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Performance, health-related treatments, and reproductive parameters of dairy cows fed protein-reduced concentrates in an organic herbage-based feeding system

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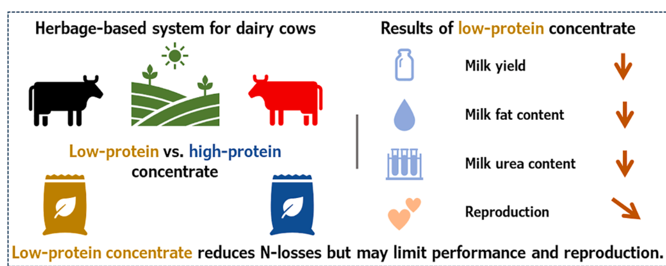
HIGHLIGHTS

- A low-protein supplement tested in an organic, herbage-based system for dairy cows.
- The low-protein supply lowered milk yield and fat, even in a herbage-based system.
- The low-protein supplement reduced milk urea, indicating lower N loss.
- The low-protein supplement seemed to impair reproduction in dairy cows.
- The health treatments were similar among cows in the low- and high-protein groups.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigated the effects of protein supply on milk production in a herbage-based feeding system. We assessed 138 lactation records from 94 Holstein and Swiss Fleckvieh cows on an organic farm across 3.5 years. During winter, the basal ration consisted of hay (kg dry matter [DM]: 111 g crude protein [CP] and 5.2 MJ net energy lactation [NEL]), and grazing started in late March (kg DM: 178 g CP and 6.1 MJ NEL). On average, the cows consumed 333 kg of concentrate per lactation (as fed). The cows were paired by breed, parity, and calving date and randomly assigned to a low-protein (LOPRO; kg DM: 137 g CP and 7.8 MJ NEL) or a higher-protein (HIPRO; kg DM: 221 g CP and 8.0 MJ NEL) concentrate treatments. Calving occurred from late December to early May. Milk recordings and reproductive parameters were analysed using linear mixed-effects models, and health treatment counts were analysed using Poisson tests. Only in early lactation did LOPRO cows produce less energy-corrected milk (26.8 vs. 28.5 kg/d; $p = 0.01$) and have lower milk fat (38.6 vs. 40.0 g/kg; $p = 0.049$) and milk urea (16.1 vs. 20.6 mg/dL; $p < 0.001$) concentrations than HIPRO cows. Although calving-to-first-insemination intervals were similar ($p = 0.18$), LOPRO cows showed poorer reproductive performance. No differences in health treatments were observed between the feeding treatments. These findings highlight a trade-off between protein supply for performance and reproduction and increased nitrogen excretion, as reflected in milk urea concentrations.

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1. Introduction

Societal concerns, including environmental impacts, high uses of resources, feed-food competition, biodiversity loss, and animal welfare, have driven the development of policy instruments and market-based initiatives aimed at promoting more sustainable dairy production. At the European level, the European Green Deal, including its Farm to Fork strategy (Wesseler, 2022), and the Common Agricultural Policy (European Parliament and Council, 2021) explicitly provide support for climate, environmental, and animal-welfare schemes in agriculture. Similar approaches and private-sector initiatives exist in many countries worldwide. In Switzerland, the grassland-based milk and meat production (GMM) programme was introduced in 2014 to promote site-adapted, herbage-based and concentrate-reduced ruminant production. According to the original guidelines, at least 75% of the annual ration for cattle in lowland areas and 85% in mountain regions must consist of fresh or preserved herbage, while concentrate use is limited to a maximum of 10% of the annual dry matter intake (DVZ, 2026). As part of the ongoing development and simplification of the GMM programme, an alternative scenario has been proposed that allows only concentrates with a maximum crude protein (CP) content of 12% for dairy cows while removing both the minimum herbage proportion and the maximum concentrate proportion in the annual ration (Schori, 2020a). Under this scenario, the protein requirements of dairy cows would need to be met primarily through herbage.

Reducing the CP content of concentrates is expected to decrease nitrogen (N) losses, as N excretion is strongly and positively related to dietary N intake in dairy cows (Yan et al., 2006; Mangwe et al., 2025). Consequently, the alternative scenario may also contribute to achieving N-related environmental targets at the national level. At the global level, a United Nations initiative has called for halving N losses by 2030 (Sutton et al., 2021). Furthermore, reducing the CP content of concentrates for cattle, particularly dairy cows, and thereby increasing reliance on locally produced herbage-based feeds could decrease dependence on large volumes of imported, protein-rich feedstuffs, such as soybean meal (Hennessy et al., 2020).

Low-protein diets for dairy cows are considered environmentally advantageous (Yan et al., 2006; Schrade et al., 2023; Mangwe et al., 2025). However, the proposed GMM scenario allowing only concentrates with a maximum of 12% CP is particularly restrictive because the milk production potential supported by the CP content is lower than that supported by its net energy for lactation (NEL) content (Agroscope, 2021). Moreover, in Ireland, where dairy feeding systems are highly grass-based, concentrates contain, on average, 18% CP on a DM basis (Dillon et al., 2021). The effects of concentrate CP content on milk yield, milk composition, animal health, and reproductive performance depend on forage quality and, in particular, the protein content of the forage. Long-term studies and meta-analyses have shown that dietary protein supply has a positive effect on milk yield and, to a lesser extent, on milk components in dairy cows (Law et al., 2009a; Zanton, 2016; Chowdhury et al., 2025). Furthermore, a high dietary protein concentration or high milk urea N concentrations (Butler, 1998; Raboisson et al., 2017; Zhao et al., 2025)—the latter also indicating an imbalanced dietary energy-to-protein ratio—are associated with reduced reproductive performance. At low milk urea N concentrations, evidence regarding reproductive performance is inconsistent (Zhao et al., 2025). However, in a study involving a large number of dairy cows, low milk urea N concentrations (<150 mg/kg) were associated with a 5–9% lower conception success (Albaaj et al., 2017). With regard to the effects of low-protein diets on immunity and disease occurrence in dairy cows, the available evidence is even more inconsistent and limited than that relating to fertility. For example, Law et al. (2009b) observed a higher incidence of metritis in dairy cows fed truly low-protein diets (114 g CP per kg DM) but found no effects on reproductive parameters compared with control diets. Zang et al. (2021) reported higher serum β-hydroxybutyrate concentrations and increased plasma 3-methylhistidine levels—an indicator of muscle breakdown—in a moderately reduced-protein treatment (101 g metabolisable protein and 153 g CP per kg DM), without any effects on disease incidence in high-yielding dairy cows. Studies in sheep have provided some indications that protein supplementation and protein quality enhance the ability of periparturient sheep to maintain immunity against parasitic infections (Donaldson et al., 2001; Sakkas et al., 2012). This underscores the need to investigate whether the new GMM scenario, allowing only concentrates with a maximum of 12% CP, affects reproductive performance or disease incidence. Especially during winter feeding with conserved herbage, the protein supply may be of particular concern due to losses in protein quantity and quality during harvest and storage (León-Tinoco et al., 2025). If these losses are substantial, they cannot be compensated for by a concentrate limited to 12% CP.

To evaluate the effects of the proposed limitation of concentrate protein content on milk production, milk composition, somatic cell counts, body weight (BW), body condition score (BCS), health treatments, and reproductive performance, a long-term study was conducted over more than three years under practical farming conditions. As the proposed scenario is primarily intended for highly herbage-based feeding systems, the experiment was carried out under such conditions and compared with a ration supplemented with additional protein.

2. Animals, materials, and methods

All experimental procedures were performed in accordance with the Swiss Animal Welfare Act and approved by the Office of Food Safety and Veterinary of the Canton of Fribourg (2020-48-FR, 2021-33-FR, and 2022-31-FR).

2.1. Animals

The experiment was carried out on the organic farm Ferme-École de Sorens, located approximately 820 m a.s.l. in Sorens, Switzerland. Including three calving seasons, the study lasted approximately 3.5 years (2021–2024). The lactating dairy cow herd of approximately 85 animals comprised both the experimental and the remaining cows, kept together as a single herd. In total, 94 dairy cows (53 Holstein and 41 Swiss Fleckvieh) were included in the study. Cows could be retained for multiple lactations if they calved again within the desired time window after a standard lactation, were suitable for pair formation, and completed another standard lactation.

2.2. Production system

A herbage-based feeding system has been implemented for dairy cows on the organic farm since 2004. Dairy cows were housed in a free-stall barn with cubicles and had access to an outdoor yard with a solid concrete floor. During the main experimental years (2021–2023), most calvings occurred within the first four months of the year. The grazing season for the dairy cows began at the end of March (2021: 29th, 2022: 22nd, 2023: 21st) and lasted until November (2021: 1st, 2022: 16th, 2023: 3rd). During the grazing season, following a transitional feeding period, pasture herbage was the main forage, with cows grazing for approximately 16–20 h per day; for the remainder of the day, they were kept in the free-stall barn and milked. When pasture herbage offers became scarce, the cows received hay supplementation in the barn. Throughout the non-grazing season, hay was the sole forage, following transitional feeding at the end of the pasture season. Table 1 presents the average chemical composition and nutritive values of the hay and grazed herbage. A rotational grazing system with a maximum of 19 paddocks, each approximately 2 ha in size and located at an altitude of 800 to 900 m a.s.l., was used for the dairy cows. Most of the pasture areas utilised (85%) consisted of long-established mixed swards. The pastures were mainly grass-dominant (>70% grasses) or balanced (50–70% grasses) plant communities (Agroscope, 2021, Chapter 13),

Table 1
Average chemical composition and estimated nutritive value of grazed herbage, hay, and concentrates.

	Herbage		Hay		LOPRO[a]		HIPRO[b]	
	n = 40		n = 18		n = 9		n = 69[b]	
	Mean	SD[c]	Mean	SD[c]	Mean	SD[c]	Mean	SD[c]
In g/kg DM								
Organic matter	874	45.9	924	7.5	926	2.7	923	2.6
Crude protein	178	32.2	111	10.7	135	7.5	221	6.6
Ether extract					48	8.3	66	4.4
ADF[d]	247	33.1	311	18.4	78	10.9	81	4.8
NDF[e]	447	61.1	554	21.3	219	34.8	193	21.3
APDE[f]	104	6.7	81	3.6	101	3.1	134	7.5
Energy value MJ/kg DM								
NEL[g]	6.1	0.25	5.2	0.15	7.8	0.14	8.0	0.10

[a] Low-protein concentrate of the treatment LOPRO (ingredients of Dairy Energy Concentrate No 8311 listed in descending order of inclusion: wheat bran, wheat feed meal, triticale grains, millet grains, barley grains, wheat grains, maize grains, minerals, oat flakes, sugar-beet molasses, soybean oil),

[b] Concentrate mixture of the treatment HIPRO (chemical composition and nutritive values for the HIPRO concentrate mixture were calculated from the amounts of concentrates retrieved per cow (n = 69) at the automatic feed stations and the mean chemical composition and nutritive values of the concentrates, ingredients of the concentrate listed in descending order of inclusion: Dairy Energy Concentrate No 8311 see above; Dairy Fortuna HP No 8361: soybean expeller, horse beans, wheat feed meal, maize grains, wheat grains, barley grains, minerals, sugar beet molasses, lupin seeds, sunflower expeller, soybean oil; Dairy Protein Concentrate No 8381 P: soybean expeller, sunflower expeller, horse beans, sugar-beet molasses, minerals, wheat bran),

[c] Standard deviation.

[d] Acid detergent fibre.

[e] Neutral detergent fibre.

[f] Absorbable protein in the intestine based on fermentable energy in the rumen (calculated according to Agroscope [2021]).

[g] Net energy for lactation (calculated according to Agroscope [2021]).

with ryegrass accounting for <50% of the grass proportion. The predominant grass species were *Lolium perenne, Poa pratensis, Phleum pratense* and *Dactylis glomerata*. The main forage legumes were *Trifolium repens* and, to a lesser extent, *Trifolium pratense*, while *Taraxacum officinale* predominated among the other species. Pre- and post-grazing sward surface heights were measured regularly using a C-Dax Pasture Meter (C-DAX Ltd., Palmerston North, New Zealand). Over the three grazing seasons, the average pre-grazing sward surface height (n = 418) was 101 mm (range: 49–179 mm), corresponding to an estimated herbage mass of 696 kg DM/ha (range: 10–1726 kg DM/ha) above 48 mm (equations: Schori, 2020b). The average post-grazing sward surface height was 53 mm (range: 39–76 mm). The cows were milked twice daily, at approximately 05:00 and 16:00 h. The mean daily ambient outdoor temperature during the three main experimental years was 10 °C, with minimum and maximum temperatures ranging from −15 °C to 35 °C. Annual precipitation ranged from 1064 to 1308 mm (MeteoSchweiz, Station Marsens, Switzerland, 1.5 km east of the farm).

2.3. Concentrate allocations and experimental treatments

The concentrate allocation scheme was the same for the two experimental treatments. During the first 90 days in milk (DIM), all cows received 3 kg of concentrate on an as-fed basis. From 100 to 150 DIM, following a 10-day adaptation period, cows were given 1 kg of concentrate. Thereafter, the cows received no further concentrate. In the low-protein (LOPRO) treatment, all cows were supplied with a commercial organic concentrate (Dairy Energy Concentrate No 8311 P, Mühle Rytz AG, Biberen, Switzerland) containing, on average, 135 ± 7.5 g CP per kg DM (mean ± standard deviation [SD]). In the high-protein (HIPRO) treatment, all cows were fed a mixture of two commercial organic concentrates (2021: Dairy Energy Concentrate No 8311 P and Dairy Protein Concentrate No 8381 P; 2022 and 2023: Dairy Energy Concentrate Nr 8311 P and Dairy Fortuna HP No 8361 P; Mühle Rytz AG, Biberen, Switzerland), resulting in an average protein concentration of 221 ± 6.6 g CP per kg DM. The CP value of the concentrate mixture for the HIPRO treatment was calculated based on the amounts of concentrate retrieved per experimental cow (n = 69) at the automatic feed stations. Detailed chemical composition and nutritive values of the concentrate supply are presented in Table 1. The concentrates were distributed using three automatic feed stations (DeLaval AG, Sursee, Switzerland) in the cubicle housing. In addition, mineral supplements, salt, and water were available to all cows. Each December, before the start of the calving season, matched pairs of healthy Holstein and Swiss Fleckvieh cows were formed within breed according to the expected calving date (mean calving date across the three calving periods ranged from 20 to 28 February ± 35 days [SD]) and number of lactations (2.5 ± 1.55 [SD]). The matched pairs were randomly allocated each year to either the LOPRO or HIPRO treatments. Each year, new cows were introduced into the experiment.

2.4. Sample collection and data recording

From the end of April to the end of October, herbage samples were collected every 14 days from two representative strips, each approximately 7.5 m in length, on the paddock scheduled for grazing. For the assessment of herbage chemical composition and nutritive value, a pooled sample of the biomass from the two strips was dried and analysed using wet chemistry. During the transitional feeding periods (winter–summer and summer–winter) as well as during winter feeding, the offered hay was sampled once per week. These weekly samples were pooled by month and subsequently analysed. From each concentrate type, nine samples were collected and analysed using wet chemistry over the three main experimental years. Every 14 days, the milk yield per cow was recorded for two consecutive milkings (evening and morning) using a Flowmaster Pro system (DeLaval AG, Switzerland). A composite milk sample from both milkings was collected by breeding association personnel (Holstein Switzerland, Posieux, CH, and Swissherdbook, Zollikofen, CH). Milk samples were analysed for fat, protein, lactose, and urea using mid-infrared spectrometry, and somatic cell counts were determined using an optical fluorescence technique (Suisselab AG, Zollikofen, CH). The BCS of the lactating cows was assessed monthly by the same trained assessor using a 1–5 scale (Edmonson et al., 1989). After each milking, the cows were weighed using an automatic weighing system (DeLaval AG). Farm employees recorded all health treatments, interventions, and reproductive events (calvings and inseminations) in the herd management programme (ALPRO, later DELPRO, DeLaval AG).

2.5. Calculations and statistical analysis

For the evaluation, the results of the fortnightly official milk recordings and the corresponding milk sample analyses were classified into three lactation stages per cow: early lactation, comprising the 1st to 6th recordings; mid lactation, covering the 8th to 14th recordings; and late lactation, including the 15th up to the last available recording for the standard lactation (19 to 21 records). The BW recorded twice daily were checked for obvious outliers and subsequently averaged per day and over 14-day periods. Using the same allocation procedure as for the milk recordings, 14-day average BW were assigned to early, mid- and late-lactation stages. The BCS (9 to 10 records per standard lactation) were classified into the same three lactation stages per cow—early, mid, and late lactation—including BCS assessments 1–3, 4–7, and 8–10, respectively. Energy-corrected milk yield (ECM) was calculated based on fat, protein, and lactose content, together with the effective milk yield (Agroscope, 2021, Chapter 7).

For the statistical analyses, R (R Core Team, 2025; version 4.5.2) was used. Milk yield, milk constituents, BW, and BCS were analysed using linear mixed models (packages lme4; Bates et al., 2015, and lmerTest; Kuznetsova et al., 2017). Experimental treatment (LOPRO, HIPRO), lactation stage (early, mid, and late), and their interaction were included as fixed effects, while individual cows were included as a random intercept. Somatic cell count was analysed using a generalised linear mixed model from the lme4 package, assuming a Gamma distribution with a log link function and including the same fixed effects and random intercept as described above. The data on milk yield, fat content, and protein content for the standard lactation of the experimental cows were calculated by the breeding organisations (Holstein Switzerland and Swissherdbook) in accordance with the guidelines of the International Committee for Animal Recording (ICAR, 2020), based on fortnightly milk recording data. Milk production traits over the standard lactation and the reproductive parameters were analysed using linear mixed models with treatment (LOPRO, HIPRO) as a fixed effect and cow pair as a random intercept. For this analysis, the calving-to-first-insemination interval was log10-transformed and back-transformed for presentation in Table 3. The insemination index was analysed using a generalised linear mixed model (package glmmTMB; Brooks et al., 2017), with treatment as a fixed effect and cow pair as a random intercept, assuming a Conway–Maxwell–Poisson distribution for count data. Health disorder treatments and the number of cows that did not calve after the experimental period were compared between treatment groups using the Poisson test. The relative distribution of health disorder categories was assessed using Fisher's exact test.

3. Results

In total, 138 lactation records from 94 dairy cows (53 Holstein and 41 Swiss Fleckvieh) were used for the evaluation. In both feeding treatments, concentrate intake per standard lactation was identical, amounting to 333 kg on an as-fed basis. On a DM basis, intake amounted to 294 ± 32 (SD) kg in LOPRO and 297 ± 36 kg in HIPRO. Cows in LOPRO tended to produce less milk (6154 vs. 6358 kg milk, standard error [SE] = 106, $p = 0.07$) per standard lactation compared with cows in the HIPRO treatment. Averaged over the entire standard lactation period, milk fat content (40.2 vs. 39.8 g per kg milk, SE = 0.44, $p = 0.55$) and milk protein content (32.2 vs. 32.2 g per kg milk, SE = 0.26, $p = 0.88$) were similar between the two treatments. Table 2 summarises the average daily milk yield and milk composition, milk urea concentrations, somatic cell counts, BW, and BCS, grouped by lactation stage (early, mid, and late) and feeding treatment. Most treatment-related differences were observed in early lactation. During this stage, cows under the LOPRO treatment produced less milk per day (–1.4 kg), showed a lower milk fat content (–1.4 g/kg), and yielded less energy-corrected milk (–1.7 kg) compared with HIPRO. Milk urea concentrations were, as expected, lower under LOPRO (–4.5 mg/dl). In early lactation, milk protein, lactose, BW, and BCS were similar between treatments. No treatment effects were found in the mid- or late-lactation stages. Lactation stage had an effect on all variables presented in Table 2 ($p < 0.001$). Interactions ($p < 0.05$) were identified for actual and energy-corrected milk yield, BW, and milk fat, lactose, and milk urea concentrations.

In each lactation, the experimental cows were inseminated at least once; however, not every lactation included in the analysis was followed by a subsequent calving. Under the LOPRO treatment, 13 cows did not calve, compared with 16 cows under the HIPRO treatment ($p = 0.71$). Reproductive parameters are presented in Table 3. Cows in both

Table 3
Reproductive parameters of dairy cows from both treatments.

	N[c]	HIPRO[a] LSM[d]	LOPRO[b] LSM[d]	SE[e]	P-values
Calving-to-first-insemination interval	138	66	63	2.4	0.18
Calving-to-conception interval	88	87	99	4.6	0.01
Calving interval	88	372	384	4.6	0.03
Insemination index	88	1.9	2.3	0.16	0.01

[a] High protein feeding treatment with an increased crude protein content (221 g/kg).
[b] Grassland-based milk and meat production scenario with a predefined maximum crude protein content of 12% (as-fed) in the concentrate.
[c] Total number of observations included; only complete pairs were considered in the analysis.
[d] Least-squares means.
[e] Standard error.

Table 2
Milk production and composition, body weight, and body condition scores by treatment during early, mid, and late lactation.

	Early HIPRO[1]	LOPRO[2]	Mid HIPRO[1]	LOPRO[2]	Late HIPRO[1]	LOPRO[2]	P-values treatment	Lact. stage[3]	Interaction
Milk yield (kg)	29.3[a]	27.9[b]	19.3[c]	19.3[c]	13.6[d]	13.7[d]	0.06	<0.001	<0.001
Standard error	0.34		0.33		0.34				
ECM (kg)[4]	28.5[a]	26.8[b]	18.6[c]	18.4[c]	14.4[d]	14.5[d]	0.01	<0.001	<0.001
Standard error	0.33		0.32		0.32				
Milk fat (g/kg)	40.0[b]	38.6[c]	39.3[bc]	38.6[c]	44.3[a]	44.5[a]	0.049	<0.001	<0.001
Standard error	0.48		0.47		0.47				
Milk protein (g/kg)	30.5[d]	30.9[cd]	31.5[bc]	31.5[b]	37.2[a]	37.2[a]	0.49	<0.001	0.26
Standard error	0.29		0.28		0.29				
Lactose (g/kg)	48.0[a]	47.8[a]	46.1[b]	46.2[b]	45.2[c]	45.0[c]	0.17	<0.001	0.03
Standard error	0.14		0.14		0.14				
Milk urea (mg/dL)	20.6[d]	16.1[e]	27.0[a]	26.2[ab]	24.2[bc]	24.2[c]	<0.001	<0.001	<0.001
Standard error	0.58		0.55		0.57				
Somatic cell counts (/mL)	59885[c]	72584[bc]	70906[bc]	74749[b]	122131[a]	123733[a]	0.14	<0.001	0.099
Standard error	6060		6525		11100				
Body weight (kg)	634[b]	629[b]	618[c]	622[c]	659[a]	664[a]	0.48	<0.001	<0.001
Standard error	6.9		6.9		6.9				
Body condition score	2.76[a]	2.74[ab]	2.69[bd]	2.69[cd]	2.75[ac]	2.77[a]	0.98	<0.001	0.48
Standard error	0.038		0.038		0.039				

Different superscripts within the same row indicate significant differences ($p < 0.05$).
[1] High protein feeding treatment with an increased crude protein content (221 g/kg).
[2] Grassland-based milk and meat production scenario with a predefined maximum crude protein content of 12% (as-fed) in the concentrate.
[3] Lactation stage.
[4] Energy-corrected milk yield.

treatments showed similar calving-to-first-insemination intervals. By contrast, the calving-to-conception interval and the calving interval were 12 days longer in cows under the LOPRO treatment compared with HIPRO. In addition, cows under LOPRO required 0.4 more inseminations per successful conception. Table 4 lists the number of health treatments per health disorder category. Pregnancy examinations are not included, as they do not constitute health treatments. In the LOPRO treatment, 101 pregnancy examinations were performed, compared with 107 in the HIPRO treatment ($p = 0.73$). There was no significant association between the experimental treatment and the number of health treatments ($p = 0.48$). The relative distribution of health treatments was similar between LOPRO and HIPRO ($p = 0.69$).

4. Discussion

This study aimed to evaluate the effects of a GMM scenario with markedly reduced CP content in concentrates on milk yield, BW, BCS, reproduction, and health treatments in dairy cows in a herbage-based, low-input feeding system. The goal of this proposed GMM scenario, with a maximum CP content of 12% in concentrates (as fed), would be to maintain a high proportion of fresh or preserved herbage—or even increase it—in the rations of cattle, sheep, and goats. This aligns with the vision of the Swiss Federal Council to feed ruminants predominantly on herbage, supplemented with by-products or former foodstuffs, thereby reducing feed–food competition (BLW et al., 2023). Furthermore, it is expected that protein self-sufficiency will increase and that N losses in ruminant production systems will be reduced.

4.1. Nutritive value of hay and grazed herbage

According to Agroscope (2021), a dietary ratio of 20 g CP per MJ NEL is considered balanced for milk production potential. When requirements for absorbable protein in the intestine are taken into account, the CP:NEL ratio increases moderately. Data from the Swiss Feed Database (Agroscope, 2016) indicate that fresh or preserved herbage typically contains between 19 and 35 g CP per MJ NEL, resulting in a protein supply that commonly exceeds the energy supply (Agroscope 2021). Consequently, a low-protein concentrate may be sufficient to supplement dairy cows in herbage-based feeding systems. In the present experiment, hay used during the winter feeding period exhibited an average CP:NEL ratio of 21 g/MJ, whereas grazed herbage during the summer feeding period averaged 29 g CP per MJ NEL. Consequently, a pronounced CP:NEL ratio shift between fresh pasture herbage and hay became apparent. Compared with the average hay values reported in a forage survey (n = 4332) for the corresponding experimental years (Graf and Manzocchi, 2025), the hay used in this study had numerically lower CP (−19 g/kg DM), lower energy concentration (−0.2 MJ NEL/kg DM), and consequently a lower CP:NEL ratio (−2.6 g/MJ NEL). This moderate hay quality can partly be attributed to restricted N fertilisation, as synthetic N fertilisers are banned in organic farming, as well as to the altitude of the forage conservation areas (900 to 1000 m a.s.l.) and a delayed harvest time (Buxton, 1996; Jeangros et al., 1999).

Considering that the pasture areas are between 800 and 900 m a.s.l., the nutritional quality of grazed herbage can, on average, be described as medium to good, according to Peyraud and Delagarde (2013), based on organic matter digestibility (76%). Based on the average CP concentration (178 ± 32.2 g CP/kg DM), the herbage falls between permanent, non-fertilised and fertilised grazed herbage, according to Keim et al. (2013). This classification reflects the actual conditions well, as the pasture consisted almost of long-established swards with a marginal N supply. The nutrient composition of forage, particularly CP concentration, is of critical importance in the LOPRO treatment group, as a sufficient protein supply must be provided. In the present study, the concentrate intake averaged 333 kg per cow per lactation, corresponding to approximately 5% of the annual ration, which represents the upper limit permitted under the organic guidelines of Bio Suisse (Bio Suisse, 2026).

Table 4
Number of health treatments by health disorder category and experimental treatment.

	HIPRO[a]	LOPRO[b]
Locomotor issues	2	6
Mastitis	12	10
Retained placenta	3	7
Reproductive issues	15	16
Metabolic disorders (predominantly milk fever)	11	12
Respiratory issues	1	1
Total	44	52

[a] High protein feeding treatment with an increased crude protein content (221 g/kg).
[b] Grassland-based milk and meat production scenario with a predefined maximum crude protein content of 12% (as-fed) in the concentrate.

4.2. Milk yield and composition

Changes over the course of lactation are not the primary focus of this study and are therefore not discussed in detail. The same applies to the interactions between concentrate feeding treatment and stage of lactation observed for several traits, which are largely driven by the concentrate allocation strategy. As expected, the most significant treatment effects (Table 1) occurred during early lactation. Three factors may have contributed to this result. First, concentrate intake was highest during this stage of lactation; consequently, the difference in CP supply between treatments was greatest during this period. Second, with a block calving pattern around mid to late winter, a substantial part of early lactation for the majority of cows coincided with the winter feeding period, when hay with, on average, a lower CP/NEL ratio (21 g/MJ) was offered. Based on the low milk urea concentration of the LOPRO cows (16.1 mg/dL), it can be assumed that the CP supply during early lactation was marginal and that further CP supplementation may improve milk yield. Glatz-Hoppe et al. (2020) reported the optimal range for milk urea concentration to be between 150 and 250 mg/L, with the highest milk yield observed in the 200–250 mg/L class. Zhao et al. (2025) observed a higher optimal range, namely between 21 and 34 mg milk urea per dL of milk, and values below this interval were associated with a low protein-to-energy ratio and poor production performance. Third, dairy cows in early lactation appear to be more responsive to dietary CP content in terms of milk production (Law et al., 2009a; Letelier et al., 2022).

The fact that the dietary CP content of rations, or increased protein supplementation, has a positive but curvilinear effect on milk yield has been demonstrated in review papers (Daniel et al., 2016; Zanton, 2016), long-term studies (Law et al., 2009a), and studies across different stages of lactation (Letelier et al., 2022). In our experiment, both actual and energy-corrected milk yields increased during early lactation. In mid-lactation, however, milk yield no longer differed between treatments, as substantially more protein was supplied through grazed herbage, and concentrate supplementation was reduced to only 1 kg per cow per day. At a dietary CP concentration between 15% and 16.5%, further increases in milk yield are often no longer observed (Olmos Colmenero and Broderick, 2006; Lavery et al., 2025). Many studies have recommended decreasing dietary protein content as lactation progresses (Wu and Satter, 2000; Law et al., 2009a; Letelier et al., 2022). In addition to CP content, other factors, such as the ruminal degradability of CP, the fermentable energy available to rumen microorganisms, and the amount and amino acid profile of intestinally available protein, may also affect milk yield, milk composition, and milk urea concentration in dairy cows (Nousiainen et al., 2004; Spek et al., 2013; Schwab and Broderick, 2017). The investigation of these factors was beyond the scope of this long-term study with grazing dairy cows.

Lactose content is hardly influenced by dairy cow feeding, except perhaps in cases of severe underfeeding (Sutton, 1989). As lactose largely determines milk volume (Sutton, 1989; Costa et al., 2019), it is not surprising that the lactose content did not differ between treatments in our study, as reported elsewhere (Law et al., 2009a; Daniel et al., 2016; Lavery et al., 2025). Although milk fat content may decrease in a curvilinear manner with increasing dietary CP or metabolisable protein content (Law et al., 2009a; Daniel et al., 2016), the milk fat content in our study was higher in the HIPRO treatment group, similar to the findings of M'Hamed et al. (2001). Daley et al. (2022) included methionine, histidine, and tryptophan in their model predicting milk fat content, but with opposite signs. Zanton (2016) found that only a small proportion of the variability in milk protein content ($R^2 < 0.15$) can be explained by dietary CP content, as found for milk fat content ($R^2 < 0.20$). Although milk protein content is expected to increase in a curvilinear manner with increasing dietary CP content (Daniel et al., 2016), many studies (Law et al., 2009a; Letelier et al., 2022), including ours, have reported no effect.

Milk urea N concentration is positively correlated with urinary N excretion (Nousiainen et al., 2004; Spek et al., 2013; Zhao et al., 2025). However, this relationship appears weaker in pasture-based feeding systems than in confinement systems (Mangwe et al., 2025). Nevertheless, lower milk urea N concentrations are generally associated with reduced urinary N excretion. Based on the equations of Jonker et al. (1998; using milk urea N as a predictor) and Beck et al. (2023; using milk urea N, dietary CP content, and BW as predictors), cows in the LOPRO treatment during early lactation were estimated to excrete approximately 25% less urinary N (−30 and −31 g/cow per day, respectively). This reduction represents a clear environmental benefit because urinary N excretion is a major source of N emissions (Dijkstra et al., 2013; Schrade et al., 2023).

4.3. Health and reproduction performance

As in other studies (Wu and Satter, 2000; Law et al., 2009a; Chowdhury et al., 2025), the protein supply within the investigated range had no effect on BW or BCS. More pronounced changes in the ration may be required for differences in BW and BCS to become evident in long-term studies. For example, Schori and Münger (2021) omitted 750 kg of concentrate per lactation and fed dairy cows an all-herbage ration, which resulted in differences in BW and BCS.

Divergences between the feeding treatments in reproductive parameters were not expected, as no relevant differences were observed in the BW, BCS, or health treatments. Moreover, the milk urea concentration in the LOPRO treatment was, on average, still within the recommended range (Glatz-Hoppe et al., 2020). In a previous experiment (Schori and Münger, 2021) with dairy cows fed an all-herbage ration without a concentrate supply, differences in reproductive parameters were observed only between cow types (Holstein cows of New Zealand or Swiss origin) and not between feeding treatments. The reproductive results should be interpreted with caution, as the number of experimental animals was relatively small for these parameters. Furthermore, only 44 complete experimental cow pairs were included in analysing the calving-to-conception interval, calving interval, and insemination index. However, statistical analyses that also included incomplete pairs yielded similar results (data not shown). Nevertheless, a shift of approximately half a cycle (12 d) or about 0.4 additional inseminations per conception would already be economically relevant in practice (González-Recio et al., 2004; Shalloo et al., 2014). According to Butler (1998), an excess of dietary CP, whether ruminally degradable or not, may reduce the fertility of high-yielding dairy cows. Furthermore, meta-analyses (Lean et al., 2012; Rodney et al., 2018) have suggested that both the amount and degradability of dietary CP are associated with reduced reproductive performance (conception risk and calving-to-pregnancy interval). However, low milk urea concentrations (≤15 mg/dl) were also associated with decreased conception success (Albaaj et al., 2017). Additionally, the relationship between dietary CP and reproduction in dairy cows appears to be influenced by the feeding system (total mixed rations vs. grazing; Berry et al., 2016). Overall, the relationship between dietary protein supply and reproduction is complex, context-dependent, and potentially confounded by other factors (Lean et al., 2012). It should also be noted that amino acids are essential for reproduction (NASEM, 2021) and that CP levels around 14–15% of DM may have no detrimental effect on cow reproduction (Sinclair et al., 2014). Nevertheless, greater attention is needed to assess reproductive performance in lower-protein diets for dairy cows (NASEM, 2021), particularly in low-protein, forage-rich diets.

The feeding treatment LOPRO does not appear to adversely affect the number of health treatments compared with HIPRO. Similarly, no differences were observed in somatic cell count, which serves as an indicator of udder health. Sinclair et al. (2014) reported that neither pre- nor post-partum protein nutrition has a major effect on somatic cell counts, the incidence of mastitis, or other diseases. Other studies that examined different levels of protein supply also found no differences in health parameters (Zang et al., 2021; Wu and Satter, 2000). However, in a long-term experiment conducted over three lactations with three dietary protein levels (14%, 16%, and 18%), veterinary and medication costs, as well as replacement costs, were highest in the treatment with the lowest dietary CP content (Reynolds, 2019). An earlier study reported a higher risk of retained placenta and uncomplicated ketosis associated with lower dietary CP content during the last three weeks of the dry period (Curtis et al., 1985). In a study by Law et al. (2009b), more treatments for metritis were required in the cow group with the lowest dietary CP concentration. Moreover, retained placenta appears to be a risk factor for metritis (Curtis et al., 1985). The absence of marked differences in health treatments in our study may be explained by the fact that the relevant differences in dietary protein concentration occurred only during the early phase of the experiment and amounted to approximately one percentage point of dietary CP.

5. Conclusion

Low dietary CP rations are increasingly popular, as they generally reduce N excretion in faeces and urine. Replacing a protein-enriched concentrate supplement with one without additional protein already led to reductions in performance in a herbage-based, low-input feeding system—possibly due to the low CP content of the hay used in early lactation. Interestingly, fertility also appeared to be impaired under the low-protein treatment. By contrast, no differences were observed in the health treatments. The effects of low-protein rations on health and fertility should be investigated further on a larger scale, including in low-input feeding systems. It appears that the restriction imposed by the new GMM scenario may also be too severe for herbage-based feeding systems. Finally, a compromise must be reached between the different interests of economic efficiency, environmental sustainability, animal welfare, and the provision of food for humans.

Data statement

Data are available from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Fredy Schori: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Münger:** Writing – review & editing, Conceptualization. **Frigga Dohme-Meier:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest.

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