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[Luis A. Vallejos-Fernández](#) , [Wuesley Alvarez-García](#) ^{*} , [Maycol Abanto](#) , Ricardo Guillén-Sánchez , [César Pinares-Patiño](#) , Jorge Piedra , Gilberto Fernández Idrogo

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Article

Selection of Alternative Forage Cultivars for High-Andean Dairy Systems: Genotype × Environment Stability, Multicriteria Desirability, and Predictive Models Along an Altitudinal Gradient in the Northern Highlands of Peru

Luis A. Vallejos-Fernández ¹, Wuesley Alvarez-García ^{2,*}, Maycol Abanto ¹, Ricardo Guillén-Sánchez ¹, César Pinares-Patiño ³, Jorge Piedra ¹ and Gilberto Fernández Idrogo ¹

- ¹ Facultad de Ingeniería en Ciencias Pecuarias, Universidad Nacional de Cajamarca, Cajamarca, Peru
² Dirección de Investigación y Desarrollo Tecnológico -DIDET, Instituto Nacional de Innovación Agraria (INIA), Cajamarca, Perú
³ New Zealand Support Project for the Peruvian Dairy Sector, General Directorate of Livestock, Ministry of Agriculture and Irrigation (MINAGRI), Lima, Peru
* Correspondence: w Alvarez@inia.gob.pe

Abstract

The decline of the ryegrass–white clover swards that underpin smallholder dairying in the northern Peruvian Andes has widened a persistent dry-season feed gap. We evaluated the agronomic and nutritional performance of eleven alternative forage cultivars across three altitudinal zones (AZ I, 2300–2800; AZ II, 2801–3300; AZ III, 3301–3800 m.a.s.l.) in Santa Cruz, Cajamarca, Peru, over one production year, in a randomized complete block design with three blocks per zone. Because brassicas are harvested in a single cut and grasses and *Lolium* hybrids repeatedly, yield was analyzed separately by cutting regime. Among multiple-cut species the environment dominated yield variation (75.0% of the treatment sum of squares), with a moderate genotype × environment interaction (20.7%; $p = 0.011$), ‘Shogun’ was the most stable and productive hybrid (yield stability index = 5) and ‘Delish’ reached the highest desirability ($D = 0.53$). Brassicas peaked in the intermediate zone (‘Groundhog’, 10.87 t DM ha⁻¹) with no significant interaction ($p = 0.51$), and ‘Green globe’ ranked first on integrated merit ($D = 0.47$). Crude protein ranged from 6.33% to 19.75% and in vitro dry matter digestibility from 53.25% to 80.66%, increasing weakly but significantly with altitude ($r = +0.29$). Cultivar choice should therefore be specific to both altitudinal zone and functional group.

Keywords: forage brassicas; perennial grasses; *Lolium hybridum*; genotype × environment interaction; AMMI; desirability index; altitudinal gradient; dairy cattle nutrition; Peruvian Andes

1. Introduction

The ryegrass (*Lolium multiflorum* L.)–white clover (*Trifolium repens* L.) association has been the basis of grazing dairy nutrition in the northern highlands of Peru for more than seven decades. Its morphogenetic and nutritional attributes have progressively deteriorated, largely because swards are grazed at an advanced maturity stage and receive little fertilization [1,2], which has constrained pasture sustainability, particularly during the dry season [3]. Plant breeding has made available alternative cultivars that tolerate low temperatures, drought, and soil acidity [4,5]; characterizing their performance is essential for effective and sustainable grassland management [6].

In the northern Peruvian Andes, family dairying depends on pastures that are frequently used at an advanced maturity stage and with scarce mineral supplementation, on acid soils with exchangeable aluminum, and under a marked dry-season forage deficit [2,4]. These constraints,

shared by high-Andean and tropical highland systems more generally [7], compromise the energy and protein supply to the herd and motivate the search for alternative cultivars with adequate adaptation and nutritive value along the altitudinal gradient.

Brassicaceae have gained importance as a complement to grazing systems during the dry season [8,9]. *Raphanus sativus* L., *Brassica rapa* L. and *Brassica napus* L. stand out for their yield potential and nutritional quality—high crude protein, low neutral detergent fiber and readily fermentable carbohydrates [10–12]—with yields of up to 10.1–10.2 t DM ha⁻¹ and in vitro dry matter digestibility of 66% to 92% [8,13], and with nutritive value reportedly favored at higher elevation [14,15]. Forage brassicas are further characterized by high digestibility, low fiber and high metabolizable energy density (12.1–14.1 MJ kg⁻¹ DM), which improves intake and animal response relative to temperate grasses [16–18], although their composition varies markedly with the bulb-to-foilage ratio [19].

Perennial grasses (*Dactylis*, *Phalaris*, *Festuca*, *Festulolium*) are strongly influenced by soil and climate [20], with cumulative yields close to 10.3 t ha⁻¹ year⁻¹ [21] and crude protein between 10.8% and 26.9% [22,23]; *Festulolium* hybrids adapt well to adverse conditions [24–27]. New Zealand-bred *Lolium hybridum* cultivars yielded 6.75–6.79 t DM ha⁻¹ with crude protein of 10% to 31.9% in southern Chile [28]. Perennial grasses and *Lolium* hybrids contribute persistence and regrowth capacity, and *Festuca* and *Festulolium* cultivars tolerate water and thermal stress through deep root systems [29,30]. Evaluating both functional groups jointly along an altitudinal gradient nevertheless requires tools that integrate production, quality, and stability.

Most cultivar evaluations are conducted in a single environment, compare yields obtained under non-equivalent cutting regimes, do not decompose the genotype × environment (G×E) interaction along the gradient, and neither integrate quality and production into a single selection criterion nor provide predictive models applicable to the region. Stability analysis based on additive main effects and multiplicative interaction (AMMI) models and joint regression, together with selection based on multicriteria and desirability indices, has proved useful for recommending genotypes in multi-environment trials [31–36], but has rarely been applied to alternative forages in the Andes.

The objective of this study was therefore to evaluate the agronomic and nutritional performance of eleven alternative forage cultivars across three altitudinal zones of the northern highlands of Peru and to identify, through stability analysis, multicriteria desirability and predictive models, the most suitable materials for each zone. Four hypotheses were formulated: H1: the pattern of altitudinal response differs between functional groups; H2: within each comparable group, the environment dominates yield variation and the G×E interaction is modest; H3: multicriteria desirability reorders selection relative to productivity alone; and H4: nutritional quality can be predicted from altitude, albeit weakly.

2. Materials and Methods

2.1. Study Site and Experimental Design

The study was conducted between March 2018 and April 2019 on farms in the province of Santa Cruz, Cajamarca, Peru (06°48' S, 78°48' W), distributed along an altitudinal gradient comprising three altitudinal zones (AZ): AZ I (2300–2800 m.a.s.l.), AZ II (2801–3300 m.a.s.l.), and AZ III (3301–3800 m.a.s.l.). Eleven alternative forage cultivars, assigned to three functional groups, were evaluated in each AZ: three brassicas [*Raphanus sativus* L. 'Groundhog' (forage radish), *Brassica rapa* L. 'Green globe' (forage turnip), and *Brassica napus* L. 'Titan' (forage rape)], five perennial grasses [*Dactylis glomerata* L. 'Savy', *Phalaris* sp. 'Confederate', *Festuca arundinacea* Schreb. 'Quantum' and 'Festival', and *Festulolium* 'Mahulena'], and three *Lolium hybridum* (hybrid ryegrass) cultivars 'Trojan', 'Shogun' and 'Delish'.

Within each AZ, cultivars were arranged in a randomized complete block design (RCBD) with three blocks (replicates). The experimental unit was a 6 m² subplot (3 m × 2 m). The altitudinal zone was treated as the environment, so that the data set formed an 11-genotypes × 3-environments × 3-blocks array, suitable for the analysis of the G×E interaction described in Section 2.4.

2.2. Soil Characterization, Weather Conditions, Seed Quality, and Establishment

Three months before tillage (ploughing and harrowing with a walk-behind tractor), composite soil samples were collected in each AZ and analyzed at the Soil Analysis Laboratory of the Universidad Nacional Agraria La Molina (Lima, Peru). Textural class, pH, organic matter, nitrogen, phosphorus, potassium, and exchangeable aluminum were determined (Table 1). Mean monthly temperature and rainfall for each AZ during the experimental period were obtained from the La Zanja Mining Weather Station (2019) (Table 2). Before establishment, germination capacity (%), purity (%), and 1000-seed weight (g) were determined for each cultivar and used to adjust the sowing rate (kg ha⁻¹) (Table 3). Sowing and fertilization were both carried out by broadcasting.

Table 1. Physico-chemical characteristics of the soil of the experimental plots in the three altitudinal zones.

Soil characteristic	AZ I	AZ II	AZ III
Textural class	Sandy clay loam	Sandy loam	Sandy loam
pH	5.05	3.54	4.43
Organic matter (%)	4.23	9.35	22.07
Nitrogen (%)	0.28	0.40	1.11
Phosphorus (mg kg ⁻¹)	10.4	2.1	2.5
Potassium (mg kg ⁻¹)	738	175	620
Exchangeable aluminum (cmol ⁺ kg ⁻¹)	0.30	5.75	8.00

AZ I: 2300–2800 m.a.s.l.; AZ II: 2801–3300 m.a.s.l.; AZ III: 3301–3800 m.a.s.l. Analyses performed at the Soil Analysis Laboratory of the Universidad Nacional Agraria La Molina, Lima, Peru.

Table 2. Mean monthly temperature (T) and rainfall (R) in the three altitudinal zones during the experimental period.

Month	AZ I		AZ II		AZ III	
	T(°C)	R (mm)	T(°C)	R (mm)	T(°C)	R (mm)
January	17.6	77	14.2	98	7.3	127.6
February	17.5	93	13.4	111	6.9	58.6
March	17.2	161	13.5	133	6.9	92.4
April	16.9	113	13.4	91	6.9	141.2
May	16.3	62	12.7	42	7.1	146.4
June	15.8	33	11.8	15	6.4	8.6
July	15.4	20	11.9	8	6.2	5.4
August	15.7	37	12.3	14	6.2	3.4
September	16.2	69	12.8	40	6.9	35.4
October	16.6	90	13.6	92	6.8	119.4
November	16.8	69	13.3	68	8.0	146.6
December	16.9	54	13.4	83	7.8	94.0

Source: La Zanja Mining Weather Station (2019). AZ I: 2300–2800 m.a.s.l.; AZ II: 2801–3300 m.a.s.l.; AZ III: 3301–3800 m.a.s.l.

Table 3. Biological and physical characteristics of the seed and sowing rate of the eleven cultivars.

Species and cultivar	Germination (%)	Purity (%)	1000-seed weight (g)	Sowing rate (kg ha ⁻¹)
<i>Raphanus sativus</i> ‘Groundhog’	93	91.9	14.02	14
<i>Brassica rapa</i> ‘Green globe’	94	97.9	2.2	1.5
<i>Brassica napus</i> ‘Titan’	88	96.3	4.1	4
<i>Dactylis glomerata</i> ‘Savy’	73	98.3	1.2	8
<i>Phalaris</i> sp. ‘Confederate’	52	98.9	1.5	4
<i>Festuca arundinacea</i> ‘Quantum’	49	93.6	2.6	25
<i>Festuca arundinacea</i> ‘Festival’	61	92.7	2.7	25
<i>Festulolium</i> ‘Mahulena’	90	97.6	3.2	25
<i>Lolium hybridum</i> ‘Trojan’	91	99.1	2.5	25
<i>Lolium hybridum</i> ‘Shogun’	96	92.8	3.4	30
<i>Lolium hybridum</i> ‘Delish’	99	98.2	3.4	35

2.3. Cutting Management, Agronomic Variables and Chemical Analyses

Variables were measured on 0.25 m² quadrats (50 cm × 50 cm) placed within each subplot. At every harvest event, plant height was measured with a 70 cm metal rule, herbage was cut at ground level and weighed fresh on a precision balance. The cutting schedule was intrinsically unbalanced because it corresponded to functional groups with contrasting utilization dynamics. Brassicas were harvested in a single cut at 117 days after sowing, during the dry season (July): they were sown in late March (rainy season) and harvested in July, because they are single cycle crops whose main use is concentrated in one defoliation. Perennial grasses and *Lolium hybridum* were managed with successive cuts throughout the year; the number of which varied with the environment and reflected actual regrowth dynamics: perennial grasses received five cuts in AZ I, two in AZ II, and three in AZ III, whereas *Lolium hybridum* received seven, three, and five cuts, respectively.

Consequently, the annual yield of perennial grasses and *Lolium hybridum* was obtained as the cumulative sum of the dry matter of all cuts taken in each plot during the year, whereas in brassicas it corresponded to the single cut. This distinction is essential for data interpretation: the brassica value derives from a single defoliation, whereas that of grasses and hybrids is cumulative, so the two magnitudes are not directly equivalent. A lower annual yield in a given altitudinal zone does not necessarily imply lower per-cut productivity but may instead reflect a smaller number of harvests over the year. Plant height and growth rate reported by cultivar and AZ correspond to the mean of the respective cuts, not to their sum.

Three agronomic variables were determined: (i) dry matter yield (t DM ha⁻¹ year⁻¹), obtained by scaling the dry weight of the 0.25 m² quadrat to the hectare and accumulating the cuts of the year; (ii) growth rate (kg DM ha⁻¹ d⁻¹), calculated as the daily biomass increment between defoliations; and (iii) plant height (cm). Dry matter content was determined by oven-drying 100 g of fresh herbage per treatment in a forced-air oven at 105 °C for 24 h.

For chemical analysis, 200 g subsamples per treatment were dried at 65 °C for 48 h to constant weight. Crude protein (CP) was determined by the AOAC method 984.13 [37] at the Soil, Water, Fertilizer and Pasture Service Laboratory of the Instituto Nacional de Innovación Agraria (INIA), Cajamarca. Neutral detergent fiber (NDF) was quantified according to Van Soest et al. [38] with a FIWE fiber analyser (VELP Scientifica, Usmate Velate, Italy), and *in vitro* dry matter digestibility (IVDMD) was determined with a DAISY incubator (ANKOM Technology, Macedon, NY, USA) according to Mabjeesh et al. [39], both at the Animal Nutrition and Food Bromatology Laboratory of the Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Peru. Metabolizable energy (ME) was estimated from IVDMD using the equation proposed by Watt et al. [8]:

$$\text{ME (MJ kg}^{-1}\text{ DM)} = 0.172 \times \text{IVDMD (\% DM)} - 1.707 \quad (1)$$

In the tuberous species (*Raphanus sativus* and *Brassica rapa*), nutritional value was determined separately in the bulb (root) and the foliage, whereas *Brassica napus* was evaluated in its foliage only. To estimate whole-plant nutritional value in the tuberous species, both fractions were weighted by their relative contribution to biomass, measured as 49% root and 51% foliage in AZ I and AZ II, and 11% root and 89% foliage in AZ III. This weighting avoids overestimating nutritional quality when a highly digestible fraction (the bulb) represents a minor proportion of the forage harvested, a situation that is particularly pronounced in the upper altitudinal zone.

2.4. Statistical Analysis

Normality and homogeneity of variance were verified with the Shapiro–Wilk and Levene tests ($p < 0.05$), respectively; where assumptions were not met, appropriate transformations or robust alternatives were applied. Because of the contrasting cutting regimes, all yield-based analyses were performed separately for brassicas (single cut) and for perennial grasses and *Lolium* hybrids (multiple-cut cumulative yield), as the two magnitudes are not equivalent. For each group, a two-way genotype × environment model with type II sum-of-squares partitioning and a linear mixed

model fitted by restricted maximum likelihood (REML) were used. The mixed model was specified as:

$$Y_{ijkl} = \mu + G_i + A_j + (GA)_{ij} + b_{k(j)} + c_{l(ij)} + \varepsilon_{ijkl} \quad (2)$$

where Y_{ijkl} is the observed response; μ is the overall mean; G_i (genotype) and A_j (environment/AZ) are fixed effects; $(GA)_{ij}$ is the genotype $\times$ environment interaction; $b_{k(j)}$ is the random effect of block within environment; $c_{l(ij)}$ is the random effect of cut within the genotype $\times$ environment combination (included as a repeated measure only for multiple-cut groups); and ε_{ijkl} is the residual error. This model quantifies and tests the G $\times$ E interaction, accommodates the unbalanced cutting schedule without discarding information, separates block from residual variance, and allows adjusted mean comparisons by Tukey's test. For multiple-cut groups, an additional per-cut model with a random plot intercept was fitted to discern whether a lower annual yield was attributable to the number of harvests or to per-cut productivity.

Yield stability across altitudinal zones was assessed with the AMMI model [40,41]:

$$Y_{ij} = \mu + G_i + A_j + \sum_n \lambda_n \alpha_{in} \gamma_{jn} + Q_{ij} \quad (3)$$

where the multiplicative terms decompose the interaction into singular values (λ_n) and interaction principal component axis (IPCA) scores for genotypes (α_{in}) and environments (γ_{jn}), and Q_{ij} is the residual. The AMMI stability value (ASV) and the yield stability index (YSI), defined as the sum of the ASV rank and the mean yield rank, were computed from the model; low values are preferable because they combine high yield with a low contribution to the interaction [42]. Because the trial comprised only three environments—a condition that saturates the interaction degrees of freedom with the first two IPCA axes—the AMMI analysis was complemented with the Finlay–Wilkinson joint regression [43], which is robust to a small number of environments:

$$Y_{ij} = \mu + G_i + b_i E_j + \delta_{ij} \quad (4)$$

where E_j is the environmental index (mean of environment j) and b_i is the regression coefficient describing the response of genotype i : $b_i \approx 1$ with low deviation variance (S^2_d) indicates general stability; $b_i > 1$ identifies cultivars responsive to favourable environments; and $b_i < 1$ identifies cultivars adapted to lower-potential environments.

To integrate yield and nutritional quality into a single metric and objectify cultivar selection, the Derringer–Suich desirability function was applied [44,45]. Each variable Y was transformed into a partial desirability $d \in [0, 1]$. For variables in which a higher value is preferable (yield, growth rate, CP, IVDMD, and ash), $d = (Y - L)/(U - L)$; for variables in which a lower value is preferable (NDF), $d = (U - Y)/(U - L)$; in both cases, bounded to $[0, 1]$, where L and U are the observed lower and upper limits. Overall desirability was obtained as the weighted geometric mean of the partial desirabilities:

$$D = (\prod_k d_k^{w_k})^{1/\sum w_k} \quad (5)$$

where w_k is the weight assigned to each variable (Table 4). The geometric form penalizes strongly any variable with null performance, so that a high-yielding but poorly digestible cultivar cannot attain a high overall desirability. The weights reflect the relative importance of each variable for dairy pasture sustainability and constitute an adjustable input; their refinement through expert elicitation with the Analytic Hierarchy Process is recommended. Metabolizable energy was excluded from the index because it is an exact linear transformation of IVDMD (Equation (1)) and therefore perfectly collinear with it ($r = 1.00$); its inclusion would double the weight of digestibility. The robustness of the ranking was checked against alternative multicriteria methods (TOPSIS and WPM) [35,36].

Table 4. Weights of the variables in the Derringer–Suich desirability function, applied within each functional group.

Variable	Direction	Weight (<i>w</i>)	Rationale
Dry matter yield (t DM ha ⁻¹)	Higher is better	0.30	Primary driver of forage sustainability
IVDMD (%)	Higher is better	0.20	Determines intake and milk production
Crude protein (%)	Higher is better	0.18	Key requirement of dairy cattle
NDF (%)	Lower is better	0.12	Limits voluntary intake
Growth rate (kg DM ha ⁻¹ d ⁻¹)	Higher is better	0.10	Speed of forage supply
Ash (%)	Higher is better	0.10	Mineral contribution; periparturient health

IVDMD: in vitro dry matter digestibility; NDF: neutral detergent fiber. Metabolizable energy was excluded because it is an exact linear transformation of IVDMD (Equation (1)).

The association between altitude and nutritional quality variables (CP and ash) was assessed with Pearson correlation coefficients and mixed models fitted on cultivar × AZ means, to isolate the genotype effect. Exact coefficients are reported, together with the actual direction and magnitude of the trends, without qualifying them a priori. Analyses were implemented in R (packages *lme4*, *emmeans*, *metan* [46] and *desirability2*) and Python (*statsmodels* and *scikit-criteria*). The original ANOVA and Tukey mean comparison test (*p* < 0.05) were performed in InfoStat.

3. Results

The analysis comprised 99 plots (11 cultivars × 3 altitudinal zones × 3 blocks) for yield and 78 observations for nutritive value. Because of the difference in cutting regime—a single cut in brassicas versus the annual cumulative yield of several cuts in grasses and *Lolium*—the yields of the two groups are not directly equivalent; productive and stability results are therefore presented in separate sections (Sections 3.1 and 3.2). Figure 1 illustrates the contrast: brassicas concentrate their productivity in the intermediate zone, whereas grasses and *Lolium* yield most in the lower and upper zones. Nutritive value, which is not affected by the cutting regime, is compared across all cultivars in Section 3.3.

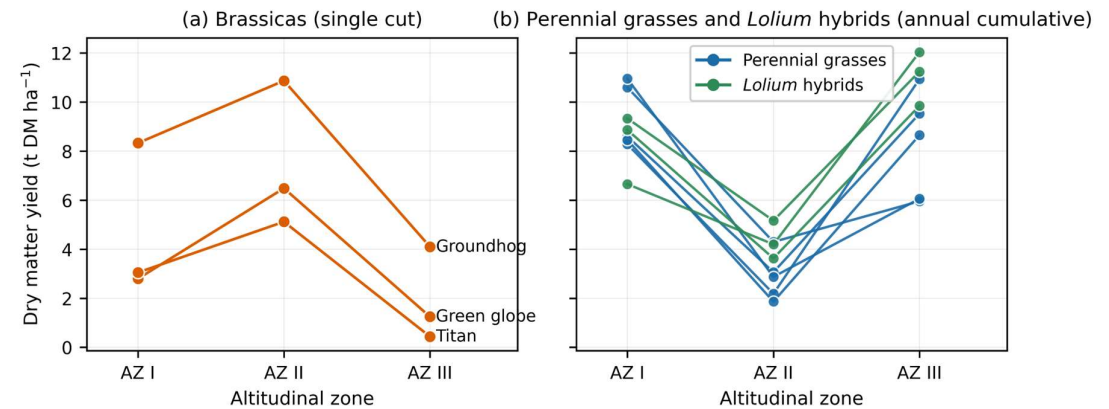


Figure 1. Yield response to altitudinal zone by functional group. (a) Brassicas (single cut), with an optimum in the intermediate zone. (b) Perennial grasses and *Lolium* hybrids (annual cumulative yield), with maxima in the lower and upper zones. AZ I: 2300-2800 m.a.s.l.; AZ II: 2801-3300 m.a.s.l.; AZ III: 3301-3800 m.a.s.l.

3.1. Forage Brassicas (Single-Cut Crops)

3.1.1. Productive Performance

Raphanus sativus ‘Groundhog’ was the most productive brassica, with an optimum in the intermediate zone (AZ II: 10.87 t DM ha⁻¹) and a pronounced decline in the upper zone (AZ III: 4.10 t DM ha⁻¹); ‘Green globe’ and ‘Titan’ followed the same pattern, with maxima in AZ II (6.48 and 5.12

t DM ha⁻¹) and minima in AZ III (1.25 and 0.44 t DM ha⁻¹) (Table 5). ‘Groundhog’ recorded the highest growth rate (66.3 kg DM ha⁻¹ d⁻¹) and plant height (106.1 cm). It should be noted that these yields correspond to a single cut and entail annual resowing, so their comparison with the cumulative yield of grasses requires caution.

Table 5. Dry matter yield (t DM ha⁻¹, single cut) by altitudinal zone, and mean plant height and growth rate of the three forage brassicas.

Cultivar	Species	AZ I	AZ II	AZ III	Height (cm)	GR (kg DM ha ⁻¹ d ⁻¹)
Groundhog	<i>Raphanus sativus</i>	8.32	10.87	4.10	106.1	66.3
Green globe	<i>Brassica rapa</i>	2.80	6.48	1.25	17.5	30.0
Titan	<i>Brassica napus</i>	3.05	5.12	0.44	16.5	24.5

GR: growth rate. Values are means of three blocks. Yields correspond to a single cut taken 117 days after sowing. AZ I: 2300–2800 m.a.s.l.; AZ II: 2801–3300 m.a.s.l.; AZ III: 3301–3800 m.a.s.l.

3.1.2. Variance Partitioning and Stability

Analysed within the group, brassica yield variation was distributed between genotype (G = 46.5%) and environment (E = 50.8%), with a small and non-significant genotype × environment interaction (G×E = 2.7%; *p* = 0.51). The three brassicas therefore respond similarly to the gradient—all optimize in the intermediate zone—and differ mainly in their mean productive level. The Finlay–Wilkinson regression was consistent: ‘Groundhog’ showed the greatest response to favourable environments (*b* = 1.22), followed by ‘Green globe’ (*b* = 0.94) and ‘Titan’ (*b* = 0.84). The absence of a relevant interaction implies that, within brassicas, there is no rank reversal across zones.

3.1.3. Integrated Merit (Desirability Index within Brassicas)

The desirability index, computed within the group, ranked ‘Green globe’ (*Brassica rapa*) first (*D* = 0.47), and it was the best cultivar in all three zones, whereas ‘Groundhog’ (*D* = 0.16) and ‘Titan’ (*D* = 0.15) ranked well below (Table 6). Despite being the most productive cultivar (the highest yield in the whole trial, in AZ II), the low weighted whole-plant digestibility of ‘Groundhog’—driven down by the bulb fraction in some zones—penalized it strongly in the geometric mean.

Table 6. Forage brassicas: mean dry matter yield, Finlay–Wilkinson response coefficient and overall and zone-specific desirability (normalized within the group).

Cultivar	Mean yield (t DM ha ⁻¹)	FW <i>b</i>	<i>D</i> overall	<i>D</i> AZ I	<i>D</i> AZ II	<i>D</i> AZ III
Groundhog	7.76	1.22	0.16	0.33	0.01	0.13
Green globe	3.51	0.94	0.47	0.50	0.62	0.31
Titan	2.87	0.84	0.15	0.04	0.40	0.00

FW *b*: Finlay–Wilkinson regression coefficient; *D*: Derringer–Suich overall desirability. Variance partitioning within the group: G = 46.5%, E = 50.8%, G×E = 2.7% (not significant; *p* = 0.51).

3.2. Perennial Grasses and Lolium Hybrids (Multiple-Cut Crops)

3.2.1. Productive Performance

Annual cumulative yield peaked in the lower and upper zones and reached a consistent minimum in the intermediate zone (Table 7). *Festuca arundinacea* (‘Quantum’, ‘Festival’) and *Dactylis glomerata* (‘Savy’) stood out in AZ I (10.59, 10.95, and 8.59 t DM ha⁻¹ year⁻¹), whereas *Phalaris* ‘Confederate’ and the *Lolium* hybrids ‘Trojan’ and ‘Shogun’ reached their maxima in AZ III (10.93, 12.03, and 11.24 t DM ha⁻¹ year⁻¹). The *Lolium* hybrids combined high yields with the greatest regularity across zones, whereas *Festulolium* ‘Mahulena’ showed an intermediate pattern.

Table 7. Annual cumulative dry matter yield (t DM ha⁻¹ year⁻¹) by altitudinal zone, mean yield, plant height, and growth rate of the perennial grasses and *Lolium* hybrids.

Cultivar	Species	AZ I	AZ II	AZ III	Mean	Height (cm)	GR
Savy	<i>Dactylis glomerata</i>	8.59	3.06	9.52	7.06	19.3	27.6
Quantum	<i>Festuca arundinacea</i>	10.59	4.30	5.95	6.95	17.4	29.5
Festival	<i>Festuca arundinacea</i>	10.95	2.87	6.06	6.63	14.4	28.4
Confederate	<i>Phalaris</i> sp.	8.27	2.18	10.93	7.13	21.1	25.5
Mahulena	<i>Festulolium</i>	8.45	1.86	8.65	6.32	14.2	24.2
Trojan	<i>Lolium hybridum</i>	6.65	4.20	12.03	7.63	18.9	27.6
Shogun	<i>Lolium hybridum</i>	9.33	5.16	11.24	8.58	21.4	31.5
Delish	<i>Lolium hybridum</i>	8.86	3.63	9.85	7.44	18.1	27.0

GR: growth rate (kg DM ha⁻¹ d⁻¹). Yield is the cumulative sum of all cuts per plot over the year (perennial grasses: 5/2/3 cuts in AZ I/II/III; *Lolium hybridum*: 7/3/5 cuts). Height and growth rate are means of the respective cuts. AZ I: 2300–2800 m.a.s.l.; AZ II: 2801–3300 m.a.s.l.; AZ III: 3301–3800 m.a.s.l.

3.2.2. Number of Cuts and Per-Cut Productivity

The low annual yield of the intermediate zone was not attributable to lower per-cut productivity but to a smaller number of harvests: the per-cut mixed model showed that AZ II received on average 2.38 cuts, compared with 5.75 in AZ I and 3.75 in AZ III, whereas per-cut productivity was similar across zones (1.62, 1.43, and 2.54 t DM ha⁻¹ cut⁻¹ in AZ I, AZ II, and AZ III, respectively). The intraclass correlation coefficient was very low (ICC = 0.08), so that variation among cuts—the seasonal regrowth regime—dominates over stable differences among plots.

3.2.3. Genotype × Environment Interaction and Stability

Within this homogeneous group, partitioning of yield variance showed that the environment (altitudinal zone) was the dominant source, accounting for 75.0% of the treatment sum of squares (SS = 523.3), against a moderate genotype × environment interaction (G×E = 20.7%; SS = 144.6; *p* = 0.011) and a small genotype effect (G = 4.3%). The eight cultivars therefore respond similarly to the gradient—all yield more in favourable zones—with a real but secondary rank reordering across zones.

The AMMI model concentrated the interaction in the first axis (IPCA1 = 91.0%). The YSI identified the *Lolium* hybrid ‘Shogun’ as the most stable and productive cultivar (YSI = 5), followed by ‘Delish’ (YSI = 6) and ‘Savy’ (YSI = 7); *Festuca* ‘Quantum’ and ‘Festival’ were the most variable (YSI = 14) (Table 8 and Figure 2). The Finlay–Wilkinson regression, with slopes close to 1 in almost all cultivars, confirmed general stability within the group: ‘Confederate’ was the most responsive to favourable environments (*b* = 1.31) and ‘Quantum’ the most buffered (*b* = 0.66).

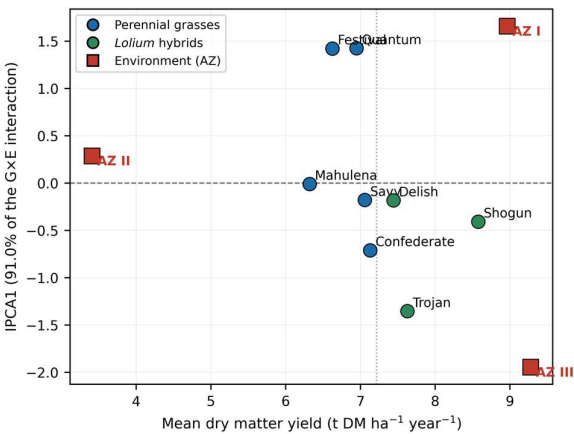


Figure 2. AMMI biplot of dry matter yields perennial grasses and *Lolium* hybrids.

Table 8. Perennial grasses and *Lolium* hybrids: mean dry matter yield, AMMI stability value, yield rank, yield stability index, and Finlay–Wilkinson parameters.

Cultivar	Mean yield (t DM ha ⁻¹ year ⁻¹)	ASV	Yield rank	YSI	FW <i>b</i>	S ² _d
Savy	7.06	1.81	5	7	1.05	0.18
Quantum	6.95	14.38	6	14	0.66	11.78
Festival	6.63	14.34	7	14	0.95	13.51
Confederate	7.13	7.22	4	9	1.31	2.52
Mahulena	6.32	0.56	8	9	1.17	0.02
Trojan	7.63	13.67	2	8	0.94	12.95
Shogun	8.58	4.14	1	5	0.91	1.32
Delish	7.44	1.85	3	6	1.01	0.22

ASV: AMMI stability value; YSI: yield stability index (lower is better); FW *b*: Finlay–Wilkinson regression coefficient; S²_d: variance of the deviations from regression. Variance partitioning within the group: G = 4.3%, E = 75.0%, G×E = 20.7%.

3.2.4. Integrated Merit (Desirability Index within Grasses and Lolium)

Within the group, the desirability index placed the *Lolium* hybrids at the top: ‘Delish’ (*D* = 0.53), ‘Trojan’ (*D* = 0.49) and ‘Shogun’ (*D* = 0.47), followed by ‘Quantum’ (*D* = 0.35); ‘Savy’ (*D* = 0.18) and ‘Mahulena’ (*D* = 0.17) closed the ranking (Figure 3). The best cultivar by zone was ‘Delish’ in AZ I (*D* = 0.59), ‘Quantum’ in AZ II (*D* = 0.26) and ‘Shogun’ in AZ III (*D* = 0.81). Although ‘Delish’ attained the highest mean desirability, ‘Shogun’ combined an almost identical desirability with the greatest stability (YSI = 5). The robustness of the ranking was verified with TOPSIS and WPM (Spearman’s ρ = 0.58–0.59), with the *Lolium* hybrids and the best perennials at the front [46].

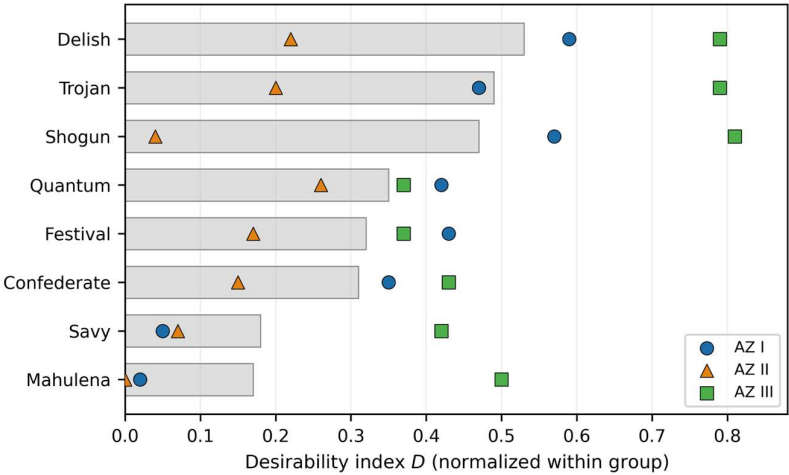


Figure 3. Overall desirability (bars) and desirability by altitudinal zone (symbols) of perennial grasses and *Lolium* hybrids, normalized within the group. The *Lolium* hybrids head the ranking.

3.3. Nutritive Value and Its Relationship with Altitude

Unlike yield, nutritive value does not depend on the cutting regime and was therefore compared across all cultivars. It differed clearly among functional groups (Table 9). The *Lolium* hybrids combined high digestibility (IVDMD $\approx$ 73%) with high CP ($\approx$ 13–15%) and moderate NDF ($\approx$ 39%). Whole-plant brassicas showed the highest IVDMD and the lowest NDF, with CP varying according to the bulb-to-foilage ratio. Temperate perennials showed higher NDF ($\approx$ 49–52%) and somewhat lower IVDMD ($\approx$ 66–69%). Differences among cultivars within each zone were significant for all variables ($p < 0.05$; Tables 10–12).

Table 9. Mean nutritive value by functional group and altitudinal zone.

Functional group	Zone	CP (%)	NDF (%)	IVDMD (%)	Ash (%)	ME (MJ kg ⁻¹ DM)
Perennial grasses	AZ I	13.1	50.2	67.9	9.3	9.97
	AZ II	14.8	43.1	71.4	8.1	10.58
	AZ III	14.6	42.9	71.1	8.4	10.52
<i>Lolium</i> hybrids	AZ I	13.8	39.5	72.9	12.7	10.84
	AZ II	12.0	43.8	74.4	9.5	11.08
	AZ III	15.7	33.2	79.2	10.3	11.91
Brassicas (whole plant)	AZ I	10.3	23.0	72.7	14.8	10.80
	AZ II	13.4	25.9	72.3	13.3	10.73
	AZ III	15.4	21.9	73.7	14.2	10.98

CP: crude protein; NDF: neutral detergent fiber; IVDMD: in vitro dry matter digestibility; ME: metabolizable energy, derived linearly from IVDMD (Equation (1)). AZ I: 2300–2800 m.a.s.l.; AZ II: 2801–3300 m.a.s.l.; AZ III: 3301–3800 m.a.s.l.

At the cultivar level (Tables 10–12), brassica fractions differed markedly: in ‘Green globe’ the bulb provided high IVDMD ($\approx 77\%$) and the foliage higher CP ($\approx 17\text{--}18\%$); in ‘Groundhog’ the contrast was more extreme, which explains its lower weighted whole-plant digestibility despite its biomass. Among the *Lolium* hybrids, ‘Shogun’ reached the highest IVDMD in the upper zone (80.66%). The highest ash concentrations corresponded to the brassicas and the *Lolium* hybrids.

Table 10. Nutritive value of the eleven cultivars in altitudinal zone I (2300–2800 m.a.s.l.).

Species and cultivar	Ash (%)	CP (%)	NDF (%)	IVDMD (%)	ME (MJ kg ⁻¹ DM)
<i>Raphanus sativus</i> (bulb)	12.74 a	6.32 c	22.39 c	72.57 a	10.78 a
<i>Raphanus sativus</i> (foliage)	15.92 a	11.56 b	41.95 b	53.25 c	7.45 c
<i>Brassica rapa</i> (bulb)	17.00 a	11.42 b	19.27 c	77.00 a	11.54 a
<i>Brassica rapa</i> (foliage)	15.94 a	17.48 a	18.08 c	75.98 a	11.36 a
<i>Brassica napus</i> ‘Titan’	13.57 a	7.44 c	17.96 c	79.01 a	11.88 a
<i>Dactylis glomerata</i> ‘Savy’	8.45 b	12.61 b	52.35 a	66.18 b	9.68 b
<i>Phalaris</i> sp. ‘Confederate’	9.50 b	13.18 a	48.46 a	68.92 b	10.15 b
<i>Festuca arundinacea</i> ‘Quantum’	9.69 b	13.50 a	48.87 a	69.00 b	10.16 b
<i>Festuca arundinacea</i> ‘Festival’	9.09 b	13.60 a	49.35 a	69.58 b	10.26 b
<i>Festulolium</i> ‘Mahulena’	9.96 b	12.59 b	52.03 a	65.67 b	9.59 b
<i>Lolium hybridum</i> ‘Trojan’	12.32 b	13.65 a	39.70 b	72.97 a	10.84 a
<i>Lolium hybridum</i> ‘Shogun’	13.16 a	13.56 a	38.60 b	72.61 a	10.78 a
<i>Lolium hybridum</i> ‘Delish’	12.52 b	14.20 a	40.22 b	73.18 a	10.88 a
<i>p-value</i>	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Different letters within a column indicate significant differences (Tukey’s test, $p < 0.05$). CP: crude protein; NDF: neutral detergent fiber; IVDMD: in vitro dry matter digestibility; ME: metabolizable energy. In the tuberous species the bulbs and the foliage were analysed separately.

Table 11. Nutritive value of the eleven cultivars in altitudinal zone II (2801–3300 m.a.s.l.).

Species and cultivar	Ash (%)	CP (%)	NDF (%)	IVDMD (%)	ME (MJ kg ⁻¹ DM)
<i>Raphanus sativus</i> (bulb)	13.30 a	13.54 a	39.26 a	57.03 c	8.10 c
<i>Raphanus sativus</i> (foliage)	12.70 a	19.74 a	36.82 a	63.77 b	9.26 b
<i>Brassica rapa</i> (bulb)	12.45 a	13.12 a	19.29 b	76.70 a	11.49 a
<i>Brassica rapa</i> (foliage)	13.44 a	17.75 a	20.81 b	77.88 a	11.69 a
<i>Brassica napus</i> ‘Titan’	14.00 a	8.09 b	19.71 b	79.16 a	11.91 a
<i>Dactylis glomerata</i> ‘Savy’	7.39 b	16.92 a	45.96 a	71.44 a	10.58 a
<i>Phalaris</i> sp. ‘Confederate’	8.06 b	16.09 a	40.59 a	71.87 a	10.65 a
<i>Festuca arundinacea</i> ‘Quantum’	8.52 b	13.73 a	45.52 a	70.52 b	10.42 b
<i>Festuca arundinacea</i> ‘Festival’	8.61 b	12.47 b	43.58 a	72.13 a	10.70 a
<i>Festulolium</i> ‘Mahulena’	8.00 b	15.02 a	40.01 a	71.24 a	10.55 a
<i>Lolium hybridum</i> ‘Trojan’	9.60 a	12.00 b	46.46 a	75.13 a	11.22 a
<i>Lolium hybridum</i> ‘Shogun’	9.80 a	11.80 b	43.36 a	73.58 a	10.95 a

Species and cultivar	Ash (%)	CP (%)	NDF (%)	IVDMD (%)	ME (MJ kg ⁻¹ DM)
<i>Lolium hybridum</i> ‘Delish’	9.17 b	12.28 b	41.46 a	74.39 a	11.09 a
p-value	0.0002	0.0016	0.0002	<0.0001	<0.0001

Different letters within a column indicate significant differences (Tukey’s test, $p < 0.05$). Abbreviations as in Table 10.

Table 12. Nutritive value of the eleven cultivars in altitudinal zone III (3301–3800 m.a.s.l.).

Species and cultivar	Ash (%)	CP (%)	NDF (%)	IVDMD (%)	ME (MJ kg ⁻¹ DM)
<i>Raphanus sativus</i> (bulb)	12.70 a	6.86 c	37.75 a	57.66 b	8.21 b
<i>Raphanus sativus</i> (foliage)	12.20 a	19.08 a	28.15 a	69.84 a	10.31 a
<i>Brassica rapa</i> (bulb)	14.18 a	15.32 a	20.03 a	77.34 a	11.60 a
<i>Brassica rapa</i> (foliage)	14.70 a	15.46 a	17.78 b	74.21 a	11.06 a
<i>Brassica napus</i> ‘Titan’	15.66 a	13.00 b	18.37 b	78.22 a	11.75 a
<i>Dactylis glomerata</i> ‘Savy’	7.96 b	14.05 b	43.56 a	70.75 a	10.46 a
<i>Phalaris</i> sp. ‘Confederate’	8.76 b	13.28 b	44.20 a	69.95 a	10.32 a
<i>Festuca arundinacea</i> ‘Quantum’	7.94 b	15.52 a	42.93 a	72.22 a	10.71 a
<i>Festuca arundinacea</i> ‘Festival’	8.39 b	14.76 a	43.26 a	71.02 a	10.51 a
<i>Festulolium</i> ‘Mahulena’	8.96 b	15.19 a	40.46 a	71.36 a	10.57 a
<i>Lolium hybridum</i> ‘Trojan’	10.30 b	15.13 a	34.98 a	77.90 a	11.69 a
<i>Lolium hybridum</i> ‘Shogun’	9.41 b	15.64 a	30.37 a	80.66 a	12.17 a
<i>Lolium hybridum</i> ‘Delish’	11.17 a	16.43 a	34.39 a	79.00 a	11.88 a
p-value	0.0002	0.0001	0.0042	0.0011	0.0011

Different letters within a column indicate significant differences (Tukey’s test, $p < 0.05$). Abbreviations as in Table 10.

The relationship between quality and altitude was statistically significant but weak. Across the 78 observations, CP increased with altitude ($r = +0.29$; $p = 0.010$), whereas ash decreased weakly and non-significantly ($r = -0.20$; $p = 0.083$). Zone means were consistent (CP of 12.4%, 14.0% and 14.6%; ash of 12.3%, 10.4% and 10.9% in AZ I, AZ II and AZ III, respectively), but altitude explained less than 10% of the variation in CP.

3.4. Predictive Models

Beyond description, predictive models were fitted to translate the data into decision rules, with the caution imposed by the small number of environments. The Finlay–Wilkinson regression — which expresses the yield of each cultivar as a linear function of the environmental index ($Y_{ij} = a_i + b_i \cdot E_{ij}$) — reproduced the observed yield of grasses and *Lolium* with a high overall fit ($R^2 = 0.82$; Figure 4a). The most stable cultivars showed almost perfect fits (‘Mahulena’ $R^2 = 1.00$; ‘Savy’ and ‘Delish’ $R^2 \geq 0.99$), whereas ‘Quantum’ ($R^2 = 0.45$) and ‘Festival’ ($R^2 = 0.59$) were less predictable because of their greater deviation from the mean response (Table 13).

Table 13. Finlay–Wilkinson equations by cultivar (perennial grasses and *Lolium* hybrids): intercept, environmental response coefficient, goodness of fit and variance of the deviations.

Cultivar	Equation ($Y = a + b \cdot E$)	R^2	S^2_d
Savy	$Y = -0.54 + 1.05 \cdot E$	0.99	0.18
Quantum	$Y = 2.18 + 0.66 \cdot E$	0.45	11.78
Festival	$Y = -0.22 + 0.95 \cdot E$	0.59	13.51
Confederate	$Y = -2.36 + 1.31 \cdot E$	0.94	2.52
Mahulena	$Y = -2.12 + 1.17 \cdot E$	1.00	0.02
Trojan	$Y = 0.86 + 0.94 \cdot E$	0.60	12.95
Shogun	$Y = 2.02 + 0.91 \cdot E$	0.93	1.32
Delish	$Y = 0.18 + 1.01 \cdot E$	0.99	0.22

E : environmental index (mean yield of the environment), equal to 8.96 (AZ I), 3.41 (AZ II) and 9.28 (AZ III) t DM ha⁻¹ year⁻¹; S^2_d : variance of the deviations from regression. Overall model fit: $R^2 = 0.82$.

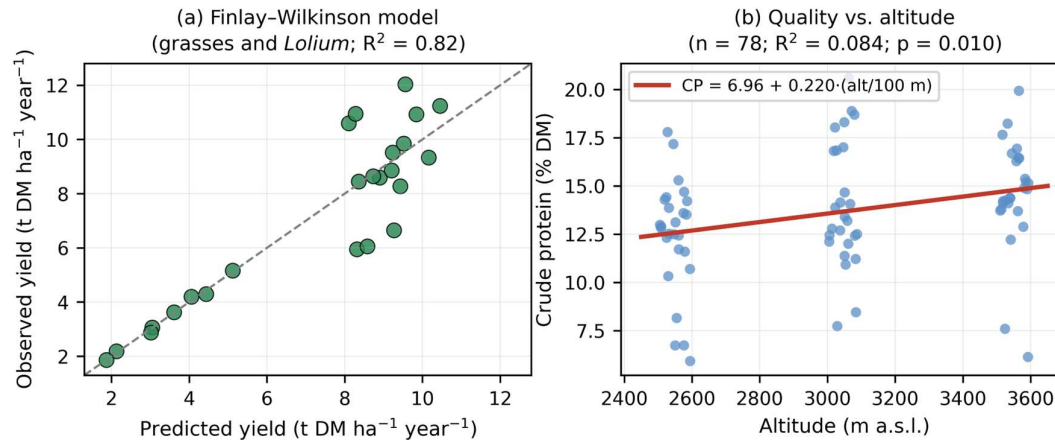


Figure 4. Predictive models. (a) Observed versus predicted yield from the Finlay–Wilkinson regression for perennial grasses and *Lolium* hybrids (dashed line: 1:1). (b) Regression of crude protein on altitude over the 78 observations (solid line: fitted model).

A linear regression across the 78 observations modeled quality as a function of altitude: CP increased significantly but weakly ($CP = 6.96 + 0.220 \times (\text{altitude}/100 \text{ m})$; $R^2 = 0.084$; $p = 0.010$; RMSE = 2.97; Figure 4b), that is, approximately 0.22 percentage points per 100 m of ascent, whereas ash, NDF, IVDMD and ME showed no significant altitudinal trends ($p \geq 0.083$). The model is valid within the sampled range (2300–3800 m.a.s.l.) and should not be extrapolated. Metabolizable energy was predicted from digestibility using Equation (1) [8], which placed energy density between 9.6 and 12.2 MJ kg⁻¹ DM in grasses and *Lolium* and between 8.7 and 11.9 MJ kg⁻¹ DM in brassicas.

4. Discussion

4.1. Contrasting Altitudinal Responses of the Two Functional Groups

The two functional groups displayed opposite altitudinal optima, which supports hypothesis H1. Brassicas concentrated their productivity at intermediate elevations and were poorly competitive above about 3300 m.a.s.l., consistent with their thermal and photoperiodic sensitivity [28,47]. The high growth rate and plant height of ‘Groundhog’ are attributable to its tuberous root and confirm its value as a rapidly established bridging crop [8,48]. The poor performance of brassicas in AZ III is consistent with the combination of low temperature, extremely low soil pH and high exchangeable aluminum recorded in that zone (Table 1) [4,5]; low temperatures may also limit microbial activity and slow nutrient release [15]. Yields obtained here for ‘Groundhog’ in AZ II exceeded those reported by Nieto-Sierra et al. [13], those of ‘Green globe’ fell within the range reported by Watt et al. [8], and those of ‘Titan’ exceeded the values of Islam et al. [47] and Dillard et al. [49], differences plausibly related to soil chemistry, altitude, fertilization and cutting time [50,51].

Conversely, perennial grasses and *Lolium* hybrids sustained high cumulative yields in both the lower and the upper zones, in line with the adaptation of *Festulolium* and hybrid ryegrass to adverse soil and climatic conditions [24,26]. Our values are lower than those reported by Butkutė et al. [21] and Sosnowski et al. [25] but higher than those of Karbivska et al. [26] and comparable to the festulolium assessments of Mwendia et al. [27] in tropical highlands, differences that most likely reflect soil properties, fertilization regime and defoliation management [20].

4.2. The Environment Dominates Yield within Comparable Cutting Regimes

Within the multiple-cut group, the environment explained three quarters of the treatment sum of squares and the G×E interaction, although significant, was moderate, which supports hypothesis H2. This result qualifies a common conclusion: the strong G×E interaction that appears when all

cultivars are analyzed jointly is largely a consequence of the opposite altitudinal responses of the two functional groups rather than of rank reordering within a comparable group. Analysing non-equivalent cutting regimes together therefore inflates the apparent interaction and can misdirect cultivar recommendations—an argument for the group-wise analytical strategy adopted here and for the use of complementary stability frameworks in multi-environment trials [31,32,34].

The per-cut model provides a mechanistic explanation for the yield minimum of the intermediate zone: the penalty is one of harvest frequency, not of per-cut productivity. In AZ II, the scope for improvement therefore lies in extending the growing season or adjusting cutting frequency—through irrigation, fertilization or a more conservative defoliation interval—rather than in replacing cultivars. The very low intraclass correlation indicates that seasonal regrowth dynamics, and not stable plot-to-plot differences, govern the observed variability, which is consistent with the strong dependence of perennial grass productivity on temperature and rainfall reported elsewhere [20,21].

4.3. Multicriteria Desirability Reorders Selection Relative to Yield Alone

The desirability index separated ‘producing more biomass’ from ‘producing the best forage’, supporting hypothesis H3. The clearest case is ‘Groundhog’: the highest-yielding cultivar of the whole trial ranked second to last within its group because its weighted whole-plant digestibility is depressed by the bulb fraction, a behavior consistent with the marked compositional heterogeneity of brassica fractions reported by Barry [19] and Kaur et al. [12]. For a dairy pasture, ‘Green globe’ therefore offers the best balance within the brassicas, whereas ‘Groundhog’ is justified where rapidly established biomass volume is the priority in the intermediate zone.

Among the multiple-cut species, ‘Delish’ achieved the highest mean desirability but ‘Shogun’ combined an almost identical value with the greatest stability and is therefore the safer choice when a single material is sought for the whole gradient. The concordance of the ranking with TOPSIS and WPM supports its robustness, in agreement with the growing use of multi-trait and multicriteria indices for cultivar recommendation [33,35,36]. The weights adopted here are an explicit, auditable and adjustable input; formal expert elicitation would allow them to be tailored to specific production objectives.

4.4. Nutritive Value, Altitude and Implications for Dairy Nutrition

Contrary to the claim of a ‘high correlation’ made in earlier accounts, the association between quality and altitude was significant but weak, so hypothesis H4 is only partially supported: nutritional value depended more on cultivar and functional group than on the gradient. The direction of the trend nevertheless agrees with reports that elevation favours the nutritive value of brassicas [14,15]. The higher NDF and lower IVDMD of temperate perennials reflect their greater proportion of cell wall [21,52], and the seasonal variability of ryegrass digestibility is well documented [22,53]. CP values for the *Lolium* hybrids fell within the range reported by Sandaña et al. [28], those of the brassicas within the ranges of Watt et al. [8] and Nieto-Sierra et al. [13], and the ME of most grasses slightly exceeded the values of Fulkerson et al. [54].

These attributes translate into consequences for the dairy cow. In energy terms, the highest-merit cultivars—‘Shogun’ (12.17 MJ kg⁻¹ DM in the upper zone), the remaining *Lolium* hybrids (≈ 11–12 MJ kg⁻¹ DM) and whole-plant brassicas (≈ 11.5 MJ kg⁻¹ DM), approach the energy density required to sustain lactation [55]. In protein terms, the CP of the *Lolium* hybrids (≈ 13–16%) and of brassica foliage (17–20%) comfortably covers requirements, in contrast with the radish bulb (6–7%), which reinforces the importance of weighting the whole plant. Voluntary intake depends largely on fiber: the low NDF of brassicas (≈ 18–22%) and the moderate NDF of the *Lolium* hybrids (≈ 39%) favour higher intake than that of temperate perennials (NDF ≈ 49–52%). Fiber digestibility is also decisive: each additional percentage unit of NDF digestibility has been associated with increases of about 0.17 kg in intake and 0.25 kg in milk yield [56,57], so the high IVDMD of the best cultivars (up to 80.66% in ‘Shogun’) is

expected to translate into greater intake and production. Supplementation with forage brassicas has been shown to modify rumen fermentation and milk production and composition [17,58,59].

The ash concentration, higher in brassicas and *Lolium* hybrids, is relevant to periparturient mineral management: in systems with scarce supplementation, the macromineral contribution of the forage affects the dietary cation–anion difference and the risk of hypocalcemia, a factor associated with metabolic disorders, reduced intake and lower production [60–62]. This point deserves emphasis in the study region, where most producers offer pastures at an advanced maturity stage with little mineral supplementation [2].

4.5. Complementarity and Practical Recommendations by Altitudinal Zone

The apparent ‘strong G×E interaction’ of the joint analysis mainly reflects the opposite altitudinal responses of the two groups, which makes them complementary in space and time rather than substitutes. Persistent, multiple-cut grasses and *Lolium* hybrids sustain forage supply in the lower and upper zones, whereas brassicas, with rapid establishment and a thermal optimum in the intermediate zone, close the seasonal gap as a rotation crop or supplement [9,63]. Table 14 summarizes the operational recommendations by zone, intended for direct use by producers and advisers.

Table 14. Operational recommendations by altitudinal zone for dairy feeding in the northern highlands of Peru, derived from the stability and desirability analyses and from the nutritive profiles by functional group.

Zone	Recommended cultivars	Utilization window	Nutritional role	Expected benefit
AZ I (lower)	<i>Lolium</i> ‘Delish’, Shogun’; <i>Festuca arundinacea</i> ‘Quantum’/ ‘Festival’	Successive cuts throughout the year	Energy and protein; moderate NDF	Sustained supply and high intake
AZ II (intermediate)	<i>Brassica rapa</i> ‘Green globe’ (quality); <i>Raphanus sativus</i> ‘Groundhog’ (biomass)	Dry season; single cut (~117 days)	High IVDMD and ME; low NDF	Closing of the dry-season feed gap
AZ III (upper)	<i>Lolium</i> ‘Shogun’, ‘Trojan’; <i>Phalaris</i> sp. ‘Confederate’	Successive cuts	Maximum IVDMD/ME and protein	Production and quality at high elevation

NDF: neutral detergent fiber; IVDMD: in vitro dry matter digestibility; ME: metabolizable energy. AZ I: 2300–2800 m.a.s.l.; AZ II: 2801–3300 m.a.s.l.; AZ III: 3301–3800 m.a.s.l.

Accordingly, in the lower zone (AZ I) the *Lolium* hybrids (‘Delish’, ‘Shogun’) and *Festuca arundinacea* offer the best combination of productivity and digestibility. In the intermediate zone (AZ II), where grasses reduce their number of harvests, brassicas—and notably ‘Green globe’—exploit their thermal optimum, ideally as a rotation crop or seasonal supplement. In the upper zone (AZ III), *Lolium* ‘Shogun’ and ‘Trojan’ and *Phalaris* ‘Confederate’ sustain the highest yields with good quality. Forage sustainability in the northern highlands is thus favored by a selection that is specific to both zone and functional group, combining the multiple-cut persistence of grasses and *Lolium* with the seasonal contribution of brassicas at intermediate elevations, an approach aligned with the wider agenda of adaptation in Andean livestock systems [6,7].

4.6. Limitations and Future Research

Three limitations should be acknowledged. First, the trial comprised a single production year and three environments, which saturates the degrees of freedom of the interaction and justifies complementing AMMI with joint regression; multi-year validation is a priority. Second, the environments differ simultaneously in temperature, rainfall and soil chemistry, so the altitudinal effect is a composite one, and the predictive models should not be extrapolated beyond 2300–3800 m.a.s.l. Third, the desirability weights, although explicit and auditable, are expert judgements; formal elicitation and sensitivity analysis would strengthen the recommendation. Future work should also incorporate animal-level measurements—intake, milk yield and composition, and enteric methane

emissions, for which forage brassicas show promising results [16,18,64,65], so as to close the loop between agronomic performance and productive response.

5. Conclusions

The eleven cultivars evaluated constitute a viable option for improving forage sustainability in the northern highlands of Peru, with a performance conditioned by both altitudinal zone and functional group. Because of their contrasting cutting regimes, the yield of brassicas (single cut) and that of grasses and *Lolium* (multiple-cut cumulative) are not equivalent and were analyzed separately. Among grasses and *Lolium*, the altitudinal zone was the dominant factor of yield (75.0% of the variation), with a moderate genotype × environment interaction; the hybrid ‘Shogun’ was the most stable and ‘Delish’ attained the highest desirability. Among brassicas there was no significant genotype × environment interaction—all optimized in the intermediate zone—and ‘Green globe’ showed the best integrated nutritional merit, as against ‘Groundhog’, the highest-yielding cultivar. The lower annual yield of the intermediate zone in multiple-cut species was due to a smaller number of harvests, not to lower per-cut productivity. Higher altitude did not limit perennial grasses or *Lolium* hybrids, but it did limit brassicas above about 3300 m a.s.l. Nutritional value depended more on cultivar and functional group than on altitude, whose association with crude protein was significant but weak; the highest ash concentrations corresponded to the brassicas. The complementarity of the two groups supports zone-specific recommendations: *Lolium* and *Festuca* in the lower zone, brassicas (Green globe) in the intermediate zone, and *Lolium* and *Phalaris* in the upper zone. The predictive models of yield (Finlay–Wilkinson, $R^2 = 0.82$) and quality (crude protein as a function of altitude), together with the translation of forage attributes into energy, protein, intake and periparturient mineral health, turn these results into a planning tool for high-Andean dairy feeding.

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Abbreviations

The following abbreviations are used in this manuscript:

AMMI	Additive main effects and multiplicative interaction
ASV	AMMI stability value
AZ	Altitudinal zone

CP	Crude protein
D	Derringer–Suich overall desirability
DM	Dry matter
FW	Finlay–Wilkinson joint regression
G×E	Genotype × environment interaction
ICC	Intraclass correlation coefficient
IPCA	Interaction principal component axis
IVDMD	In vitro dry matter digestibility
ME	Metabolizable energy
NDF	Neutral detergent fiber
RCBD	Randomized complete block design
REML	Restricted maximum likelihood
RMSE	Root mean square error
TOPSIS	Technique for order of preference by similarity to ideal solution
WPM	Weighted product model
YSI	Yield stability index

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