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Linking post-grazing sward height to sward structure and harvest dynamics in dairy systems

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Abstract

Background

The post-grazing residual state governs the leaf area left after defoliation and the herbage available at the next grazing, but how it shapes sward structure and the allocation of herbage within the grazing cycle of supplemented dairy systems is poorly documented. In a three-year experiment with four farmlets – a low (LR, 6–7 cm target) and a high (HR, 9–10 cm target) post-grazing residual at each of two stocking rates – we evaluated how the post-grazing sward height affects the sward at grazing, regrowth, herbage allocation, and animal and whole-system responses. Inference focused on August–December, the spring growth period, when grazing contributes most to the diet and the achieved post-grazing heights differed. Treatment effects were tested between paddock halves for the sward variables and between farmlet-years for the herd, animal and grazing-area variables.

Results

values are given as HR vs LR. HR left a higher post-grazing sward height than LR (10.0 vs 7.8 cm; $P < 0.001$) and a less severe defoliation (66.8 vs 74.7% of sward height removed per grazing event; $P < 0.001$), whereas pre-grazing sward height did not differ ($P = 0.78$). HR offered more herbage per cow (21.7 vs 19.2 kg DM/cow/d; $P = 0.007$) and its cows consumed more conserved forage (3.35 vs 2.58 kg DM/cow/d; $P = 0.007$), with no significant difference in herbage dry matter intake ($P = 0.15$). Herbage growth rate was lower under HR (25.3 vs 29.7 kg DM/ha/d; $P = 0.045$). No treatment differences were detected in average grazing-area herbage mass, NDVI, the interval between successive grazings, milk yield per cow (20.9 vs 20.5 L/cow/d) or per hectare, milk composition, body condition score or live weight; with two farmlets per treatment these are absences of evidence rather than evidence of equivalence.

Conclusions

Despite a moderate contrast in post-grazing sward height, the higher target resulted in less severe defoliation, a larger herbage allowance and a greater use of conserved forage. The post-grazing residual thus acted on how herbage was allocated within the grazing cycle, without detectable change in the sward offered at the next grazing.

Background

Pasture-based dairy systems rely on efficient grazing management to optimize forage utilization, sustain pasture productivity, and maintain high levels of animal performance. In these systems, grazing management determines the balance between forage production and herbage intake, thereby influencing both pasture productivity and milk production. Consequently, management decisions regarding grazing

intensity and defoliation frequency play a central role in regulating plant growth processes and animal responses [1, 2].

Among the indicators used to control grazing intensity, the post-grazing sward height determines the leaf area remaining after defoliation and therefore strongly influences canopy light interception, photosynthetic capacity, and the rate of regrowth [3, 4]. Post-grazing sward height is widely recognized as a practical and reliable tool to manage sward state. Maintaining adequate residuals is critical: too severe defoliation may reduce carbohydrate reserves and delay recovery, whereas too high residuals decrease grazing efficiency and promote accumulation of senescent material in the lower canopy [5, 6].

Grazing intensity also affects the structure of the sward canopy and therefore grazing behavior and intake. Residual height determines the vertical distribution of leaves and consequently affects bite mass, intake rate, and total dry matter intake [1, 7, 8]. Lower residuals can increase pasture utilization and herbage harvested per unit area, but may compromise animal performance if excessive defoliation reduces intake or quality [6, 9]. Conversely, higher residuals may increase individual intake and milk production per cow but can reduce utilization efficiency and production per hectare [10, 11].

These responses reflect the fundamental trade-off between individual animal performance and production per unit of land, a central challenge in pasture-based dairy systems. Strategies that increase grazing intensity may raise stocking rate and utilization, whereas more lenient grazing may improve individual intake and animal performance [6, 10–12]. At a given stocking rate, grazing intensity and the residual achieved are closely associated with the level of supplementation. Supplementation with conserved forages is a key driver to sustain animal performance and stabilize milk production, but may alter grazing behavior and induce substitution effects that reduce pasture intake [6, 13].

The optimal post-grazing sward height varies with pasture species, sward composition, environmental conditions and system objectives, and the existing evidence remains fragmentary for the systems that matter most in practice. Few long-term experiments have evaluated contrasting post-grazing sward heights on pasture dynamics and whole-system productivity under commercial conditions, and fewer still on diverse, multi-species forage bases where grazing is combined with conserved-forage and concentrate supplementation [6, 9, 10, 12]. Most of this evidence, moreover, describes the residual through annual or whole-period means, which leaves unresolved when during the year, and through which steps of the grazing cycle, the post-grazing sward height acts.

The objective of this study was to examine how two contrasting post-grazing sward heights modify the state of the sward at grazing, its regrowth, and the allocation and harvest of herbage in supplemented dairy farmlets, at monthly resolution and during the spring growth period, when grazing contributes most to the diet and control of the post-grazing sward height is most demanding; and whether these within-cycle differences were carried over to animal and whole-system responses. We hypothesized that a higher post-grazing residual would reduce defoliation severity and increase the herbage offered per cow, and examined whether it would also modify the state of the sward at the next grazing.

Methods

Study site and treatment description

The study was conducted at the dairy unit of the Centro Regional Sur research station, School of Agronomy, Universidad de la República (34°36.810' S, 56°13.088' W), as part of a larger trial reported by Ortega et al. [14]. In that study the four combinations of stocking rate and residual height were compared as whole production systems on an annual basis; Additional file 1 gives, for every response variable, the scale and frequency at which it was recorded, the years covered, and whether it was measured or derived, and whether it was reported there as an annual mean. The experimental period spanned from June 2016 to December 2019. A total of 56 ha (16 ha per farmlet at 1.5 cows/ha and 12 ha per farmlet at 2.0 cows/ha) and 96 Holstein-Jersey crossbred cows were assigned to four treatments by parity (2.3 ± 1.3), body weight (534 ± 83 kg) and body condition score at calving (3.4 ± 0.45), in a factorial combination of two stocking rates (1.5 or 2.0 lactating cows/ha) and two post-grazing sward heights. The grazing area comprised nine paddocks, five at 1.5 cows/ha and four at 2.0 cows/ha, giving 16 ha per farmlet at the lower and 12 ha at the higher stocking rate, each grazed by 24 cows. Each paddock was split in half and the two halves were randomly allocated, one to the low-residual and one to the high-residual system of that stocking rate. Each forage resource occupied a pair of paddocks, one at each stocking rate — the fifth paddock at 1.5 cows/ha being an additional perennial pasture — so that every component of the forage rotation was present in all four systems, and the rotation advanced synchronously across them. The two treatments (HR and LR) were therefore interspersed across the whole grazing area rather than segregated in separate parts of it. The two treatments contrasted grazing intensity through the post-grazing sward height they maintained. Nominal residual-height targets were as reported in the parent trial [14]: a conventional target of 6–7 cm maintained year-round under LR, and a more lenient target averaging 9–10 cm year-round under HR. During August–December, the period analysed here, the achieved post-grazing sward heights averaged 7.8 cm under LR and 10.0 cm under HR (Table 1). This study focuses on the effect of the post-grazing sward height; both stocking rates were retained in the analysis as a blocking factor (24 cows per farmlet, 48 cows per treatment).

Table 1
Sward state at grazing under low (LR) and high (HR) post-grazing residual, August–December.

Item	LR	HR	HR − LR (95% CI)	Treatment P	Month P	T × M P
Pre-grazing sward height, cm	32.3	32.0	−0.3 (− 2.5; 1.9)	0.778	0.005	0.664
Post-grazing sward height, cm	7.8	10.0	2.2 (1.4; 3.0)	< 0.001	0.517	0.298
Pre-grazing herbage mass, kg DM/ha	2533	2522	−11 (− 98; 75)	0.778	0.005	0.664
Post-grazing herbage mass, kg DM/ha	1580	1665	86 (54; 117)	< 0.001	0.517	0.298
Defoliation severity, %	74.7	66.8	−7.9 (− 11.1; −4.8)	< 0.001	0.073	0.054
Leaf number at grazing	3.42	3.36	−0.07 (− 0.24; 0.11)	0.400	0.026	0.455

LR = low residual; HR = high residual. Values are estimated marginal means; HR − LR = estimated difference between treatments with its 95% confidence interval. Treatment P = P-value of the treatment effect (HR vs LR) from the model; Month P and T × M P = P-values of the month effect and of the treatment × month interaction.

Forage base

The grazing area consisted of a structured four-year forage rotation representative of Uruguayan pasture-based dairy systems, combining annual forage crops (*Avena sativa*, *Lolium multiflorum*, *Sorghum bicolor*) and three-year mixed perennial pastures (*Dactylis glomerata* and *Trifolium repens, or Medicago sativa and Bromus catharticus*). Each autumn, 50% of the grazing area was resown (half perennial pasture, half annual crops). Nitrogen was applied after each grazing between July and November as urea (46-0-0) at 75–100 kg/ha per application (four applications per paddock per year). A starter fertilizer (7-40-0) supplied 7.5 kg N/ha and 43 kg P/ha at sowing; subsequent P was adjusted to soil Bray P (minimum 12 mg/kg for grass pastures).

Grazing and feeding management

Cows were rotationally strip-grazed, with new strips allocated after each milking. Grazing rules aimed to align daily intake with average pasture growth rate and to maintain an average herbage mass on grazing area of about 1800 kg DM/ha, estimated by the comparative-yield method [15]. Cows had access to grazing once or twice daily depending on average herbage mass and expected herbage growth rate *(net herbage accumulation rate, estimated from the change in herbage mass between successive measurements)*. When herbage mass or growth rate were insufficient, cows were supplemented with

silage (sorghum or maize) on a feeding pad using a weighing mixer wagon; these reserves were sourced from land outside the grazing area. When herbage mass or growth rate exceeded demand, surplus forage was mechanically harvested and conserved as haylage. After the feed pad, cows moved to 2-ha resting paddocks with water, where haylage bales were offered in case cows needed. The phenological stage of grasses was monitored weekly (number of expanded leaves) [5], complementing herbage-mass data to define grazing intervals (target of two to three expanded leaves for grasses). In January and February the 96 cows grazed as a single herd over the whole experimental area (56 ha), so the overall stocking rate and the grazing criteria of each paddock were maintained, but the stocking-rate contrast was suspended until March, when the cows returned to their farmlets.

The grazing cycle was characterized from the paddock records as the sum of the occupation period and the subsequent regrowth interval. Because herbage mass is estimated at two scales - on the individual strip immediately before and after grazing, and on the whole paddock along a weekly transect - the two are reported separately and are not used interchangeably: the strip estimate refers to the portion of sward actually offered, whereas the paddock estimate averages the spatial heterogeneity of the paddock.

Pasture and grazing-area determination

Every fortnight the comparative-yield method was used to calibrate visual estimates in each paddock (five categories, three replicates each; 0.51 x 0.30 m quadrats, five height measurements and ground-level harvest, dried at 60°C for 48 h). Calibration equations relating rating, sward height and dry-matter yield were then used weekly, along fixed transects (at least 20 determinations/paddock by the same trained observer), to estimate herbage mass and growth rate for each paddock. Pre- and post-grazing sward heights were recorded before and after each grazing strip (about 30 measurements per strip). Pre-grazing dates per paddock were recorded, enabling the grazed area per day (ha/d). NDVI was derived from Sentinel-2 imagery for the paddocks in the grazing rotation. To estimate the average herbage mass of the grazing area from NDVI, paddock NDVI was calibrated against the herbage mass of the same paddocks from the double-sampling assessment (paddocks in the rotation, excluding those being grazed or recorded as post-grazing residual): herbage mass, kg DM/ha = 717 + 1,389 × NDVI ($n = 498$; $R^2 = 0.20$; RMSE = 401 kg DM/ha; RMSE = 412 kg DM/ha when each year was predicted from the other two). Paddock NDVI was converted to herbage mass with this calibration, and NDVI-estimated average herbage mass was computed in the same way as the ground estimate, as the area-weighted mean of the paddocks in the grazing area. The two estimates were compared on the monthly means of each farmlet and year. Strip-level pre- and post-grazing records were available for 2017 and 2018; paddock-scale, feeding and animal records cover 2017–2019. Grazing-area variables (herbage growth rate, leaf number, NDVI, NDVI-estimated average herbage mass and the interval between successive grazings) were computed on the paddocks in the grazing area, excluding paddocks in fallow, destined for conserved forage or in transition between crops. The share of the farmlet area destined for conserved forage was computed from the same weekly paddock census.

Strip herbage mass is a derived quantity, obtained by applying a linear height-mass function to the mean sward height of each strip (herbage mass, kg DM/ha = 1,276 + 38.9 x sward height, cm). The same function was applied to pre- and post-grazing heights, so that the derived disappearance depends only on its slope. The function is anchored to the paddock-scale comparative-yield system, with which it is consistent in standing herbage mass (mean grazing-area herbage mass 1,825 kg DM/ha; n = 1,638 paddock-week records).

Defoliation severity was computed for each strip as 100 x (pre-grazing height - post-grazing height) / pre-grazing height. Being the ratio of two directly measured heights, it is independent of the height-mass calibration and provides a measure of grazing intensity that does not inherit calibration uncertainty.

Individual feed-intake components

Herbage allowance and herbage dry-matter intake (HDMI) are derived quantities, calculated daily for each farmlet from the grazing records, as in Ortega et al. [14]. Herbage allowance was the herbage mass on offer multiplied by the area allocated and divided by the number of cows. HDMI was estimated from pasture disappearance, as the difference between the pre- and post-grazing herbage mass of each daily strip, multiplied by the strip area and divided by the number of grazing cows; pre- and post-grazing herbage mass were estimated in each strip and calibrated against the paddock comparative-yield system [15]. Silage intake was recorded daily by weighing refusals on the mixer wagon; haylage and hay intake were estimated from bale weights and a visual quarter-scale. Total conserved-forage intake was the sum of silage, hay and haylage. Concentrate intake equalled the amount delivered by the automatic feeders (seasonal concentrate of 7.0, 5.0 and 3.0 kg DM/cow/d), following the forage-growth curve and the lactation curve of autumn-calving cows.

Animal measurements

Individual milk yield was recorded fortnightly; fat and protein were measured on morning and evening milkings and milk-solids yield estimated. Body weight and body condition score [16] were recorded monthly. The number of daily grazing shifts (0, 1 or 2) was recorded for every grazing event over the year.

Statistical analysis

All analyses were performed in R v4.3.2 [17] with the lme4 [18], lmerTest [19], emmeans [20] and ordinal [21] packages; figures were drawn with ggplot2 [22].

The experiment was a 2 × 2 factorial of post-grazing sward height (LR, HR) and stocking rate (1.5 and 2.0 cows/ha), with one farmlet per combination. The factorial structure of the experiment, including the residual × stocking-rate interaction, was analysed by Ortega et al. [14]; in the present framing stocking rate blocks the treatment comparison, so the interaction is not revisited here. Randomisation operated at two levels. Each of the nine paddocks was divided into two halves, and the halves were randomly allocated, one to the LR and one to the HR farmlet of the same stocking rate, so that the treatment

comparison is made within paddock, between neighbouring halves that carry the same forage resource on the same soil. Cows were allocated to farmlets within blocks defined by parity, calving date, live weight and body condition at calving, cows that remained in the experiment were re-randomised each March, and the heifers that entered each year to replace culled cows (about 20% of the herd) were allocated to the four farmlets by the same criteria. Responses were recorded at two scales: on the grazed strip, where post-grazing sward height target was applied, and on the grazing area of the farmlet as a whole. Each response was tested against the variation appropriate to its scale — between paddock halves for the strip-scale sward variables, and between farmlet-years for the herd, animal, grazing-area and whole-system variables, which are properties of the farmlet and not of any paddock within it.

The design imposed two contrasting post-grazing sward heights, but the contrast was not achieved uniformly through the year. From March to July the monthly difference in achieved post-grazing sward height was below 1 cm (0.3–0.95 cm), so over that period the two treatments were not effectively contrasting; from August to December it was 1.1–3.2 cm, with 71–225 grazed strips per treatment and month. Inference was therefore restricted to August–December, the period over which the treatment was actually expressed, which coincides with the spring growth period, when grazing contributes most to the diet (herbage was on average 59% of the dry-matter intake, against 45% in the rest of the year) and control of the post-grazing sward height is most demanding. This restriction was defined on the manipulated variable, the achieved post-grazing sward height, and not on the response variables. Annual dynamics are shown in the figures but were not tested.

Three models were used, one for each scale of measurement. Sward variables recorded on the grazed strip were analysed with Eq. 1, fitted to the individual grazing events:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_s + u_k + b_r + p_l + \varepsilon_{ijkl} \qquad (1)$$

where Y_{ijkl} is the value recorded on one strip, i.e. one daily grazing event, in month j (j = August to December) of year k on paddock half l; μ is the overall mean; α_i is the fixed effect of treatment (i = LR, HR), β_j the fixed effect of month and $(\alpha\beta)_{ij}$ their interaction; γ_s is the stocking-rate block (s = 1.5, 2.0 cows/ha); $u_k \sim N(0, \sigma^2_{year})$ is the random effect of year (k = 2017–2018 for strip records); $b_r \sim N(0, \sigma^2_{resource})$ is the forage resource, which accounts for differences in sward height and structure among *Avena–Lolium*, *Medicago–Bromus* and first- to third-year *Dactylis–Trifolium* pastures; $p_l \sim N(0, \sigma^2_{paddock})$ is the paddock half; and ε_{ijkl} is the residual, which contains the variation among strips, and therefore among grazing days, within a paddock half. Measurements were taken on the strips, but the unit of replication for the treatment is the paddock half: each paddock was split in two and the halves were randomly allocated to LR and HR, so the treatment effect is a contrast between paddock halves and is tested against $\sigma^2_{paddock}$ (7 to 11 denominator degrees of freedom), not against the variation among strips. Each paddock half was coded by paddock and farmlet, because the two halves of a paddock share its name. Month and the treatment × month interaction describe how each farmlet changed through the season, not how a single paddock changed, because each paddock was grazed only at

certain points of the rotation; they were therefore tested in a separate model fitted to the monthly means of each farmlet and year, with farmlet within year as a random effect.

Responses recorded on the animal group and those recorded on individual cows were analysed with Eq. 2:

$$Y = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_s + u_k + g_{ks} + (g\beta)_{ksj} + b_r + c_p + \varepsilon \qquad (2)$$

where the fixed effects and the year term are as in Eq. 1; $g_{ks} \sim N(0, \sigma^2_{farmlet})$ is the farmlet within year, the experimental unit against which the treatment is tested; $(g\beta)_{ksj} \sim N(0, \sigma^2_{farmlet\text{-}month})$ is the farmlet × month term, the error stratum for the treatment × month interaction; b_r is the animal block defined above; and $c_p \sim N(0, \sigma^2_{cow})$ the individual cow, crossed with the treatment because cows were re-randomised each year. Milk yield and composition, body condition score and live weight were recorded on individual cows, but the treatment was tested between farmlet-years, the cow entering only as a random effect. Variables offered to the whole herd — herbage, conserved forage and concentrate allowance and intake, and the number of daily grazing shifts — have no individual record; they were aggregated to the farmlet-year-month level and retained only year and farmlet within year as random terms. The daily number of grazing shifts is an ordinal response (0, 1 or 2 per day); its proportions are shown descriptively, and the treatment effect on its distribution was tested with a cumulative-link mixed model on the daily records, with year and farmlet within year as random effects [21].

Variables describing the grazing area as a whole, and the whole-system totals per hectare, were analysed with Eq. 3, on one value per farmlet and year:

$$Y_{isk} = \mu + \alpha_i + \gamma_s + u_k + \varepsilon_{isk} \qquad (3)$$

where Y_{isk} is the August–December mean, or total, of the farmlet with treatment *i* and stocking rate *s* in year *k* (*k* = 2017–2019); $u_k \sim N(0, \sigma^2_{year})$ is the year effect; and ε_{isk} is the between-farmlet-year residual against which the treatment is tested. Eq. 3 contains no month term, because each farmlet-year contributes a single August–December value. The month effect and the treatment × month interaction reported for the grazing-area variables (Table 2) were therefore tested separately, as for Eq. 1, in a model fitted to the monthly means of each farmlet and year, with farmlet within year as a random effect; the per-hectare totals have a single value per farmlet-year and therefore no month terms. Whole-system responses per hectare (milk and milk-solids yield, forage production, directly harvested herbage, conserved forage and concentrate) were computed as August–December totals per farmlet-year: the mean daily value per cow multiplied by the number of cows per hectare and by 153 days or, for forage production, the mean daily growth rate multiplied by 153 days.

Table 2
Herbage regrowth and grazing-area variables under LR and HR, August–December.

Item	LR	HR	HR − LR (95% CI)	Treatment P	Month P	T × M P
Herbage growth rate, kg DM/ha/d	29.7	25.3	−4.4 (− 8.7; −0.1)	0.045	0.002	0.935
Grazing-area herbage mass, kg DM/ha	1791	1840	49 (− 17; 115)	0.123	< 0.001	0.921
NDVI-estimated average herbage mass, kg DM/ha[d]	1780	1780	0 (− 16; 16)	0.979	< 0.001	0.831
NDVI	0.764	0.764	0.001 (− 0.016; 0.017)	0.904	< 0.001	0.682
Grazing-area leaf number	2.16	2.10	−0.06 (− 0.17; 0.06)	0.274	< 0.001	0.931
Interval between successive grazings	28.4	27.3	−1.0 (− 5.5; 3.4)	0.613	< 0.001	0.077

LR = low residual; HR = high residual. Values are estimated marginal means; HR − LR = estimated difference between treatments with its 95% confidence interval. Treatment P = P-value of the treatment effect (HR vs LR) from the model; Month P and T × M P = P-values of the month effect and of the treatment × month interaction.

For each variable we report the estimated marginal means of LR and HR, their difference (HR − LR) with its 95% confidence interval, and the P-values of the fixed effects, with denominator degrees of freedom approximated by the Satterthwaite method [19, 20]. Multiplicity was limited by restricting inference to a single period and by testing only the treatment effect and the treatment × month interaction. A treatment effect was considered significant when $P < 0.05$. Month-by-month comparisons were not tested, because no treatment × month interaction was significant; the monthly patterns in the figures are therefore descriptive. The treatment effect must be tested against the variation between farmlet-years, the experimental unit. For five responses the model estimated this variation as zero, so the treatment would have been tested against the variation among months or cows, overstating the precision of the comparison. For these responses we therefore averaged the data to one value per farmlet-year and tested the treatment on those means; they are marked with superscript b in the tables. The residuals of every model were examined for normality, with quantile plots and the Shapiro–Wilk test, and for homogeneity of variance, with residual-versus-fitted plots. Residuals departed from normality only in the tails; outlying observations (standardised residual beyond ± 4) were at most 0.9% of the records of any response, and removing them changed no conclusion. A first-order autoregressive correlation among months was weak (median 0.24 across 25 responses); although it improved the fit by more than two AIC units in seven responses, it did not change the treatment conclusions, so the simpler structure was retained.

Results

Results are presented for August–December (Tables 1–4); the monthly dynamics over the year are shown in Figs. 1–5. Treatment means are given throughout as HR vs LR, and the difference as HR − LR; the tables list LR and HR in separate columns. Annual values of the variables common to both articles were reported by Ortega et al. [14] and are not repeated here.

Table 4
Animal and whole-system responses under LR and HR, August–December.

Item	LR	HR	HR − LR (95% CI)	Treatment P	Month P	T × M P
Milk yield, L/cow/d	20.5	20.9	0.4 (− 1.7; 2.4)	0.704	< 0.001	0.780
Milk solids, kg/cow/d	1.61	1.64	0.03 (− 0.10; 0.16)	0.584	< 0.001	0.810
Milk fat, %	4.28	4.24	−0.04 (− 0.17; 0.09)	0.521	0.021	0.818
Milk protein, %	3.58	3.62	0.04 (− 0.04; 0.12)	0.315	0.104	0.921
Body condition score (1–5)	2.90	2.93	0.03 (− 0.06; 0.11)	0.455	< 0.001	0.793
Live weight, kg	512	506	−7 (− 17; 4)	0.164	< 0.001	0.658
Milk yield, L/ha	5562	5643	81 (− 400; 562)	0.702	–	–
Milk solids, kg/ha	436	444	8 (− 20; 36)	0.531	–	–
Forage production, kg DM/ha	4549	3874	−674 (− 1328; −21)	0.045	–	–
Directly harvested herbage, kg DM/ha	2850	3034	183 (− 155; 521)	0.241	–	–
Conserved forage, kg DM/ha	705	901	196 (35; 357)	0.024	–	–
Concentrate, kg DM/ha	1259	1254	−5 (− 32; 22)	0.675	–	–

LR = low residual; HR = high residual. Values are estimated marginal means; HR − LR = estimated difference between treatments with its 95% confidence interval. Treatment P = P-value of the treatment effect (HR vs LR) from the model; Month P and T × M P = P-values of the month effect and of the treatment × month interaction.

Sward state at grazing

In August–December, HR left a higher post-grazing sward height than LR (10.0 vs 7.8 cm; difference 2.2 cm, 95% CI 1.4 to 3.0; P < 0.001) and, consequently, a higher post-grazing herbage mass (1665 vs 1580 kg DM/ha; difference 86 kg DM/ha, 95% CI 54 to 117; P < 0.001; Table 1, Fig. 1b). Defoliation severity, which does not depend on the height–mass function, was 7.9 percentage points lower under HR (66.8 vs 74.7% of sward height removed; 95% CI of the difference − 11.1 to − 4.8; P < 0.001; Fig. 1c). The sward offered at grazing did not differ between treatments: pre-grazing sward height was 32.0 cm under HR and 32.3 cm under LR (P = 0.78; Fig. 1a), and neither pre-grazing herbage mass (P = 0.78) nor leaf number at grazing (3.36 vs 3.42; P = 0.40) differed. No treatment × month interaction was significant for the strip variables, the closest being defoliation severity (P = 0.054).

Herbage regrowth and grazing area

Herbage growth rate was lower under HR than under LR (25.3 vs 29.7 kg DM/ha/d; difference − 4.4 kg DM/ha/d, 95% CI − 8.7 to − 0.1; P = 0.045; Table 2, Fig. 2a). Growth rate was computed on the paddocks in rotation and therefore describes the regrowth of the grazed area rather than the herbage production of the whole farmlet: in summer it was driven mainly by *Medicago* and *Dactylis* pastures, since summer forage crops were excluded, whereas in September–October 12–17% of the farmlet area was destined for conserved forage and did not enter the calculation (Fig. 2d). The share of the farmlet area destined for conserved forage in August–December did not differ between treatments (6.8 vs 8.4%; difference − 1.7 percentage points, 95% CI − 6.2 to 2.9; P = 0.42; Fig. 2d). No treatment differences were detected in grazing-area herbage mass (1840 vs 1791 kg DM/ha; P = 0.12; Fig. 2b), NDVI (P = 0.90), NDVI-estimated average herbage mass (P = 0.98; Fig. 2c), grazing-area leaf number (P = 0.27) or the mean interval between successive grazings (27.3 vs 28.4 d; P = 0.61). No treatment × month interaction was significant for these variables (P ≥ 0.077). Average herbage mass estimated from NDVI matched the ground estimate on average (mean difference − 45 kg DM/ha in August–December; root-mean-square difference 211 kg DM/ha) but followed its month-to-month variation only loosely (r = 0.39).

Herbage allocation and intake

The higher post-grazing height (HR) provided more herbage per cow than LR (21.7 vs 19.2 kg DM/cow/d; difference 2.5, 95% CI 0.9 to 4.0; P = 0.007; Table 3, Fig. 3a), and its cows consumed more conserved forage (3.35 vs 2.58 kg DM/cow/d; difference 0.77, 95% CI 0.29 to 1.25; P = 0.007; Fig. 3c). HDMI did not differ significantly (11.4 vs 10.6 kg DM/cow/d; 95% CI of the difference − 0.3 to 1.9; P = 0.15; Fig. 3b), nor did concentrate offered (P = 0.56; Fig. 3d). The proportion of days with two grazing shifts was 0.64 in LR and 0.57 in HR (P = 0.060; Fig. 4b). For the interval between successive grazings, the treatment × month interaction was also not significant (P = 0.077; Fig. 4a).

Table 3
Herbage allocation, intake and grazing shifts under LR and HR, August–December.

Item	LR	HR	HR − LR (95% CI)	Treatment P	Month P	T × M P
Herbage allowance, kg DM/cow/d	19.2	21.7	2.5 (0.9; 4.0)	0.007	< 0.001	0.396
Herbage intake, kg DM/cow/d	10.6	11.4	0.8 (− 0.3; 1.9)	0.149	< 0.001	0.659
Conserved forage intake, kg DM/cow/d	2.58	3.35	0.77 (0.29; 1.25)	0.007	< 0.001	0.941
Concentrate offered, kg DM/cow/d	4.70	4.68	−0.02 (− 0.11; 0.06)	0.562	< 0.001	0.998
Days with no grazing shift, proportion	0.12	0.12	−0.00 (− 0.04; 0.04)	–	–	–
Days with one grazing shift, proportion	0.24	0.31	0.07 (− 0.03; 0.18)	–	–	–
Days with two grazing shifts, proportion	0.64	0.57	−0.07 (− 0.17; 0.02)	–	–	–

LR = low residual; HR = high residual. Values are estimated marginal means; HR − LR = estimated difference between treatments with its 95% confidence interval. Treatment P = P-value of the treatment effect (HR vs LR) from the model; Month P and T × M P = P-values of the month effect and of the treatment × month interaction.

Animal and whole-system responses

No treatment differences were detected in milk yield per cow (20.9 vs 20.5 L/cow/d; difference 0.4 L/cow/d, 95% CI − 1.7 to 2.4; P = 0.70; Table 4, Fig. 5), milk-solids yield (P = 0.58), milk fat (P = 0.52) or protein concentration (P = 0.32), body condition score (P = 0.46) or live weight (P = 0.16). Per hectare, neither milk yield (5643 vs 5562 L/ha; difference 81 L/ha, 95% CI − 400 to 562; P = 0.70) nor milk-solids yield (P = 0.53) differed. HR used more conserved forage per hectare (901 vs 705 kg DM/ha; P = 0.024), consistent with its greater conserved-forage intake per cow, and produced less herbage (3874 vs 4549 kg DM/ha; P = 0.045), the latter being the accumulated growth rate reported above. Directly harvested herbage (P = 0.24) and concentrate per hectare (P = 0.68) did not differ.

Discussion

The two treatments differed in how the sward was left after grazing, but no difference was detected in the state in which it was found at the next grazing. HR left about 2 cm more post-grazing sward height and a defoliation about 8 percentage points less severe, and this was sustained with a larger herbage allowance per cow; the pre-grazing sward height and herbage mass, grazing-area herbage mass, NDVI and leaf number did not differ (Tables 1 and 2). The contrast in post-grazing sward height was therefore

created at every grazing event and appears to have been absorbed during regrowth. These differences were detected with the paddock half as the unit of replication for the sward variables and the farmlet-year for the herd and animal variables; no treatment × month interaction was significant once each was tested at the level at which it operates, so the monthly patterns are interpreted here only descriptively.

This pattern - sward height regulating the state of the sward and the amount of herbage on offer, but without a detectable effect on the state of the sward at the next grazing - is consistent with the principle that above a non-limiting residual leaf area index, light interception and regrowth are already near-maximal [2, 5, 23]. We interpret the convergence of the pre-grazing state as indicating that the LR residual (7.8 cm; about 1580 kg DM/ha post-grazing) still left a non-limiting residual leaf area, although leaf area was not measured. Consistent with this, short-term ryegrass regrowth is governed by the residual leaf area retained rather than by defoliation severity once a minimum residual leaf area is present [24].

The lower herbage growth rate estimated under HR ($P = 0.045$) should be interpreted cautiously. Herbage growth rate was estimated on the ungrazed paddocks of the rotation, whose number and state may differ between treatments because of the contrasting grazing intensity, which may have biased the estimates [25, 26]. Just as importantly, a growth rate derived from the change in herbage mass measures net herbage accumulation (gross tissue production minus senescence) rather than gross growth. One possible explanation, which we could not test because tissue turnover was not measured, is that the taller sward and larger standing herbage mass under HR sustain greater tissue turnover and senescence, so that a larger share of gross production is lost to death and less is captured as an increase in standing herbage mass [4, 26]. This is consistent with net herbage accumulation becoming relatively insensitive to - or even declining with - increasing sward mass, as gross growth plateaus once light interception is near-complete while senescence continues to rise [2, 23]. It would therefore be premature to read the difference as a physiological advantage of the more severe defoliation.

Two estimates of herbage mass were available in this study and they describe different objects. The strip is the fresh, ungrazed portion selected for allocation on a given day, so its pre-grazing height represents the local maximum of the sward, whereas the weekly comparative-yield transect averages the whole paddock, including short and rejected patches [15]; the strip estimate is therefore necessarily the higher of the two. Strip-scale herbage mass is accordingly reported as a derived index anchored to the paddock-scale system, alongside post-grazing sward height and defoliation severity, which are independent of any calibration. At the scale of the grazing area, average herbage mass is the variable against which grazing is managed, here a target band of 1700–1900 kg DM/ha. Neither NDVI nor NDVI-estimated average herbage mass differed between treatments (Table 2), consistent with the convergence of the sward between grazings observed at strip scale. With a calibration built from the frequent paddock records of the system itself, NDVI reproduced the level of average herbage mass at low cost but compressed its variation: it dampened the spring peak (Fig. 2b, c), and half of the NDVI estimates in August–December fell within the target band, against about one third of the ground assessments, so NDVI would under-signal departures from the target. NDVI is closely related to the

radiation absorbed by the canopy [27] and has been used to monitor forage production for grazing decisions [28], but it saturates in dense canopies and its relationship with herbage mass varies with season and forage resource [29, 30]. Frequent paddock records allow such a calibration to be built and updated within each system, but it would need to be season- and resource-specific before NDVI could replace ground assessment of average herbage mass.

The main consequence of the post-grazing sward height for the herd concerned the allocation of herbage rather than its intake. HR offered 2.5 kg DM/cow/d more herbage in August–December, yet herbage intake did not differ significantly, and HR cows consumed 0.8 kg DM/cow/d more conserved forage. The larger allowance thus did not translate into a detectable increase in HDMI: under HR a larger fraction of the herbage offered remained in the residual, as intended by the treatment. The greater use of conserved forage is consistent with the way the higher residual had to be managed. In the present systems the herd grazed in fixed 8-hour shifts (one or two per day) that could not be shortened further, so the post-grazing residual could not be fine-tuned below that unit; maintaining the post-grazing residual target height - particularly the higher residual under HR - therefore depended on removing the herd from the pasture once the target was reached, which required a holding area and a reserve of conserved forage and concentrate to sustain the animals off the sward [13, 31]. The greater conserved-forage intake measured under HR is consistent with this operational cost. It did not stem from setting aside more land, since the share of the farmlet area destined for conserved forage was similar between treatments (Fig. 2d).

Because the animals spent part of the day off the pasture, the holding facility becomes a component of this type of system [32]. Excreta deposited on the sward, particularly urinary nitrogen, are spatially concentrated and a major pathway of nutrient loss [33, 34]; capturing part of the excretion during the hours off the pasture and returning it to the land as effluent or manure is an opportunity to improve nutrient-use efficiency, although it was not quantified in this study.

The distribution of grazing shifts followed the seasonal growth curve, with double-shift grazing concentrated in spring (Fig. 4b), and acted as an operational descriptor of grazing pressure [1]. No treatment effect was detected on the number of daily grazing shifts ($P = 0.060$) or on the interval between successive grazings ($P = 0.61$), and the treatment × month interaction for the interval was not significant ($P = 0.077$). The monthly patterns in Fig. 4 are therefore descriptive; whether a higher post-grazing sward height changes the frequency of grazing or the pace of the rotation remains to be tested with replicated systems.

Menegazzi et al. [10] compared post-grazing residuals of 5–7 and 12–15 cm on tall fescue and reported that the higher residual required 36% more grazing area per cow (1.60 vs 1.18 ha per four cows) and tended to reduce milk yield per hectare by 21%. In that design the land base was allowed to adjust, so the cost of the higher post-grazing height was expressed directly as a lower stocking rate. Two differences with the present study are informative. First, the magnitude of the contrast: the residual difference achieved here was about 1.5 cm annually [14] and 2.2 cm in August–December, against approximately 7

cm in Menegazzi et al. [10]. Second, the design: here the land base was fixed. With a fixed land base and a much smaller residual contrast, we did not detect differences in milk or harvested herbage per hectare, although the experiment could not exclude moderate differences. Read together, the two experiments suggest a hypothesis that deserves testing with replicated systems: that the system-level cost of a higher residual becomes detectable when the contrast is large enough that the land base, or the feed imported to substitute for it, must adjust. In the present experiment part of that substitution was visible, as the greater use of conserved forage under HR. The same gradient is visible across the literature: larger residual contrasts on perennial ryegrass and tall fescue have altered herbage removal and cow performance [9, 10, 35, 36], whereas moderate contrasts under supplementation have not [6, 11].

The context of the present experiment differs from that of most studies on post-grazing sward height in three respects, and each bears on how the results should be read. First, grazing was combined with supplementation: in August–December herbage made up about 59% of the dry-matter intake, the rest being conserved forage and concentrate. In such systems the herd can be withdrawn from the pasture once the post-grazing target height is reached and fed off the sward, so a higher post-grazing height can be held without reducing herbage allowance, as observed here, but at the cost of more conserved forage; the response of milk yield to the residual is therefore buffered by the supplement, as reported for supplemented herds [6, 11, 13]. Second, the grazing area combined several forage resources in rotation — *Avena–Lolium*, *Medicago–Bromus* and first- to third-year *Dactylis–Trifolium* pastures — that differ in height and structure at grazing (pre-grazing height ranged from about 29 cm in *Dactylis* pastures to 36 cm in *Avena–Lolium* pastures). The contrast between treatments was nevertheless consistent across them, since it was estimated within paddock and with the forage resource accounted for in the model; most of the evidence on post-grazing height, by contrast, comes from single-species swards of perennial ryegrass or tall fescue [7, 9, 10, 36]. Third, the experiment was conducted in a humid subtropical environment, where summer heat and water deficits limit the survival of temperate perennial grasses and an excessively low residual can compromise their productivity [37]. In this environment a moderately higher post-grazing height may matter less for the immediate regrowth, which was not greater under HR, than for the perennial base of the sward over successive years, a hypothesis that the present three-year experiment could not test.

At the animal level we did not detect differences in milk yield or composition, body condition score or live weight. This agrees with reports that only severe reductions in post-grazing sward height depress herbage intake and milk yield [7, 35, 36], and the LR residual (7.8 cm) was above the sward heights at which bite mass and instantaneous intake rate begin to decline [1, 38]. However, with two farmlets per treatment the confidence intervals are wide — for milk yield per cow, from − 1.7 to 2.4 L/cow/d — and the absence of a detected difference should not be read as evidence that the post-grazing sward height has no effect on animal performance.

From a practical standpoint, the results indicate that the post-grazing sward height can be raised by about 2 cm during the spring growth period without a detectable change in the state of the sward at the next grazing, at the cost of a greater use of conserved forage. A less severe defoliation leaves more

residual leaf area, and we hypothesize that it may help preserve the water-soluble carbohydrate reserves, tiller survival and leaf area that drive regrowth [5, 24]; these attributes were not measured in this study. The magnitude of these responses is likely to depend on pasture species, soil fertility and climate, and may not transfer directly to systems with contrasting sward composition or substantially lower forage supply; the present experiment was conducted under a relatively high forage-production level (about 9000 kg DM/ha/yr) [14]. These results support adaptive residual targets that follow seasonal growth and herd demand rather than fixed annual setpoints [39, 40].

Two trade-offs argue for a moderate rather than a maximal residual. First, holding a higher residual increased the use of conserved forage (Table 3), so part of the herbage left in the paddock had to be replaced by stored feed. Second, allowing the residual to rise too far risks a decline in sward nutritive value, as ungrazed stem and senescent material accumulate and depress digestibility [23, 41]. In this experiment no difference in milk composition was detected at an average residual of about 10 cm (Table 4), which is consistent with raising the residual moderately and tracking it to seasonal growth rather than fixing it at a high value throughout the year.

Limitations. With one farmlet per combination of treatment and stocking rate, the treatment effect rests on two LR and two HR farmlets replicated over years and cannot be fully separated from persistent differences between the herds that grazed them; the results should therefore be read as a comparison of grazing systems. In addition, inference was restricted to August–December, and the achieved contrast in post-grazing sward height was moderate (about 2 cm).

Conclusions

A higher post-grazing residual changed how herbage was allocated within the grazing cycle: it left about 2 cm more post-grazing sward height, reduced defoliation severity by about 8 percentage points, and was sustained with a larger herbage allowance and a greater use of conserved forage during the spring growth period. The herbage growth rate of the grazed area was lower under HR, but the sward returned to a similar state before the next grazing, with no differences detected in grazing-area herbage mass or NDVI, and no differences in animal or whole-system output were detected. A moderate increase in the post-grazing residual is therefore a feasible way to make defoliation less severe without a detectable loss of milk output, provided that conserved forage is available to hold the herd off the pasture once the target residual is reached.

Abbreviations

CI
confidence interval
DM
dry matter
HDMI

herbage dry-matter intake
HR
high post-grazing residual
LR
low post-grazing residual
NDVI
normalized difference vegetation index
T × M
treatment × month interaction.

Declarations

Ethics approval and consent to participate: Animal procedures complied with the regulations of the Honorary Commission for Animal Experimentation (CHEA), Universidad de la República, Uruguay, which approved the experimental protocol (protocol no. 371).

Consent for publication: Not applicable.

Availability of data and materials: The datasets and analysis scripts used during the current study are available from the corresponding author on reasonable request.

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Figures

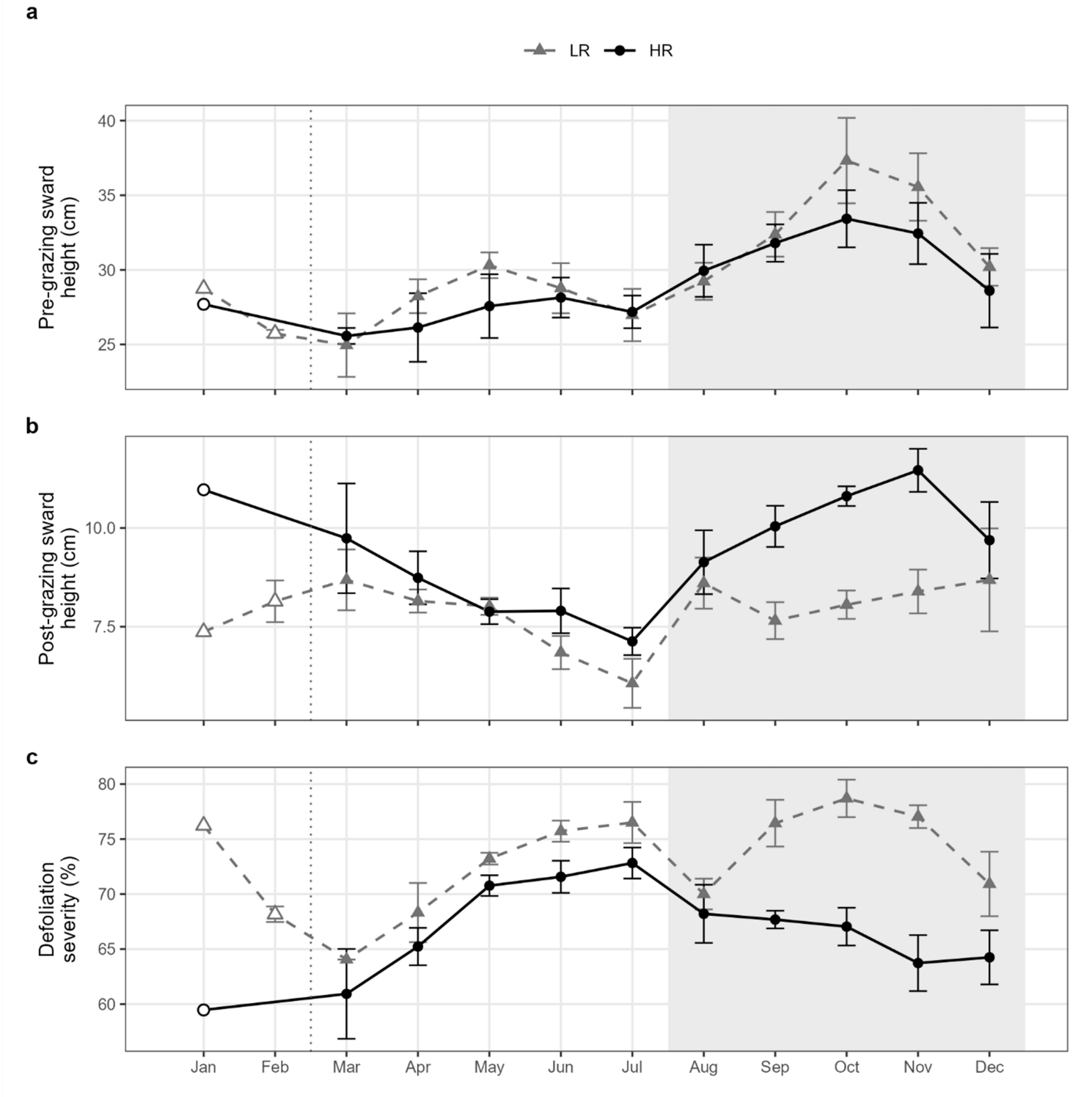


Figure 1

Sward state at grazing by month under low (LR) and high (HR) post-grazing residual. (a) Pre-grazing sward height, (b) post-grazing sward height and (c) defoliation severity. Points are means of farmlet-years (four per treatment, 2017–2018) and bars the standard error between farmlet-years; shaded band = August–December, the period of inference (Table 1); open symbols = January–February, when the

cows grazed as a single herd. No treatment × month interaction was significant, so the monthly patterns are descriptive.

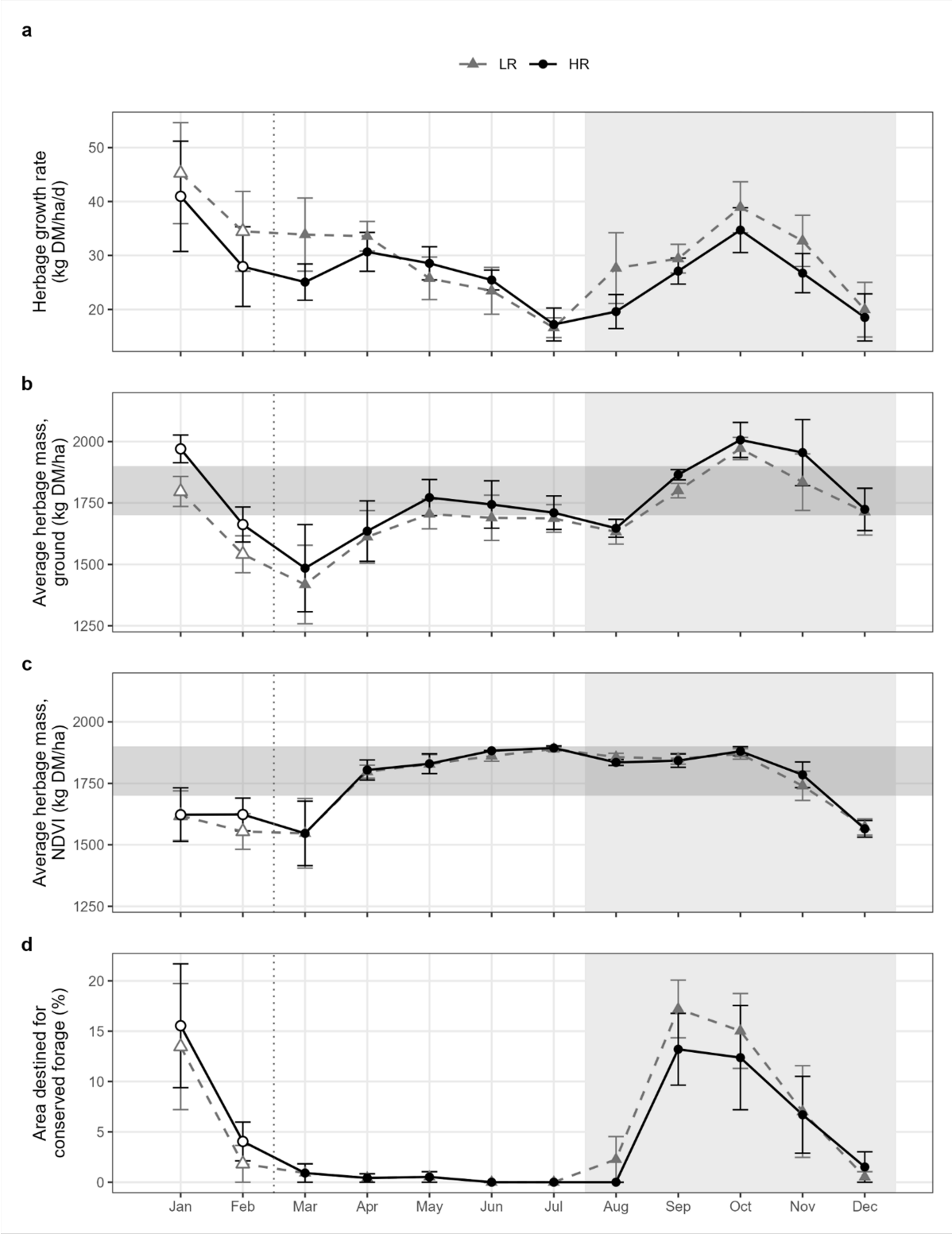


Figure 2

Herbage regrowth and grazing area by month. (a) Herbage growth rate, (b) average herbage mass of the grazing area measured on the ground and (c) estimated from NDVI, and (d) share of the farmlet area

destined for conserved forage. Means ± standard error of farmlet-years (six per treatment, 2017–2019); shaded band = August–December; horizontal band in (b) and (c) = target grazing-area herbage mass (1800 ± 100 kg DM/ha) (Table 2); open symbols = January–February, when the cows grazed as a single herd.

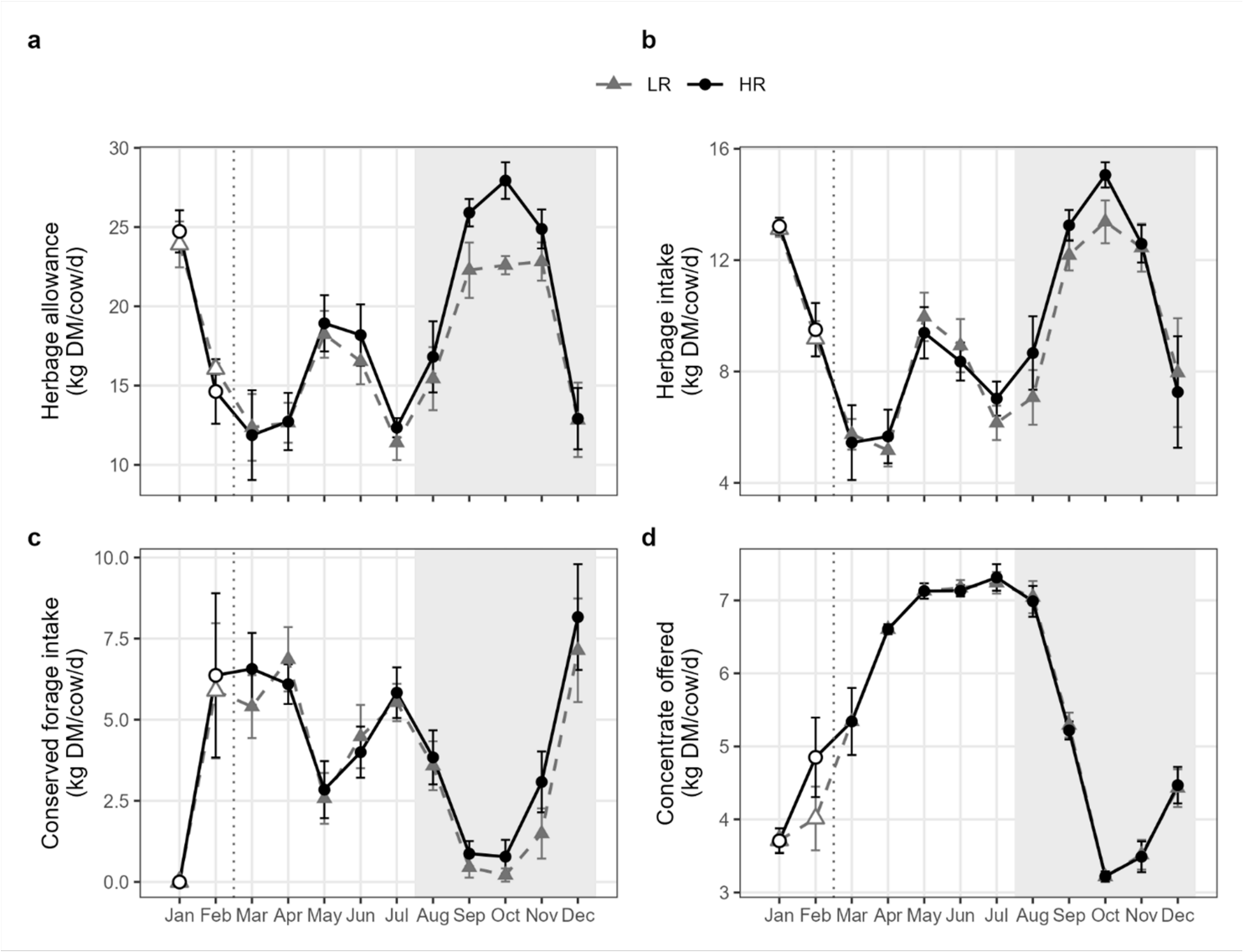


Figure 3

Herbage allocation and intake per cow by month. (a) Herbage allowance, (b) herbage intake, (c) conserved forage intake and (d) concentrate offered. Means ± standard error of farmlet-years (six per treatment); shaded band = August–December (Table 3); open symbols = January–February, when the cows grazed as a single herd.

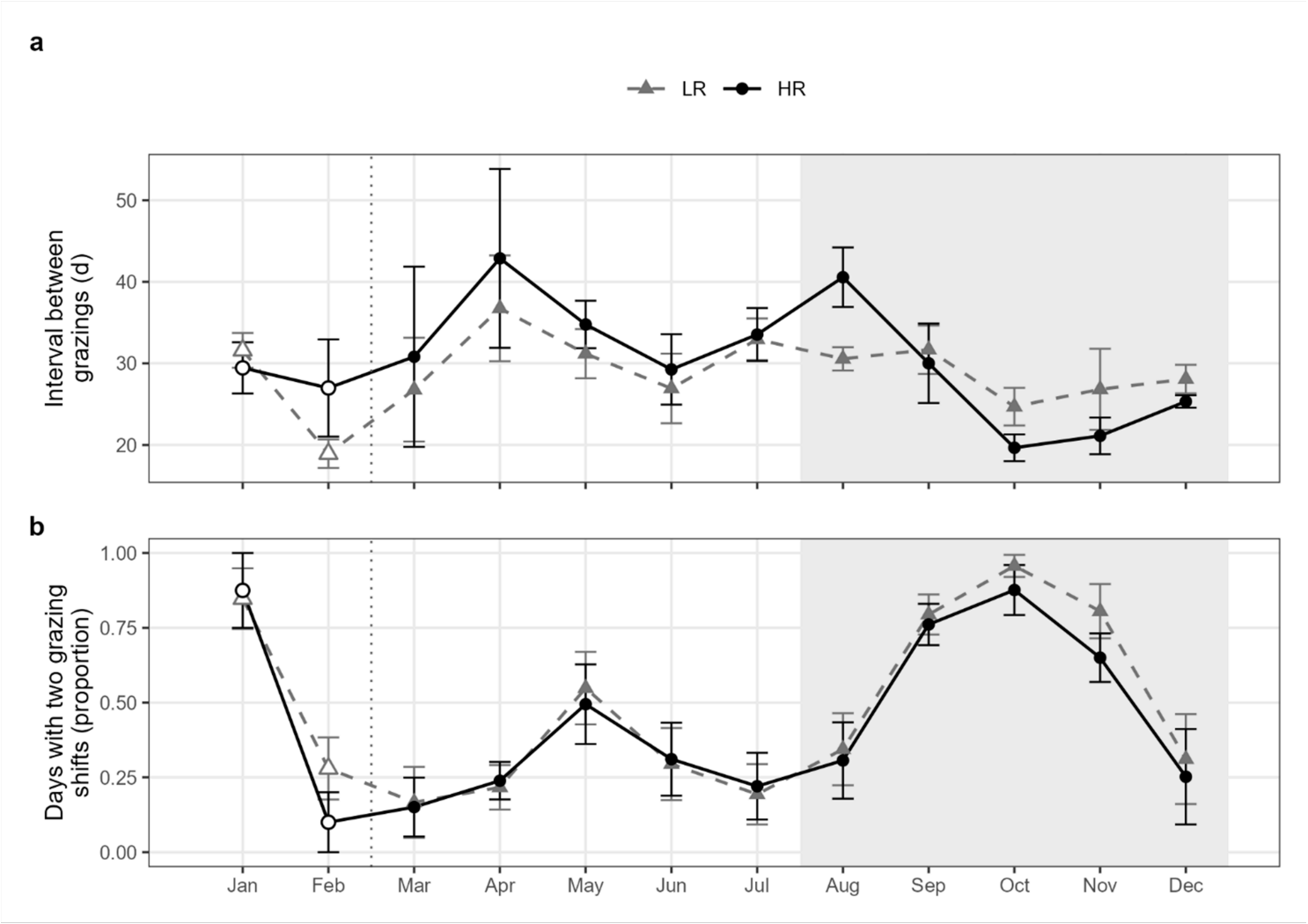


Figure 4

Rotation management by month. (a) Interval between successive grazings and (b) proportion of days with two grazing shifts. Means ± standard error of farmlet-years (six per treatment); interval computed on paddocks in the grazing rotation; shaded band = August–December; open symbols = January–February, when the cows grazed as a single herd. The treatment × month interaction for the interval was not significant (P = 0.077); the monthly patterns are descriptive.

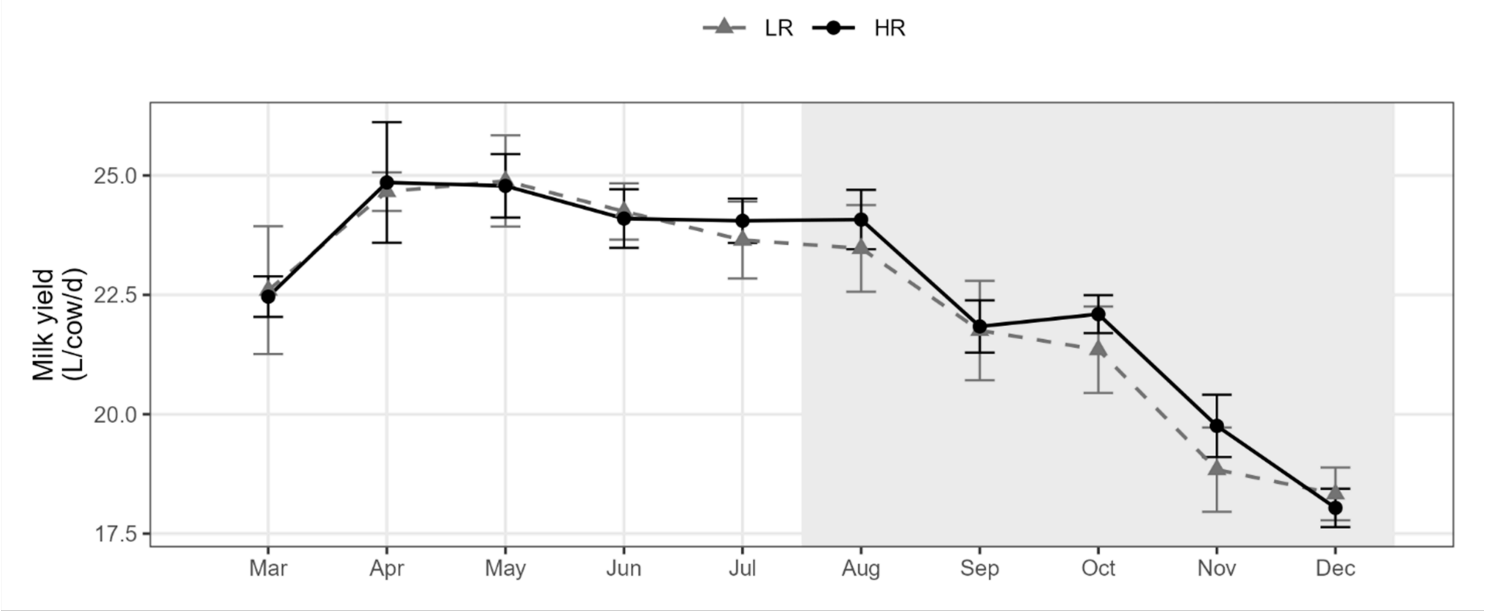


Figure 5

Milk yield per cow by month, March–December. Means ± standard error of farmlet-years (six per treatment); shaded band = August–December (Table 4).

Supplementary Files

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