock (and the land associated with its production) and other farm animals (not linked to milk production) were excluded. As a large variety of rearing systems for replacement stock (including on- and off-farm rearing) are practiced and farmers often do not have records on replacement stock feeding (particularly when off-farm rearing occurs), standardised feeding rations for replacement stock were defined according to Swiss feeding recommendations and the age at first calving was used for DM intake calculations (Münger and Kessler, 2017; Supplementary Table S1). The land area used for the rearing of replacement stock was obtained from the “ecoinvent Database V3.3” (Wernet et al., 2016). It consisted of 2.33, 17.28 and 3.5 m^2 * year and kg LW of arable land, intensive grassland and extensive grassland, respectively. These areas were multiplied by the LW input of heifers at the weight at first calving. The weight at first calving was assumed to be 80% of the average LW of the dairy cows on farm.

Human-edible feed conversion ratio and edibility of feeds and products

Direct feed-food competition, with respect to the feed consumed by cows, was assessed as proposed by the human-edible feed conversion ratio (**eFCR**) concept (Wilkinson, 2011), where the human-edible feed is divided by the edible products (milk and meat). Other authors have expressed the same concept with a reversed ratio, referring to the term of feed conversion efficiency as the reciprocal value of the FCR. Oltjen and Beckett (1996) computed the human-edible returns in animal products divided by the human-edible feed input. Ertl et al. (2015) and Rouillé et al. (2023) have computed the human-edible feed efficiency also by dividing output through input.

Here, values lower than one indicate that more human-edible food was produced by the dairy system than the cows consumed and vice versa. Human-edible energy conversion ratio (**eECR**) was computed for gross energy (**GE**):

$$eECR = \frac{\sum_n (GJ\ \ GE\ \ feed_i * human\ \ edible\ \ energy\ \ proportion\ \ of\ \ feed_i)}{\sum_m (GJ\ \ GE\ \ animal\ \ product_j * human\ \ edible\ \ energy\ \ proportion\ \ of\ \ proudct_j)} \tag{1}$$

where n is the number of feedstuffs, i is the type of the feed, m is the number of animal products and j is the animal product.

As animal-sourced protein often better matches human nutritional requirements and is therefore of higher value for human nutrition, a correction for protein quality according to the Digestible Indispensable Amino Acid Score (FAO, 2013) as suggested by Ertl et al. (2016a) was applied (values are given in Supplementary Table S2). For milk and meat, they were set to 1.16 and 1.12, respectively.

The protein quality of all edible feed components and edible animal products, as a weighted dry mass mean, was computed. The protein quality score refers to the ratio of the mean protein quality of the feed divided by the mean protein quality of the animal products. Human-edible protein conversion ratio (**ePCR**) was computed for CP and then multiplied by the protein quality score:

$$ePCR = \frac{\sum_n (kg\ \ CP\ \ feed_i * human\ \ edible\ \ protein\ \ proportion\ \ of\ \ feed_i)}{\sum_m (kg\ \ CP\ \ animal\ \ product_j * human\ \ edible\ \ protein\ \ proportion\ \ of\ \ proudct_j)} \times PQS \tag{2}$$

where n is the number of feedstuffs, i is the type of the feed, m is the number of animal products, j is the animal product and PQS refers to the protein quality score.

The potential edibility of feedstuffs in human nutrition depends on socio-economic circumstances, and the technology applied to recover edible nutrients from food-processing by-products and may vary with space and time. We assumed a scenario with low edibility of feedstuffs according to the “Low” scenario in Ertl et al. (2015) and the “Current” scenario in Ertl et al. (2016b). This scenario was assumed to realistically reflect the current Swiss context. Edible fractions for all feeds registered in the Swiss feed database (Agroscope, 2016) were determined based on Ertl et al. (2015) as well as on our own calculations (Supplementary Table S3).

Many Swiss dairy farmers use compound feeds to balance forage-based diets. Based on interviews with six Swiss compound feed producers, the average composition of standard dairy compound feeds was determined. In practice, the nutritional values of any given compound feed remain relatively stable, however, the exact combination of components depends on crop prices and market availability. As the components vary, human edibility of the compound feed varies as well. Nonetheless, nutritional values and the human edibility of the compound feeds were set according to the compositions in Supplementary Table S4 and are given in Table 1.

More than 40% of Swiss milk is used for cheese production (SMP, 2019). In contrast to liquid milk and most processing technologies, relevant amounts of milk proteins remain in the whey when milk is processed into cheese and are not used in human nutrition in current socio-economic circumstances (Kopf-Bolanz et al., 2015). Based on figures in Kopf-Bolanz et al. (2015), we computed the human edibility of milk protein and energy at 0.93 and 0.91, respectively. Surplus calves were expected to yield 410 g edible meat per kg of live weight and culled cows 310 g. The CP concentration was assumed to be an average of 32 g, 170 g and 190 g whereas the GE concentration was 750 kcal, 2909 kcal and 1438 kcal per kg for milk, veal and beef, respectively.

Land use ratio

Land use competition was assessed according to the four steps proposed by van Zanten et al. (2016) to generate the LUR. In brief:

(a) Quantify the land area needed for milk production and the associated ASF output
(b) Determine the suitability of that area for cultivating food crops
(c) Assess the production potential for plant-sourced food on that area
(d) Relate the potential plant-sourced food production with the actual ASF production (Eq. (2))

$$LUR = \frac{Potential\ \ plant\ \ sourced\ \ food\ \ production}{Actual\ \ animal\ \ sourced\ \ food\ \ production} \tag{3}$$

Calculations for LUR were performed for CP and GE.

The total land area managed by the farms and the type of land use (e.g. grassland intensity and crops grown) were obtained from mandatory official records for compliance with Swiss agricultural subsidy requirements (FOAG, 2019). Since not all of the land managed by a dairy farm may exclusively be used for dairy cow feeding, the land area used for this purpose needs to be demarcated. Land use for dairy feed production was determined for each on-farm grown feedstuff by dividing the amount of annual feed DM used for dairy cows and replacement stock by the farms’ individual yields of the respective feedstuff. A land area surcharge of up to 9% for seed production was added (see Supplementary Table S5). Bought feeds were considered off-farm produced. The required land area for each crop was computed by dividing the amount of DM fed by its reference yield. Reference yields (see Supplementary Table S5) were computed by weighted averages, considering average Swiss yields, level of self-supply and the yields and import proportions of the main countries of origin for the respective crop (FAO, 2017; FOCBS, 2017; Richner and Sinaj, 2017). Land use of crop co-products (e.g. rapeseed expeller) were physically allocated according to the concentration of CP and NEL, as allocation according to physical properties is less dependent on time and market prices than economic allocation. The allocation factor was determined by calculating the relative contribution of the co-product to the CP and NEL production of the crop per ha. Land area needed for processed feeds consisting of more than one by-product (e.g. compound feeds) was determined by using the “ecoinvent Database V3.3” (Wernet et al., 2016). For mineral feeds and vitamins, it was set to zero.

Table 1
Nutritional values for five compound concentrate dairy cow feeds, their potential human edibility and protein quality for human nutrition.

	Concentration per kg DM		Edibility[1] in human nutrition		
Compound feed	g CP	MJ NEL[2]	Protein	Energy	PQ[3]
High protein	489	7.6	0.36	0.21	83.8
High protein, no soy	501	8.5	0.13	0.08	57.3
High energy	122	8.4	0.46	0.46	45.1
Balanced A	210	8.3	0.41	0.38	47.1
Balanced B	276	8.2	0.36	0.32	59.3

[1] Edibility in human nutrition was calculated as weighted mass means of all compounds (see Supplementary Table S3) based on values from Ertl et al. (2015) and our own calculations, given as a proportion.
[2] NEL = net energy lactation
[3] Protein quality (PQ) according to Digestible Indispensable Amino Acid Score (DIAAS), calculated as weighted mass means of compounds (see details in Supplementary Table S2).

Suitability for crop production was assessed on-farm (Table 2), considering the slope of the fields, soil depth and water permeability as well as the clay, humus and skeleton concentration based on soil analyses and farmers' assessments. Based on these soil properties, soil quality was classified into "high", "moderate" and "unsuitable" for crop production. Climatic suitability was classified based on climate maps (Holzkämper et al., 2015) deriving categories of "warm" (suitable for grain maize and soya bean production), "cool" and "unsuitable" for crop production. Proportions of each soil quality and climatic condition category combination were computed for the total land area used.

Yields for high soil quality and warm climates were based on Swiss references (Richner and Sinaj, 2017). Under cool climate conditions, yields were expected to be 21% lower on average, following Swiss capitalised income guidelines (FOAG, 2018). For moderate soil quality, a reduction of 33% of the estimated yield for warm climates and of 39% for cool conditions were assumed.

Soil quality and climatic conditions of feeds produced off-farm and the replacement stock rearing areas were unknown. For feeds originating from crops (as well as alfalfa) in Switzerland and abroad, climatic conditions were set to "warm" and soil quality to "good". For roughage, soil quality and climatic conditions were computed according to Swiss land use statistics (FSO, 2018). For warm climates, 17% were assumed to be of high and 22% of moderate soil quality. For cool climates, 7% were considered of high and 15% of moderate soil quality, whereas 38% of all Swiss grasslands were assessed to be unsuitable for crop production. No plant production potential for direct human consumption was computed for areas considered unsuitable for crop production.

To compute the plant production potential of the total land area used for dairy production, standard crop rotations were defined to maximise plant production potential in terms of protein and energy for warm and cool climatic conditions (Table 3, Supplementary Table S2). Crops not suitable for "cool" climate could not be incorporated into the crop rotations for "cool" climate zones. A crop rotation of four years was chosen as the Swiss subsidy regulations require farms to (1) grow at least four crops per year while a maximal land use proportion must not be exceeded or (2) implement breaks between growing the same crop from one to six years (FOAG, 2019). Crop rotations consider agronomic feasibility in terms of sowing time as well as pest and disease transmission. According to the LUR approach proposed by van Zanten et al. (2016), this plant production potential was then divided by the actual ASF on the same area (Eq. (3)).

Table 2
Assessment criteria of soil suitability for crop production of on-farm areas in lowland and mountain dairy cow farms.

Property	High	Moderate	Unsuitable
Slope (proportion)	<0.18	0.18–0.25	>0.25
Soil depth (cm)	>50	30–50	<30
Water permeability	Normal	Moderate	Very slow
Topsoil DM clay proportion	0.10–0.40	< 0.10	>0.60
Topsoil DM humus proportion		0.40–0.60	>0.30
	0.02–0.10	0.10–0.30	
Topsoil DM skeleton proportion	<0.18	0.20–0.40	>0.40

Feedstuff edibility and protein quality scenarios

Edibility of feed components strongly depends on socio-economic and cultural circumstances as mentioned above. Nutritional developments (such as plant-based diets), evolving processing industries (rendering plant proteins accessible for human nutrition) and transregional food supply may increase human-edible fractions of feeds. We thus compared the standard "current" with a "potential" edibility scenario, where edible fractions of feedstuffs were maximised according to Ertl et al. (2015), Ertl et al. (2016b) and our own calculations (see Supplementary Table S3). To investigate the effects of the protein quality correction, we also computed scenarios without the protein quality correction for both indicators (eFCR and LUR).

Statistical analyses

All analyses were conducted using the 'stats' package in R version 4.2.1 (R Core Team, 2022). Differences between production zones were tested by ANOVA. Normality was assessed visually by plotting normal quantile–quantile plots distribution tested with the Shapiro-Wilk test. Homoscedasticity was assessed visually by plotting residuals versus the fitted values and by testing with Bartlett and Levene tests. The significance level was set to 0.05 for all tests. In the case of non-normally distributed or non-homoscedastic data, the Kruskal-Wallis rank sum test was used instead. Pairwise comparisons among means were performed applying Tukey's procedure for parametric and Wilcoxon rank sum (using the 'exactRankTests' package) for non-parametric but possibly tied data tests, respectively. The unbalanced experimental design was considered when performing Tukey's parametric pairwise comparisons. Due to the unbalanced design and the low number of farms, a power analysis was conducted applying a simulation approach. To test the redundancy of eFCR and LUR indicators as well as more easily on-farm available parameters, Pearson correlations between the two indicators and total land use in annual square meters per kg of energy-corrected milk (m^2 * year per kg ECM), arable land use (m^2 * year per kg ECM) feed conversion efficiency (kg DM/kg ECM), concentrate feed use (g DM/kg ECM) and milk yield (kg ECM/cow) were computed. In case of non-normally distributed data, the Spearman method was applied.

Table 3
Crop rotations designed to maximise annual human-edible protein (g CP/m^2) and energy (MJ gross energy/m^2) yields per area for warm and (Swiss) climatic zones based on the official Swiss ecological performance standards.

Objective	Year 1	Year 2	Year 3	Year 4	Mean yield/m^2 per year[1,2]	
					Good soil	Medium soil
Protein						
Warm	Soybeans	Potatoes	Beans	Rapeseed	67 g CP	52 g CP
Cool	Beans	Potatoes	Wheat	Linseed	39 g CP	30 g CP
Energy						
Warm	Rye	Sugar beets	Maize	Potatoes	11.9 MJ GE	9.2 MJ GE
Cool	Oats	Sugar beets	Rye	Potatoes	8.0 MJ GE	6.17 MJ GE

[1] g CP and MJ gross energy (GE).
[2] Potential protein yield was corrected for human edibility (Ertl et al., 2015) and protein quality (FAO, 2013). Energy yield was corrected for human edibility (see details in Supplementary Table S2).

Results

Dairy ration characteristics

Across production zones, the mean annual milk yield was 7 616 (±1 635.0) kg ECM/cow and the mean herd size was 46 (±26.3) cows. Milk yield was on average higher on lowland farms than on mountain farms (Table 4). Although mean live weight of cows was slightly higher on mountain farms, mean DM intake was highest on lowland farms. Concentrate feed was 0.108 (±0.0712) kg/kg ECM over all farms assessed, where farms in the lowland used the most and those located in the hills used on average less concentrate feeds per kg of ECM. Annual proportions of DM intake were 0.78 (±0.158) roughage (including 0.25 (±0.203) pasture, 0.11 (±0.137) fresh cut grass, 0.12 (±0.132) grass-silage and 0.29 (±0.119) hay), 0.10 (±0.105) whole plant maize (dried or ensiled), 0.02 (±0.032) other forages (such as sugar beet pulp or straw) and 0.10 (±0.075) concentrates over all farms assessed. On mountain farms, grass proportion was highest, while the proportion of concentrates fed was larger than whole plant maize. Farms located in the hills relied mainly on roughage, followed by maize. Hill farms fed slightly larger proportions of grass than farms in the lowlands, while the latter used larger proportions of concentrates. On all farms, only minor proportions of forages, other than roughage or maize, were fed. Mean CP concentration in the ration was 163 (±10.5) g/kg DM and NEL concentration 6.14 (±0.145) MJ/kg DM over all farms assessed. The highest CP concentration was recorded for farms located in the mountains, while the same group had the lowest NEL concentration. Mean FCR of all farms was 0.94 (±0.108) kg DM/kg ECM, 5.39 (±0.854) kg/kg and 6.50 (±0.921) MJ/MJ for DM, CP and GE intake, respectively. It was lowest on lowland farms with respect to DM, CP and GE. Mean FCR for DM and GE on hill and mountain farms were similar, while FCR with respect to CP was lower for farms located in the hills compared to mountain but not to lowland farms (Table 4).

Human-edible feed conversion ratio

The human-edible proportion of the feeds consumed by the dairy herd, was on average over all farms 0.07 (±0.049) and 0.05 (±0.033) for CP and GE, respectively. The proportion was largest on lowland farms for both CP and GE (Table 4).

With respect to all farms assessed, mean ePCR – including a correction for protein quality – was 0.17 (±0.126) and mean eECR 0.31 (±0.184). Values ranged from 0.02 to 0.54 for ePCR and 0.03 to 0.68 for eECR. The competition of dairy production with human protein supply was much lower than that with energy supply. When protein quality was considered, ePCR was roughly halved. Lowland farms had the highest ePCR and eECR. Farms located in the hills had slightly lower ePCR than farms in the mountains, while for eECR it was inverted. Variability was largest for lowland farms (±0.161 for ePCR and ±0.221 for eECR), followed by the hills (±0.075 for ePCR and ±0.148 for eECR) and the mountains (±0.033 for ePCR and ±0.056 for eECR, Supplementary Fig. S1). As all ePCR and eECR values were lower than one, all farms can be considered net energy and protein contributors to the human food supply. Many farms rarely competed with human food supply at all as their eFCR tended towards zero. However, when computing with the maximised human edibility potential of the feeds, ePCR increased by 108% to 0.349 (±0.052) and eECR by 122% to 0.684 (±0.079). In this scenario, ePCR ranged from 0.02 to 1.11 and eECR from 0.05 to 1.50.

Land use characteristics

Managed land area per farm, across all production zones, was 35.0 (±18.53) ha, whereas the area to produce forage was 29.0 (±12.65) ha on average. Total area used for milk production was 1.59 (±0.368) m^2 * year per kg ECM (on- and off-farm area as well as rearing area) and did not significantly differ between production zones. It was lowest for lowland farms, followed by the farms located in the mountains and those in the hills (Table 5). On average, only 52% of the land totally used for milk production was on-farm, namely 0.83 (±0.309) m^2 * year per kg ECM. On lowland farms, this proportion was lowest (49%), followed by farms located in the hills (54%) and in the mountains (57%). The area used for rearing replacement stock contributed 34%, 37% and 28% of total land use in the lowlands, the hills and the mountains, respectively. Lowland farms used 1.18 m^2 * year of land suitable for crop production to produce one kg of ECM, while the farms in the hills and the mountains used 1.30 m^2 * year and 0.85 m^2 * year, respectively. In the lowlands, 80% of the total land area used for dairy production was suitable for crop production, while this applied to 73% of the area for the farms located in the hills and only 51% for those in the mountains. While 57% of the on-farm area on lowland farms was suitable for crop production and 58% for those in the hills, it was significantly lower for the farms located in the mountains (38%).

With respect to soil quality and climatic conditions, the land area of lowland farms was statistically best rated. Fifty-four percent of the land used for milk production was of high soil quality in a warm climate, while farms in the hills used equal areas of high and moderate soil quality in warm climates. Areas of high and moderate soil quality with warm climates were lowest for farms located in the mountains. Of all production zones, the most land situated in cool climatic conditions was located on mountain farms, while the lowland farms rarely used land classified as cool with respect to Swiss climate conditions.

With respect to land use characteristics, statistical significance has to be judged with caution, as the number of farms in the moun-

Table 4
Milk yield, feed rations characteristics and productivity of 25 Swiss dairy cow farms located in the lowlands (n = 14), the hills (n = 7) and the mountains (n = 4). ECM = energy-corrected milk, DMI = DM intake, NEL = net energy for lactation, GE = gross energy, ePCR = human-edible protein conversion ratio, eECR = human-edible energy conversion ratio.

	Zone			
Item	Lowlands	Hills	Mountains	SEM[1]
Live weight cow (kg)	645	640	662	12.2
Milk yield (kg ECM/cow/year)	7 956	7 238	7 091	327.2
DMI (kg/cow/day)	19.7	18.6	18.5	0.49
Concentrate intensity (g/kg ECM)	121	80	112	14.2
Annual feed ration composition (ratio of DMI)				
Roughage	0.74	0.78	0.87	0.032
Pasture	0.25	0.24	0.28	0.041
Fresh cut grass	0.13	0.13	0.00	0.028
Grass silage	0.09	0.11	0.21	0.023
Hay	0.26	0.30	0.39	0.024
Maize (whole plant)	0.12	0.12	0.03	0.021
Other forages	0.03	0.02	0.01	0.006
Concentrates	0.12	0.07	0.09	0.015
Mean annual feed ration concentration				
Protein (g CP/kg DM)	163	160	168	2.1
Energy (MJ NEL/kg DM)	6.18	6.13	6.06	0.030
Feed conversion ratio				
DM (kg DM/kg ECM)	0.93	0.96	0.96	0.02
Protein (kg CP/kg CP)	5.29	5.44	5.65	0.171
Energy (MJ GE/MJ GE)	6.39	6.64	6.65	0.184
Human-edible fraction (ratio)				
Protein (CP)	0.07	0.06	0.06	0.010
Energy (GE)	0.06	0.04	0.04	0.007
Protein quality score[2] (ratio)	0.46	0.51	0.47	0.014
Human-edible feed conversion ratio				
ePCR (CP)	0.18	0.15	0.15	0.025
eECR (GE)	0.34	0.27	0.25	0.037

[1] As no significant differences in group means were detected, *P*-values are not given.
[2] Ratio of (weighted mass mean) protein quality input in feeds over protein quality of animal products. Protein quality was assessed by applying the Digestible Indispensable Amino Acid Score.

Table 5
Soil quality (suitable or unsuitable for crop production) and climatic conditions of the area used for milk production (mean and SD) of 25 Swiss dairy cow farms located in the lowlands (n = 14), the hills (n = 7) and the mountains (n = 4). All areas are given in m^2 * year per kg ECM. The land use ratio (LUR) was derived from the plant production potential compared to the amount of protein/energy produced by dairy production. ECM = energy-corrected milk, GE = gross energy.

	Zone				
Item	Lowland	Hill	Mountain	SEM	*P*-value
Area on-farm	0.73	0.95	0.96	0.062	0.23[1]
Suitable for crops	0.67^{ab}	0.76^{a}	0.32^{b}	0.064	0.07
Unsuitable	0.06^{a}	0.19^{b}	0.64^{b}	0.055	0.03[1]
Area off-farm feed production	0.23	0.16	0.25	0.023	0.26
Suitable for crops	0.19	0.15	0.22	0.023	0.60
Unsuitable	0.04	0.01	0.02	0.014	0.62
Area for rearing	0.51^{ab}	0.65^{a}	0.47^{b}	0.028	0.05
Suitable for crops	0.32	0.39	0.30	0.015	0.13
Unsuitable	0.19^{ab}	0.26^{a}	0.17^{b}	0.013	0.02
Total area	1.48	1.76	1.68	0.074	0.23[1]
Area of high soil quality					
Warm climate	0.80^{a}	0.51^{b}	0.31^{c}	0.059	<0.01[1]
Cool climate	0.04	0.16	0.17	0.029	0.17[1]
Area of moderate soil quality					
Warm climate	0.28	0.51	0.11	0.066	0.10[1]
Cool climate	0.07^{a}	0.12^{b}	0.25^{b}	0.025	0.05[1]
Unsuitable[2] area	0.30	0.46	0.83	0.057	0.07
Land use ratio					
Protein (CP)	1.83^{a}	1.77^{a}	1.05^{b}	0.091	<0.01
Energy (GE)	4.03^{a}	3.98^{a}	2.42^{b}	0.201	0.01

[a–c] Different superscript letters within a row illustrate differing means at $P < 0.05$.
[1] As normal distribution or homoscedasticity was rejected, *P*-value is given according to Kruskal-Wallis rank sum test.
[2] Area unsuitable for crop production based on soil properties and climate conditions (on- and off-farm).

tain region was very small (n = 4), leading to a very variable power of the ANOVA which ranged from 15.4 to 87.7%.

Land use ratio

Mean LUR for all farms was 1.69 (±0.454) and 3.76 (±1.008) for CP and GE, respectively. It ranged from 0.69 to 2.64 for CP and 1.52 to 5.93 for GE. Lowland farms had the highest LUR for both CP and GE but only slightly higher than the mean LUR of farms located in the hills (Table 5). Mountain farms had significantly lower LUR than the farms in the other production zones with respect to both CP and GE. The power of the ANOVA was 87.4 and 79.1% for CP and GE, respectively. Variability was lowest for farms located in the lowland (±0.290 for CP and ±0.659 for GE), followed by those located in the mountains (±0.438 for CP and ±1.099 for GE) and the hills (±0.473 for CP and ±1.056 for GE).

Most LUR values were greater than one (Fig. 1). This means that more human-edible food could have been generated on the area used for feed production when producing crops for direct human consumption. Farms with a LUR close to one were situated in mountainous regions where limited areas were rated as suitable for crop production. Nonetheless, even farms that do not have arable land areas on-site may make use of external arable land areas, as they import feed that was produced on arable land and replacement stock that were raised on feedstuffs derived from land suitable for crop production.

Protein quality

Average protein quality score for all farms was 0.48 (±0.068). This means that the protein quality of the animal products was found to be about twice as valuable to human nutrition as the quality of the feed components (Table 4). Thus, if the ePCR was not corrected for protein quality, it doubled to 0.33 (±0.231) on average, ranging from 0.02 to 0.93. If no dietary protein quality correction was included in the assessment, the LUR increased by 33% to 2.43 (±0.13) for CP but remained lower than LUR for GE.

Redundancy of efficiency parameters

When comparing human-edible inputs (feed intake) with human-edible outputs (animal products), increasing amounts of ASF per cow were found, as the amount of human-edible feed input per cow increased (Fig. 2). Simultaneously, the ratio (eFCR) increased the larger the human-edible feed intake was. For farms that fed more than 200 kg human-edible CP per cow and year, eFCR increased towards one, whereas it was lower than 0.3 for farms feeding less than 50 kg human-edible CP per cow and year. Thus, the increase in milk yield did not compensate for the increased amount of human-edible inputs with regard to decreasing direct feed-food competition.

Regarding parameters that are more easily available on farm, rather strong correlations of relevant human-edible in- (concentrate feeds) and output (milk yield per cow) parameters for ePCR and eECR were observed (Table 6). The larger the concentrate input was, the larger ePCR and eECR became. In contrast, productivity gains, by increasing milk yield, have a strongly negative correlation with the FCR.

Total land area used for milk production correlated negatively with milk yield per cow but there was a strong, positive correlation with FCR (Table 6). More milk per cow correlated with less feed per kg of milk and less area used. While only a weak correlation

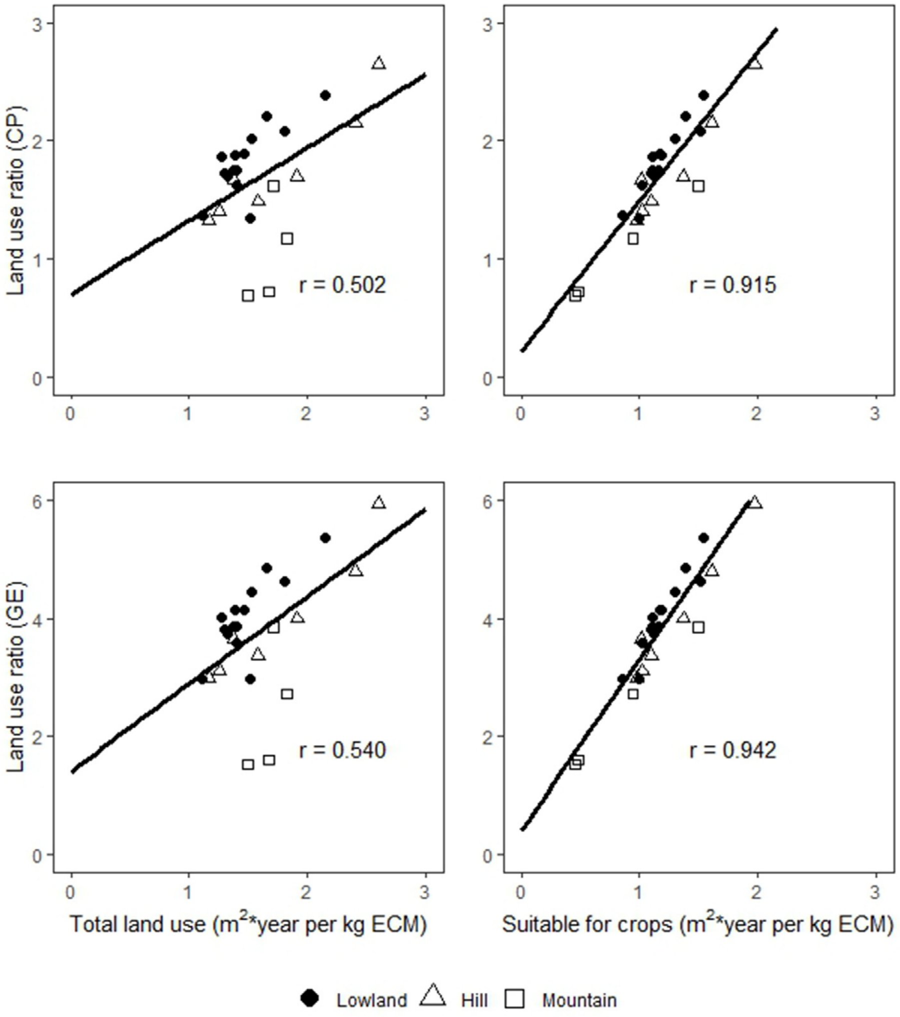

Fig. 1. Land use ratio for CP and GE and its relation to total area and arable land area used for milk production of 25 Swiss dairy cow farms (located in three different production zones). Abbreviations: GE = gross energy; ECM = energy-corrected milk.

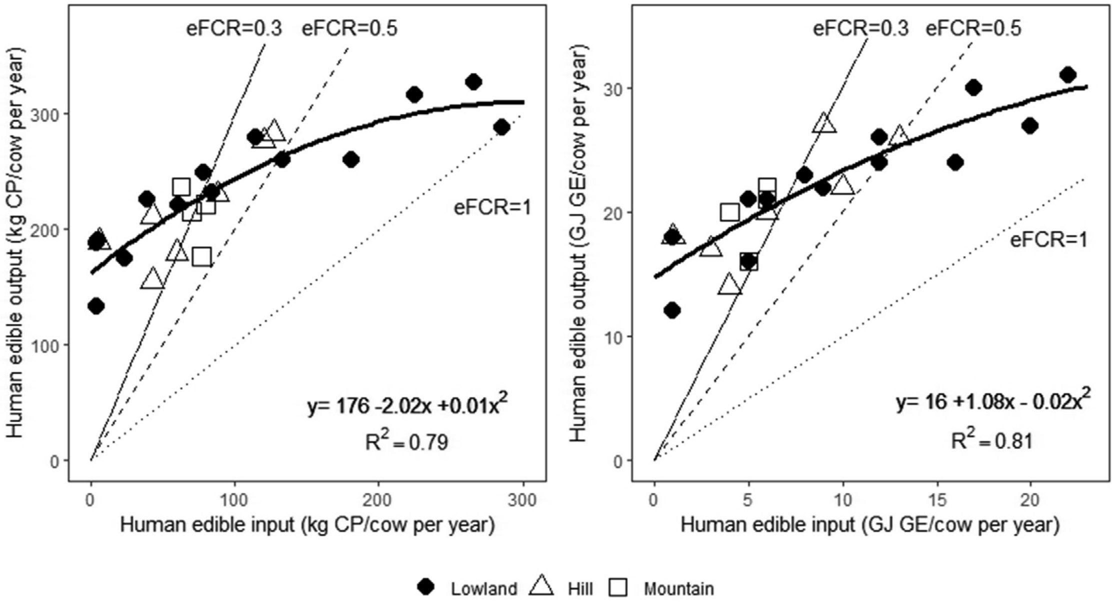

Fig. 2. Human-edible inputs (feed) per cow on 25 Swiss dairy farms (located in three different production zones) and their respective human-edible output (milk and meat) in terms of CP and GE. For CP in- and outputs, no protein quality correction was applied. The ratio between in- and output is referred to as eFCR. Three different levels of eFCR (ratios between in- and outputs) are depicted as references and symbolised by solid, dotted and dashed lines. Abbreviations: GE = gross energy; ECM = energy-corrected milk; eFCR = human-edible feed conversion ratio.

Table 6
Pearson correlation coefficients for the land use ratio (LUR), land area used for milk production, feed conversion ratio (FCR), human-edible protein conversion ratio (ePCR), human-edible energy conversion ratio (eECR), concentrate feed intensity and annual milk yield per cow. ECM = energy-corrected milk, GE = gross energy.

Item	LUR (CP)	LUR (GE)	Total land area[1]	Land area suitable for crops[1]	FCR[2]	ePCR (CP)	eECR (GE)	Conc. feed intensity[3]	Milk yield[4]
LUR (CP)	1	0.996	0.502	0.915	0.541	−0.082	−0.087	−0.196	−0.379
LUR (GE)		1	0.540	0.942	0.571	−0.104	−0.111	−0.214	−0.415
Total land area[1]			1	0.671	0.852	−0.332	−0.525	−0.479	−0.770
Land area suitable for crops[1]				1	0.644	−0.151	−0.196	−0.240	−0.505
FCR[2]					1	−0.482	−0.578	−0.582	−0.884
ePCR (CP)						1	0.879	0.835	0.710
eECR (GE)							1	0.859	0.796
Conc. feed intensity[3]								1	0.737
Milk yield[4]									1

[1] m^2 * year per kg ECM.
[2] kg DM/kg ECM.
[3] Concentrate feed intensity (kg DM/kg ECM); all feeds containing less than 12% crude fibre were considered concentrates.
[4] kg ECM/cow per year.

between the LUR and the total land area required for dairy production was observed, the LUR correlated strongly with the land area suitable for crop production for CP and GE. Therefore, the suitability for crop production of the land used for milk production is much more important to assess LUR than the productivity of the total area. Strong correlations between the ePCR and the eECR were observed. The same holds true for the LUR correlation with CP and GE. However, very low correlations between the ePCR and the eECR with LUR indicators were observed.

Discussion

Impact on the human-edible feed conversion ratio

When considering ration composition, all farms assessed contributed to the net human food supply in the present study. Observed eFCR values correspond in the lower boundary to values other authors have reported. It should be noted that most past studies did not correct for dietary protein quality. Hence, results should be compared to the uncorrected ePCR in the present study (0.33 on average). For a mainly grass-based UK dairy production system, Wilkinson (2011) computed 0.71 and 0.47 for ePCR and eECR, respectively. Converted to the ratio applied in this study, Ertl et al. (2015) reported a mean ePCR of 0.58 and a mean eECR of 1.03, applying the same edibility scenario as in the present study for a wide range of Austrian dairy farms. For numerous French dairy farms, reflecting different systems and production zones, Rouillé et al. (2023) found values ranging from 0.24 to 0.71 for ePCR and 0.37 to 1.49 for eECR, respectively (ratios were also converted).

The relatively low eFCR values in the present study can be explained by the large roughage proportions in the rations of the farms assessed, and the rather low concentrate proportions, which correlated strongly with eFCR. Only the dairy production system with the lowest concentrate proportion in the study by Rouillé et al. (2023) appears to be comparable to the mean concentrate proportion observed in the present study. Hence, mean eFCR values of the two most comparable production systems correspond quite well, although Rouillé et al. (2023) based human-edible fractions of feedstuffs on Laisse et al. (2016), whereas in the present study, they were derived from Ertl et al. (2015 and 2016b). As demonstrated in the present study, it is very challenging to maintain eFCR values below one when increasing the amounts of human-edible feed components, as each additional kg of human-edible input is required to equally increase the subsequent output (Fig. 2). Wang et al. (2022) argued that industrialised dairy systems, relying mainly on highly concentrated feeds, are much more likely to compete with human food supply than grass-based systems, which was previously demonstrated by Mottet et al. (2017). There, grazing cattle in European countries were attributed an ePCR of 0.5, whereas it was 4.1 and 0.7 for cattle in feedlots and mixed system, respectively.

With the exception of Wilkinson (2011), most studies investigating eFCR with respect to protein and energy found lower values for ePCR than for eECR, whereas mean ePCR and eECR values in the present study were similar. Evidently, the edible proportion in the dairy ration of comparable studies was larger for energy than for protein, indicating that the energy supply for dairy cows relied more on human-edible components.

When considering the dietary quality of proteins of edible feed inputs and ASF, Ertl et al. (2016a) showed that ePCR was approximately halved. We found a similar effect when including protein quality in the assessment. Including the protein quality in the assessment, Hennessy et al. (2021) reported an ePCR of 0.22 for the Irish pasture-based dairy production system whereas Ertl et al. (2016a) reported a mean ePCR of 0.53 for Austrian dairy farms. The lower ePCR found in the present study can be explained by the considerably lower concentrate intensity (108 g/kg ECM) compared to the Irish (305 g/kg ECM) and the Austrian (227–338 g/kg ECM) cases. However, it should be noted, that when comparing different concentrate intensities, differing concepts for classifying concentrates as well as standardising energy-corrected milk might have been applied.

The inclusion of differing qualities of plant- and animal-sourced proteins remains methodologically disputed. Combining different plant protein sources in human nutrition may complement otherwise limiting concentrations of essential amino acids (Day, 2013). No such blending effects were considered in the present study. It has been argued that the risk of insufficient essential amino acid uptakes may be modest in industrialised countries as protein consumption often exceeds dietary requirements (van Zanten et al., 2019). However, protein quality may play a larger role in low-income societies and ASF also provides significant amounts of micronutrients (i.e. vitamins and minerals) that contribute to balanced human diets beyond protein supply (Beal et al., 2023). With respect to the abundance of different protein sources in the Swiss food system, a protein quality correction according to the method applied in the present study neglects amino acid complementation effects, potential protein overconsumption but also additional dietary benefits from ASF und may thus be too simplistic.

Due to the limited number of farms assessed, the unbalanced design and the large variation within groups, no statistically significant differences in feeding characteristics between production zones could be observed. However, the group averages indicate differences in milk production intensity, as milk yield per cow and concentrate use per kg ECM were highest on lowland farms. As eFCR values strongly correlate with concentrate use, the larger eFCR values on lowland farms may be explained by intensified milk production in lowland areas. The larger variability of lowland farms regarding the eFCR values corresponds to the high variability of production systems, (from pasture-based systems with no additional concentrate feeding to fully housed systems with higher concentrate proportions), whereas dairy production systems in the mountains are more restrained by topographic and climatic conditions.

Estimating human-edible proportions in feedstuffs highly depends on the assumptions chosen, as arguably crops intended as feed are usually not consumed by humans (Takiya et al., 2019). Human-edible proportions reflect a potential edibility, which strongly depends on social, cultural and economic circumstances. The main findings in the present study refer to a scenario in which currently existing and scalable technologies are applied if biomass currently used as feed was consumed as food (either processed or unprocessed). Several authors have investigated on different edibility scenarios that are suitable to reflect shifts in this framework (Wilkinson, 2011; Ertl et al., 2015; Laisse et al., 2016). As an example, the human edibility of rapeseed cake ranges, depending on the author and edibility scenario, from 0 to 90% (Laisse et al., 2016). Such large variabilities reflect the potential of rapeseed as a plant-sourced protein and the challenges the processing technologies face regarding scalability (Mupondwa et al., 2018). Uncertainties about the potential edibility of animal feeds are immense and even increase as processing technologies evolve. Our scenario computation showed that eFCR is vastly affected by the underlying edibility scenario, too. However, this scenario would require shifts in human nutritional habits, which is obviously challenging (Mottet et al., 2017; Kronberg et al., 2021; Beal et al., 2023). To model which shifts in nutritional habits are required if biomass was to be allocated to maximise net human food supply, a larger food-system approach as proposed by Schader et al. (2015) or van Zanten et al. (2019) could be applied.

Independent of the actual eFCR level the edibility scenario generates, this concept allows a comparison of direct feed-food competition between production systems or farm types. However, the main issue with the eFCR concept may be the fact that presumably non-edible feeds were grown on land that would yield more food when used to grow crops for human consumption (Takiya et al., 2019; Berton et al., 2020). This indirect feed-food competition via the land use was in the present study indicated by the LUR.

Impacts of land area and suitability for crop production on land use ratio

On most farms, the LUR was greater than one. This applied remarkably even in conditions where dairy cows' rations were based on grass and climate and soil conditions that were not expected to be perfectly suitable for food crop production. van Zanten et al. (2016) reported a similar LUR for dairy production on arable mineral soil (2.07 for protein and 4.35 for energy) as were found for lowland farms (1.83 protein and 4.02 for energy on average) in the present study. For dairy production on peat soil (rated as not suitable for crop production), van Zanten et al. (2016) reported LUR values of 0.67 for protein and 1.22 for energy, which is more comparable to the LUR that we observed in mountainous conditions (1.05 for protein and 2.42 for energy on average). Contradictory, Hennessy et al. (2021) reported clearly lower LUR for protein for the Irish dairy system (0.58) that may be explained by the limited suitability for crop production of the area used for milk production. Further, they applied a crop rotation to assess the plant production potential as we have done in the present study, whereas van Zanten et al. (2016) compared ASF per area with the maximised protein production potential of a single crop only. The implementation of a crop rotation decreases the maximum protein production potential, as not only the maximum protein-yielding crop is chosen but agronomic restrictions are equally considered. Total land use per kg ECM affects the LUR. Nevertheless, land use does not imply much about the potential to contribute to human food supply of that land area. Highly productive farmland may be used in an inefficient way while marginal land, even if well managed, may still not lead to the same output. The LUR showed a higher correlation with the area suitable for crop production than with the total land area used for milk production, although land is more productive under favorable climatic and soil conditions and thus less land is required per kg ECM. For areas unsuitable for crop production there is, to date, no other sustainable way of contributing to the human food supply other than "upcycling" by herbivores. Since the LUR concept includes climatic suitability, it is more accurate to compare the potential of animal- and plant-sourced food production for a given location than if the output was simply compared with the land suitable for crop production. As van Zanten et al. (2016) demonstrated, the concept of the LUR can be seen as an instrument to consider opportunity costs. It raises the question of how much food could have been produced on that very same area by applying a different production system. It should be noted that the LUR concept applied here follows a product life cycle assessment approach, which poses certain limitations regarding a food system perspective. For instance, the arable land used by dairy cows is determined by allocating land use to main and co-products, whereas in a food system approach as applied by Schader et al. (2015), allocation can be avoided. The LUR outcome may further depend on the allocation method applied as was shown by van Hal et al. (2019).

Further, a number of challenges in the determination of the LUR remain. For instance, the suitability of the land used to produce feed for dairy cows (and its potential productivity if used for crop production) may be difficult to assess on farm level, especially when the area has not been used as cropland before. Local data to evaluate soil quality and climatic suitability are often not available and the resolution of country-specific data may not be accurate enough. Tichenor et al. (2017) applied geospatial data for crop suitability and yield estimation at different resolution levels to address this issue. More detailed soil maps would allow land to be attributed to the most efficient use. As soil mapping is costly and time-consuming, machine learning offers great potential in modeling soil properties (Baltensweiler et al., 2021).

If the feed used was not grown on the farm, assumptions about the most probable origin of the feed, as well as the potential crop productivity, are made that largely affect the LUR. Besides producing feed for dairy cows, off-farm areas are frequently required for rearing replacement stock. As not all farms rear their own replacement stock, different rearing strategies come into play with a lack of data regarding on-farm practices. In the present study, rations and land occupation were standardised. The actual rearing practices on farm (if replacement stock was reared on farm) were thus not reflected in the results. Feed produced off-farm and the rearing of replacement stock contributed to almost half of the total land occupation of dairy production, with an overwhelming majority originating from arable land areas. This demonstrates the importance of assessing the off-farm land area. More detailed information on feeding practices of replacement stock is desirable.

Strategies to mitigate feed-food competition

It is known that efficiency gains may increase with higher milk yields (Dijkstra et al., 2013). However, in the present study, these gains did not compensate for increasing human-edible proportions in diets of high-yielding cows. Therefore, increasing milk yield does not appear to be a valid strategy to mitigate the eFCR, especially if rations shift towards more concentrated feeds. This was demonstrated in the present study and is in agreement with several previous studies (Capper et al., 2009; Wilkinson et al., 2019). Additionally, increasing milk yields is often associated with increased nitrogen intake which is likely to increase nitrogen excretion and lower nitrogen efficiency (Dijkstra et al., 2013). Excess nitrogen represents relevant environmental burdens from dairy production (Dijkstra et al., 2013). Slight increases in human-edible proportions in rations may be a suitable strategy when it comes to complementing unbalanced diets (Wilkinson and Lee, 2018). However, it appears to be promising to replace conventional concentrate feeds, which are often suitable for human nutrition, with by-products from the food industry (Karlsson et al., 2018). Beneficial effects on milk yield (Fessenden et al., 2020) and significant effects on net feed conversion efficiency (Pang et al., 2018) have been demonstrated with this approach. Additionally, efficiency gains that do not require shifts in rations (e.g. lower replacement rates and improved animal health) may decrease the eFCR, as the outputs (milk and beef) may increase while the inputs (human-edible feeds) remain stable.

Reducing the human-edible feed component input rather than increasing productivity leads to lower eFCR, whereas decreasing the FCR offers an effective strategy to reduce the LUR. Less feed for the production of one kg ECM means decreased land use for the same amount of product. In Switzerland, Alig et al. (2015) showed that pasture-based systems required more land. However, only grass-based systems can make use of land that is not suitable for crop production, offering a LUR mitigation strategy.

The most efficient use of limited resources (such as feed or land) is highly relevant for future food security and policy making (Tichenor et al., 2017). On a farm or regional level, this requires the allocation of dairy production to non-arable land or the reduction of the amount of concentrated feeds with high NEL or CP concentrations (as arable land is allocated to their production even if they were derived from so-called by-products) while maintaining productivity. The latter demonstrates the importance of well-managed and productive grasslands, as high-quality forage is key to retaining productivity under limited concentrate feeding (Peyraud and Delagarde, 2013).

The LUR level was strongly affected by the location of the farm and consequently, its soil and climate suitability for food production in the present study. Farms located in mountainous regions with little arable land and harsh climatic conditions had the lowest LUR. As dairy farmers cannot influence the suitability of the land they manage for crop production, they can improve their LUR by choosing low-opportunity cost feedstuffs when buying additional feed. When shifting towards low-opportunity cost dairy feeds, milk performance per cow may decrease, therefore economic considerations may prevent farmers from implementing changes in their production systems. Despite this, the average income on Swiss pasture-based dairy systems is not lower than in indoor-feeding systems (Hofstetter et al., 2014). Recently, Zorn and Zimmert (2022) clearly demonstrated the importance of agricultural policy for structural changes in the Swiss dairy sector. However, subsidies for grass-based dairy and beef production in Switzerland have only effected minor shifts (Mack et al., 2017). The indicators proposed to assess feed-food competition presented in the present study might therefore complement the subsidy programs in terms of net human food supply.

Application of indicators

For the eFCR as well as for the LUR, the protein and the energy perspective correlated strongly. As ASF is assumed to be more important for human protein than energy supply (van Zanten et al., 2016), we suggest focusing on the protein perspective in future studies. Both of these methods are applicable in assessing how much dairy production contributes to net human food supply under different climate and soil conditions in Switzerland. These concepts may serve to derive the future role of livestock feeding when used as resource efficiency indicators alongside with life cycle impact assessments. Considerations on the net contribution to human food supply could be incorporated into the land use impact category, or – stressing the function of food production even more – in the functional unit itself which could refer to the impact per "kg net edible protein" (Grassauer et al., 2021). Additional research is required to determine which approach turns out to be preferable from a net food supply perspective. Regardless, environmental consequences (Herrero et al., 2013) due to land use changes (e.g. carbon release when tilling grassland) need to be considered when assessing ruminant systems. Mixed animal and crop production systems may be pertinent in providing adequate nutrients for crop production (Kronberg et al., 2021; Wang et al., 2022). Successive bush vegetation is known to establish on grassland neither cut nor grazed, affecting the botanical composition of alpine grassland and hence biodiversity (Pornaro et al., 2013). Additionally, growing crops on suitable areas formerly used for dairy feed production does not imply sustainable land use nor does it consider the willingness of consumers to switch to plant-based diets (Kronberg et al., 2021).

To assess the net contribution to the human food supply of current food systems, the concepts discussed in the present study should also be applied to non-ruminant ASF. As an example, van Hal et al. (2019) demonstrated that the LUR concept is also well suited in the consideration of the complex roles non-ruminant animals play in the food system. The production of monogastric ASF was indeed shown to compete more for food and land than mixed and grass-based ruminant production system production systems (Mottet et al., 2017).

Conclusions

Both methods (eFCR and LUR) to assess the net contribution to the human food supply from dairy production are well established and applicable methods. However, challenges in applying both on farm level remain. Indicator values strongly depend on the underlying scenarios, such as the human-edible fraction of feeds or the suitability of land and climate for crop production. Used together, they offer an opportunity to holistically evaluate the net contribution of dairy production to the human food supply under different environmental conditions and stress the importance of production systems well suited to specific farm site characteristics.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2023.101028.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository. The data and models that support the findings are available upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence-assisted technologies in the writing process.

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Declaration of interest

None.

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References

Agroscope, 2016. The Swiss Feed Database. Retrieved 8 August 2017 from http://www.feedbase.ch.

Alig, M., Sutter, M., Nemecek, T., 2015. Eco-efficiency of grass-based dairy systems in Switzerland. Proceedings of the 18th Symposium of the European Grassland Federation (EGF 2015). Wageningen Academic Publishers, Wageningen, NL.

Baltensweiler, A., Walthert, L., Hanewinkel, M., Zimmermann, S., Nussbaum, M., 2021. Machine learning based soil maps for a wide range of soil properties for the forested area of Switzerland. Geoderma Regional 27, e00437.

Beal, T., Gardner, C.D., Herrero, M., Iannotti, L.L., Merbold, L., Nordhagen, S., Mottet, A., 2023. Friend or foe? The role of animal-source foods in healthy and environmentally sustainable diets. The Journal of Nutrition 153, 409–425.

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. Agricultural Systems 181, 11.

Bozic, M., Newton, J., Thraen, C.S., Gould, B.W., 2012. Mean-reversion in income over feed cost margins: Evidence and implications for managing margin risk by US dairy producers. Journal of Dairy Science 95, 7417–7428.

Capper, J.L., Cady, R.A., Bauman, D.E., 2009. The environmental impact of dairy production: 1944 compared with 2007. Journal of Animal Science 87, 2160–2167.

Day, L., 2013. Proteins from land plants–potential resources for human nutrition and food security. Trends in Food Science & Technology 32, 25–42.

Dijkstra, J., France, J., Ellis, J.L., Strathe, A.B., Kebreab, E., Bannink, A., 2013. Production efficiency of ruminants: feed, nitrogen and methane. In: Kebreab, E. (Ed.), Sustainable Animal Agriculture. CABI, Wallingford, UK, pp. 10–25.

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. Agricultural Systems 137, 119–125.

Ertl, P., Knaus, W., Zollitsch, W., 2016a. An approach to including protein quality when assessing the net contribution of livestock to human food supply. Animal 10, 1883–1889.

Ertl, P., Steinwidder, A., Schönauer, M., Krimberger, K., Knaus, W., Zollitsch, W., 2016b. Net food production of different Livestock: A national analysis for Austria including relative occupation of different land categories. Bodenkultur 67, 91–103.

FAO, 2013. Dietary protein quality evaluation in human nutrition: Report of FAO Expert Consultation. FAO Food and Nutrition Paper 92, Rome, IT.

FAO, 2017. FAOSTAT. Retrieved 24 September 2017 from http://www.fao.org/faostat/en/#data/QC.

Fessenden, S.W., Ross, D.A., Block, E., Van Amburgh, M.E., 2020. Comparison of milk production, intake, and total-tract nutrient digestion in lactating dairy cattle fed diets containing either wheat middlings and urea, commercial fermentation by-product, or rumen-protected soybean meal. Journal of Dairy Science 103, 5090–5101.

Foag, 2018. Anleitung für die Schätzung des landwirtschaftlichen Ertragswertes. BBL, Vertrieb Bundespublikationen, Bern, CH.

Foag, 2019. Directives on the regulation on direct payments (Weisungen zur Verordnung über die Direktzahlungen an die Landwirtschaft). FOAG, Bern, CH.

FOAG, 2021. Directives on the regulation on agricultural production zones (Weisungen zur Landwirtschaftliche Zonen-Verordnung). FOAG, Bern, CH.

FOCBS, 2017. Swiss Import-Export Database (Swiss-Impex). Retrieved on 24.01.2023 from https://www.gate.ezv.admin.ch/swissimpex/public/bereiche/waren/query.xhtml.

FSO, 2018. Arealstatistik: Standardnomeklatur (NOAS04) nach Bezirk und Gemiende, in Hektaren. FSO, Bern, CH.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: The challenge of feeding 9 billion people. Science 327, 812–818.

Grassauer, F., Herndl, M., Nemecek, T., Guggenberger, T., Fritz, C., Steinwidder, A., Zollitsch, W., 2021. Eco-efficiency of farms considering multiple functions of agriculture: Concept and results from Austrian farms. Journal of Cleaner Production 297, 126662.

Hennessy, D.P., Shalloo, L., van Zanten, H.H.E., Schop, M., De Boer, I.J.M., 2021. The net contribution of livestock to the supply of human edible protein: the case of Ireland. The Journal of Agricultural Science 159, 463–471.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences 110, 20888–20893.

Hofstetter, P., Frey, H.J., Gazzarin, C., Wyss, U., Kunz, P., 2014. Dairy farming: indoor v. pasture-based feeding. The Journal of Agricultural Science 152, 994–1011.

Holzkämper, A., Fossati, D., Hiltbrunner, J., Fuhrer, J., 2015. Spatial and temporal trends in agro-climatic limitations to production potentials for grain maize and winter wheat in Switzerland. Regional Environmental Change 15, 109–122.

Hristov, A.N., Ott, T., Tricarico, J., Rotz, A., Waghorn, G., Adesogan, A., Dijkstra, J., Montes, F., Oh, J., Kebreab, E., Oosting, S.J., Gerber, P.J., Henderson, B., Makkar, H. P., Firkins, J.L., 2013. Special topics–Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. Journal of Animal Science 91, 5095–5113.

Jans, F., Kessler, J., Münger, A., Schlegel, P., 2015. Fütterungsempfehlungen für die Milchkuh. Agroscope, Posieux, CH.

Karlsson, J., Spörndly, R., Lindberg, M., Holtenius, K., 2018. Replacing human-edible feed ingredients with by-products increases net food production efficiency in dairy cows. Journal of Dairy Science 101, 7146–7155.

Kopf-Bolanz, K., Bisig, W., Jungluth, N., Denkel, C., 2015. Quantitatives Potential zur Verwertung von Molke in Lebenmitteln in der Schweiz. Agrarforschung Schweiz 6, 270–277.

Kronberg, S.L., Provenza, F.D., van Vliet, S., Young, S.N., 2021. Review: Closing nutrient cycles for animal production – Current and future agroecological and socio-economic issues. Animal 15, 100285.

Laisse, S., Rouillé, B., Baumont, R., Peyraud, J.-L., 2016. Évaluation de la contribution nette des systèmes bovins laitiers français à l'approvisionnement alimentaire protéique pour l'être humain. Rencontres Recherches Ruminants 23, 4.

Mack, G., Heitkämper, K., Käufeler, B., Möbius, S., 2017. Evluation der Beiträge für Graslandbasierte Milch- und Fleischproduktion (GMF). Agroscope Science. Agroscope, Ettenhausen, CH.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security 14, 1–8.

Münger, A., Kessler, J., 2017. Fütterungsempfehlung für die Aufzucht des Rindes. Agroscope, Posieux, CH.

Mupondwa, E., Li, X., Wanasundara, J.P.D., 2018. Technoeconomic Prospects for Commercialization of Brassica (Cruciferous) Plant Proteins. Journal of the American Oil Chemists' Society 95, 903–922.

Oltjen, J.W., Beckett, J.L., 1996. Role of ruminant livestock in sustainable agricultural systems. Journal of Animal Science 74, 1406–1409.

Pang, D., Yan, T., Trevisi, E., Krizsan, S.J., 2018. Effect of grain- or by-product-based concentrate fed with early- or late-harvested first-cut grass silage on dairy cow performance. Journal of Dairy Sciences 101, 7133–7145.

Peyraud, J.L., Delagarde, R., 2013. Managing variations in dairy cow nutrient supply under grazing. Animal 7, 57–67.

Pornaro, C., Schneider, M.K, Macolino, S., 2013. Plant species loss due to forest succession in Alpine pastures depends on site conditions and observation scale. Biological Conservation 161, 213–222.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, AT.

Richner, W., Sinaj, S., 2017. Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017). Agrarforschung Schweiz 8 (6: Spezialpublikation), 276.

Rouillé, B., Jost, J., Fança, B., Bluet, B., Jacqueroud, M.P., Seegers, J., Charroin, T., Le Cozler, Y., 2023. Evaluating net energy and protein feed conversion efficiency for dairy ruminant systems in France. Livestock Science 269, 105170.

Schader, C., Muller, A., Scialabba, N.-E.-H., Hecht, J., Isensee, A., Erb, K.-H., Smith, P., Makkar, H.P.S., Klocke, P., Leiber, F., Schwegler, P., Stolze, M., Niggli, U., 2015. Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. Journal of The Royal Society Interface 12, 20150891.

SMP, 2019. Swiss Dairy Economy in Figures 2019/20. Swiss Milk Producers (SMP), Bern, CH.

Takiya, C.S., Ylioja, C.M., Bennett, A., Davidson, M.J., Sudbeck, M., Wickersham, T.A., VandeHaar, M.J., Bradford, B.J., 2019. Feeding dairy cows with "leftovers" and the variation in recovery of human-edible nutrients in milk. Frontiers in Sustainable Food Systems 3, 114.

Tichenor, N.E., van Zanten, H.H.E., de Boer, I.J.M., Peters, C.J., McCarthy, A.C., Griffin, T.S., 2017. Land use efficiency of beef systems in the Northeastern USA from a food supply perspective. Agricultural Systems 156, 34–42.

van Hal, O., Weijenberg, A.A.A., de Boer, I.J.M., van Zanten, H.H.E., 2019. Accounting for feed-food competition in environmental impact assessment: Towards a resource efficient food-system. Journal of Cleaner Production 240, 118241.

Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C., De Boer, I.J.M., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biology 24, 4185–4194.

van Zanten, H.H.E., Mollenhorst, H., Klootwijk, C.W., van Middelaar, C.E., de Boer, I.J. M., 2016. Global food supply: land use efficiency of livestock systems. The International Journal of Life Cycle Assessment 21, 747–758.

van Zanten, H.H.E., van Ittersum, M.K., De Boer, I.J.M., 2019. The role of farm animals in a circular food system. Global Food Security 21, 18–22.

van Zanten, H.H.E., Muller, A., Frehner, A., 2022. 5 – Land use modeling: from farm to food systems. In: Peters, C., Thilmany, D. (Eds.), Food Systems Modelling. Academic Press, London, UK, pp. 89–105.

Vandehaar, M.J., 1998. Efficiency of nutrient use and relationship to profitability on dairy farms. Journal of Dairy Science 81, 272–282.

Wang, Y., de Boer, I.J.M., Hou, Y., van Middelaar, C.E., 2022. Manure as waste and food as feed: environmental challenges on Chinese dairy farms. Resources, Conservation & Recycling 181, 106233.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 21, 1218–1230.

Wilkinson, J.M., 2011. Re-defining efficiency of feed use by livestock. Animal 5, 1014–1022.

Wilkinson, J.M., Lee, M.R.F., 2018. Review: Use of human-edible animal feeds by ruminant livestock. Animal 12, 1735–1743.

Wilkinson, J.M., Lee, M.R.F., Rivero, M.J., Chamberlain, A.T., 2019. Some challenges and opportunities for grazing dairy cows on temperate pastures. Grass and Forage Science 75, 1–17.

Zorn, A., Zimmert, F., 2022. Structural change in the dairy sector: exit from farming and farm type change. Agricultural and Food Economics 10, 7.