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INTRODUCTION

Livestock production constitutes a vital component of agricultural systems in sub-Saharan Africa, contributing significantly to food security and rural livelihoods. Nigeria's livestock population comprises approximately 76 million goats, 43.4 million sheep, and 18.4 million cattle, predominantly concentrated in northern regions (FMARD, 2017; FAO, 2023). Feed remains the primary production constraint, accounting for 60-70% of operational costs in intensive systems (USDA FAS, 2024). The semi-arid northeastern region faces acute forage scarcity during dry seasons, necessitating identification of high-yielding forage species adapted to harsh environmental conditions (Muhammad, 1999; Malami *et al*., 2020).

Columbus grass (*Sorghum almum* Parodi), a natural hybrid between Johnson grass (*S. halepense*) and grain sorghum (*S. bicolor*), has emerged as a promising tropical and subtropical forage crop (Cook *et al*., 2005). It exhibits fast growth and high-yielding potential, generally producing 4-12 t DM ha^{-1}, occasionally reaching 20 t DM ha^{-1} under optimal conditions (Dahlberg *et al*., 2011). Columbus grass provides quality forage for pasture, cut-and-carry systems, hay, and silage when properly managed (Cook *et al*., 2005; Lanyasunya *et al*., 2007).

Nitrogen availability represents a major constraint to forage productivity in tropical soils, where low nitrogen levels limit dry matter yields and necessitate fertilizer applications (Diaz, 2014). Nitrogen fertilization significantly influences yield and quality characteristics of forage sorghum (Eltelib *et al*., 2006; Sogut *et al*., 2023). Recent studies demonstrate that nitrogen application increases forage yield, dry matter percentage, and crude protein content while reducing structural fiber components (Sogut *et al*., 2023). However, optimal nitrogen rates vary with environmental conditions, soil type, and cultivar characteristics, requiring location-specific evaluation (Diaz, 2014).

Inter-row spacing influences crop growth, yield, light interception, and resource competition (Batista *et al*., 2021). Row spacing affects canopy closure, light penetration, and dry matter yield, with spacing optimization depending on cultivar characteristics and environmental conditions (Andrews, 1970; De Souza *et al*., 2024). Narrower rows generally increase plant density and provide weed suppression benefits, while wider spacing reduces intra-plant competition and may enhance individual plant development (Andrews, 1970). Previous research on sorghum in Nigeria has demonstrated significant spacing effects on growth and yield parameters (Andrews, 1970), though limited information exists on optimal spacing for Columbus grass under Damaturu's agro-ecological conditions.

Forage quality is determined by fibre composition, particularly neutral detergent fibre (NDF) and acid detergent fibre (ADF), which affect digestibility and voluntary intake by ruminants (Van Soest *et al*., 1991; NRC, 2001). Cell wall components including NDF, ADF, and acid detergent lignin (ADL) are important quality characteristics related to crop maturity and growth stage (Van Soest, 1963). High fiber concentrations reduce forage digestibility and limit animal performance. Research on Columbus grass shows that crude protein decreased from 15.6 to 5.2% DM between 6 and 14 weeks of growth, while NDF increased from 52 to 69% DM (Lanyasunya *et al*., 2007), highlighting the importance of understanding fiber dynamics relative to management practices.

Nitrogen fertilization affects fiber fractions through its influence on plant morphology, maturity, and tissue composition. Studies on forage sorghum demonstrate that nitrogen application reduces NDF and ADF concentrations by promoting leaf development over stem growth and delaying tissue lignification (Sogut *et al*., 2023). Understanding these interactions is crucial for optimizing management practices that maximize both yield and nutritive value.

Despite the potential of Columbus grass as a forage crop for semi-arid Nigeria, comprehensive information on the interactive effects of nitrogen fertilization and inter-row spacing on its productivity and quality remains limited, particularly for northeastern Nigeria. Previous Nigerian studies on Columbus grass (Muhammad, 1999; Olanite *et al*., 2010; Malami *et al*., 2020) have established the species' adaptability but require local validation under Damaturu conditions. This study was therefore designed to evaluate the effects of nitrogen fertilizer rates and inter-row spacing on dry matter yield and fiber fractions of Columbus grass. Specific objectives were to: (i) Determine the effect of nitrogen fertilizer rates on dry matter yield and fiber fractions of Columbus grass; (ii) Assess the influence of inter-row spacing on dry matter yield and fiber fractions of Columbus grass; and (iii) Evaluate the interactive effects of nitrogen fertilizer and inter-row spacing on dry matter yield and fiber fractions of Columbus grass

MATERIALS AND METHODS

Experimental Site

The study was conducted at Yobe State University Teaching and Research Farm, Damaturu (11°44′40″–11°45′N, 11°57′40″–11°58′E), approximately 7 km along Damaturu–Biu road. The area experiences hot, dry climate with 500–1000 mm annual rainfall concentrated between June and September. Temperatures peak at 30–42°C during March–May. Vegetation is Sudano-Sahelian savanna with an eight-month dry season. Soils are well-drained, moderately deep tropical sandy loam.

Experimental Design and Treatments

A 5 × 3 factorial arrangement in Randomized Complete Block Design (RCBD) with four replications was employed. Treatments comprised five nitrogen levels (0, 75, 150, 175, 200 kg N ha^{-1}) applied as urea (46% N) and three inter-row spacings (30, 50, 70 cm), yielding 15 treatment combinations randomly assigned to 16 m^2 plots (4 m × 4 m) with 0.5 m inter-plot spacing and 1 m alleys between blocks.

Soil Analysis

Composite topsoil samples (0–15 cm depth) were collected from nine random locations before planting, air-dried, and sieved through 2 mm mesh. Soil analyses included pH (1:2.5 soil:water ratio using pH meter), organic carbon (Walkley-Black chromic acid wet oxidation method), particle size distribution (hydrometer method; Bouyoucos, 1951), total nitrogen (Macro-Kjeldahl digestion method; Jackson, 1964), available phosphorus (Bray No. 1 extraction method; Bray and Kurtz, 1945), exchangeable cations (K^+ and Na^+ by flame photometry; Ca^{2+} and Mg^{2+} by EDTA titration), and cation exchange capacity (ammonium acetate extraction method at pH 7.0).

Planting Material and Management

Certified *S. almum* seeds were obtained from National Animal Production Research Institute (NAPRI), Shika, Kaduna State. Seeds were treated with fungicide-insecticide seed dressing compound (Cardinal® dust containing 20% w/w thiamethoxam, 20% w/w metalaxyl-M, and 2% w/w difenoconazole) at 1 g per 400 g seed before planting. Seeds were sown at treatment-specified spacings (30, 50, or 70 cm between rows) following rainfall onset in June 2023, with 10 cm intra-row spacing. Nitrogen fertilizer was applied in two split doses: 50% at 3 weeks after sowing (WAS) and 50% at 6 WAS. Manual weeding occurred at 3 and 6 WAS using hand hoes.

Data Collection and Laboratory Analysis

At 12 WAS (physiological maturity), herbage biomass was harvested from one 0.25 m^2 quadrat (0.5 m × 0.5 m) randomly placed within the net plot area of each experimental unit. Herbage was cut at 5 cm above ground level using hand sickle, weighed fresh, and air-dried under shade to constant weight for dry matter determination. Dry matter yield per hectare was calculated by extrapolation.

Dried herbage samples were ground through 1 mm screen using a Wiley mill and analyzed for fiber fractions using the Van Soest detergent system (Van Soest *et al*., 1991; Van Soest, 1963). Neutral detergent fiber (NDF) was determined by refluxing samples with neutral detergent solution containing sodium lauryl sulfate and EDTA. Acid detergent fiber (ADF) was determined by sequential extraction with acid detergent solution containing cetyltrimethylammonium bromide in 1N H_2SO_4. Acid detergent lignin (ADL) was determined by treating ADF residue with 72% H_2SO_4. Hemicellulose content was calculated as NDF − ADF, and cellulose content as ADF − ADL.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate for factorial experiments in RCBD using Statistix 10.0 software (Analytical Software, Tallahassee, FL). Treatment means showing significant F-test ($P < 0.05$) were separated using Duncan's New Multiple Range Test (DNMRT) at 5% probability level.

RESULTS

Soil Characteristics

The experimental site soil had loamy sand texture (80.96% sand, 6.56% silt, 12.48% clay) with slightly acidic to neutral pH (6.9 H_2O; 7.2 $CaCl_2$). Soil fertility was characterized by low organic carbon (8.12 g kg^{-1}), total nitrogen (0.92 g kg^{-1}), and available phosphorus (0.70 mg kg^{-1}). Exchangeable bases showed high Na^+ (0.36 cmol kg^{-1}), low K^+ (0.87 cmol kg^{-1}), moderate Ca^{2+} (0.85 cmol kg^{-1}), and relatively high Mg^{2+} (0.53 cmol kg^{-1}). Cation exchange capacity was moderate (5.61 cmol kg^{-1}). The low nitrogen and phosphorus levels indicated need for fertilizer application to support optimal forage production.

Table 1: Soil Physical and Chemical Properties (0 – 15cm) of the Soil at the Experimental Site during the 2023 Rainy Season

Parameter	Unit
Sand	80.96%
Silt	6.56%
Clay	12.48%
Textural class	Loamy sand
PH (H_2 o)	6.9
PH (cacl$_2$)	7.2 spacing
Organic carbon	8.12 gkg^{-1}
Total nitrogen	0.92 gkg^{-1}
Ca	0.85 cmol (+) kg^{-1}
Mg	0.53 cmol (+) kg^{-1}
K	0.87cmol (+) kg^{-1}
Na	0.36cmol (+) kg^{-1}
TEB	2.61cmol (+) kg^{-1}
CEC	5.61 %

Ca = Calcium, K = Phosphorus, Mg = Magnessium, TEB = Total exchangeable bases, CEC = Cation exchangeable capacity

Herbage Dry Matter Yield

Nitrogen fertilization significantly ($P < 0.05$) affected dry matter yield, with progressive increases from 0.49 t ha^{-1} at 0 kg N ha^{-1} to 1.78 t ha^{-1} at 200 kg N ha^{-1} (Table 2). All nitrogen rates differed significantly from each other, demonstrating clear dose-response relationship. Inter-row spacing also significantly ($P < 0.05$) influenced dry matter yield, with 70 cm spacing producing highest yield (1.29 t ha^{-1}), followed by 50 cm (1.21 t ha^{-1}) and 30 cm (0.95 t ha^{-1}).

Table 2: Herbage Dry Matter Yield of Columbus Grass as Influenced by Nitrogen Fertilizer and Inter-Row Spacing

Treatment	Herbage Dry Matter Yield (t ha^{-1})
Nitrogen Fertilizer (kg ha^{-1})	
0	0.49^{f}
75	0.94^{e}
150	1.23^{c}
175	1.39^{b}
200	1.78^{a}
SEM	0.022
Significance	**
Inter-row Spacing (cm)	
30	0.95^{c}
50	1.21^{b}
70	1.29^{a}
SEM	0.017
Significance	**

^{abcdef} Means within a column followed by different superscripts differ significantly ($P < 0.05$) by Duncan's New Multiple Range Test. ** = $P < 0.01$; SEM = Standard Error of Mean.

Significant ($P < 0.05$) nitrogen-spacing interaction occurred (Table 3), with 200 kg N ha^{-1} × 70 cm producing optimal yield (1.83 t ha^{-1}), statistically similar to 200 kg N ha^{-1} × 50 cm (1.76 t ha^{-1}) but superior to all other combinations. The lowest yield (0.41 t ha^{-1}) occurred with 0 kg N ha^{-1} × 30 cm spacing.

Table 3: Interaction Effect of Nitrogen Fertilizer and Inter-Row Spacing on Herbage Dry Matter Yield of Columbus Grass at 12 Weeks after Sowing

Treatment Combination	Dry Matter Yield (t ha⁻¹)
0 kg N ha⁻¹ × 30 cm	0.41[k]
0 kg N ha⁻¹ × 50 cm	0.54[j]
0 kg N ha⁻¹ × 70 cm	0.56[j]
75 kg N ha⁻¹ × 30 cm	0.80[i]
75 kg N ha⁻¹ × 50 cm	0.98[h]
75 kg N ha⁻¹ × 70 cm	1.05[gh]
150 kg N ha⁻¹ × 30 cm	1.09[fg]
150 kg N ha⁻¹ × 50 cm	1.18[ef]
150 kg N ha⁻¹ × 70 cm	1.28[de]
175 kg N ha⁻¹ × 30 cm	1.13[fg]
175 kg N ha⁻¹ × 50 cm	1.31[cd]
175 kg N ha⁻¹ × 70 cm	1.39[bc]
200 kg N ha⁻¹ × 30 cm	1.48[b]
200 kg N ha⁻¹ × 50 cm	1.76[a]
200 kg N ha⁻¹ × 70 cm	1.83[a]
SEM	0.039
Significance	**

[abcdefghijk] Means followed by different superscripts differ significantly ($P < 0.05$) by Duncan's New Multiple Range Test. ** = $P < 0.01$; SEM = Standard Error of Mean.

Fibre Fractions

Nitrogen fertilization significantly ($P < 0.05$) influenced all fiber fractions (Table 4). Increasing nitrogen from 0 to 200 kg ha⁻¹ progressively reduced NDF (40.91 to 30.76%), ADF (28.72 to

22.54%), ADL (8.47 to 6.95%), and hemicellulose (12.19 to 8.22%). Cellulose content increased slightly from 7.09% at 0 kg N ha^{-1} to 9.49% at 200 kg N ha^{-1}. Dry matter content increased with nitrogen application, ranging from 88.63% at 0 kg N ha^{-1} to 93.06% at 200 kg N ha^{-1}.

Inter-row spacing had no significant effect ($P > 0.05$) on any fiber fraction parameter measured (NDF, ADF, ADL, hemicellulose, cellulose) or dry matter content. Values remained relatively stable across the three spacing treatments (30, 50, and 70 cm).

Table 4: Fibre Fractions of Columbus Grass as Influenced by Nitrogen Fertilizer and Inter-Row Spacing

Treatment	DM (%)	NDF (%)	ADF (%)	ADL (%)	HEM (%)	CEL (%)
Nitrogen Fertilizer (kg ha^{-1})						
0	88.63^{d}	40.91^{a}	28.72^{a}	8.47^{a}	12.19^{a}	7.09^{c}
75	90.18^{c}	38.11^{b}	26.95^{b}	8.39^{a}	11.11^{b}	8.20^{bc}
150	92.30^{ab}	35.25^{c}	25.24^{c}	7.24^{a}	10.01^{c}	8.89^{b}
175	92.37^{ab}	33.80^{d}	23.81^{d}	7.11^{b}	9.69^{c}	9.41^{a}
200	93.06^{a}	30.76^{e}	22.54^{e}	6.95^{c}	8.22^{d}	9.49^{a}
SEM	0.483	0.681	0.281	0.330	0.276	0.352
Significance	*	**	**	*	**	*
Inter-row Spacing (cm)						
30	92.46	36.08	25.70	8.23	10.38	9.24
50	92.58	35.92	25.54	8.13	10.38	9.09
70	91.88	34.32	25.12	8.34	10.20	9.28
SEM	0.382	1.211	1.110	0.248	0.146	0.284
Significance	NS	NS	NS	NS	NS	NS

^{abcde} Means within a column followed by different superscripts differ significantly ($P < 0.05$) by Duncan's New Multiple Range Test. * = $P < 0.05$; ** = $P < 0.01$; NS = Not significant; SEM = Standard Error of Mean; DM = Dry matter; NDF = Neutral detergent fibre; ADF = Acid detergent fibre; ADL = Acid detergent lignin; HEM = Hemicellulose; CEL = Cellulose.

DISCUSSION

Herbage Dry Matter Yield Response to Nitrogen

The superior dry matter yield at 200 kg N ha^{-1} (1.78 t ha^{-1}) reflects enhanced nitrogen availability for vegetative growth and biomass accumulation. Nitrogen enhances chlorophyll synthesis, photosynthetic efficiency, and protein formation, thereby increasing growth rates and herbage output (Diaz, 2014). Similar findings were reported by Eltelib *et al*. (2006), who observed significant yield increases in forage sorghum with nitrogen application up to 240 kg ha^{-1}. More recently, Sogut *et al*. (2023) demonstrated progressive yield improvements in sorghum with increasing nitrogen rates, consistent with our results.

The yields obtained in this study (0.49–1.78 t ha^{-1} at first harvest, 12 WAS) are comparable to ranges reported by Malami *et al*. (2020) for Columbus grass under semi-arid Nigerian conditions, though lower than yields reported in more humid regions of southwestern Nigeria by Olanite *et al*. (2010). These differences likely reflect rainfall distribution, soil characteristics, and total growing season length variations between locations. Our single harvest at 12 weeks represents one cut; annual yields with multiple harvests would be substantially higher.

The low yields at zero nitrogen (0.49 t ha^{-1}) underscore the severe nitrogen limitation in the experimental site soil (0.92 g kg^{-1} total N), confirming the critical need for nitrogen fertilization in this environment. The progressive response to increasing nitrogen rates through 200 kg ha^{-1} without evidence of yield plateau suggests that Columbus grass in this environment has high nitrogen demand and utilization capacity.

Inter-Row Spacing Effects on Yield

The higher yield at 70 cm spacing (1.29 t ha^{-1}) compared to 50 cm (1.21 t ha^{-1}) and 30 cm (0.95 t ha^{-1}) likely resulted from reduced intra-plant competition for light, moisture, and nutrients at wider spacing. While higher plant densities from narrow spacing typically increase yield per unit area in grain crops, forage grasses respond differently due to their tillering capacity and compensatory growth mechanisms (Andrews, 1970). Similar results were reported by Batista *et al*. (2021) in forage sorghum, where moderate to wide row spacing (100–150 cm) optimized dry matter yield by balancing plant density with individual plant development.

The yield advantage of 70 cm spacing may be particularly important under the semi-arid conditions of Damaturu, where moisture availability can limit plant growth. Wider spacing allows individual plants greater access to soil moisture between rainfall events. Andrews (1970) reported similar spacing responses for tall sorghum cultivars in northern Nigeria, noting that wider spacing reduced lodging and improved air circulation, which may also have contributed to enhanced performance in our study.

Nitrogen-Spacing Interaction

The significant interaction between nitrogen and spacing demonstrates that optimal spacing varies with nitrogen availability. At zero nitrogen, spacing had minimal effect due to severe nutrient limitation constraining growth regardless of plant arrangement. However, at 200 kg N ha^{-1}, the combination with 70 cm spacing (1.83 t ha^{-1}) maximized yield by providing both adequate nutrients and sufficient space for individual plant development. This finding has practical implications: under high fertility conditions, wider spacing should be used to capitalize on enhanced plant growth potential, while under lower fertility, spacing effects diminish in importance.

De Souza *et al*. (2024) recently reported similar nitrogen-spacing interactions in sorghum densification studies, where optimal plant arrangement changed with fertility level. The statistically similar performance of 200 kg N ha^{-1} with both 70 cm (1.83 t ha^{-1}) and 50 cm (1.76 t ha^{-1}) spacing suggests flexibility in row configuration at high nitrogen levels, allowing farmers to optimize based on equipment availability and other management considerations.

Nitrogen Effects on Fiber Fractions

The progressive reduction in NDF, ADF, ADL, and hemicellulose with increasing nitrogen application represents improved forage quality. Nitrogen promotes development of younger, more digestible leaf tissues with lower structural carbohydrate accumulation (Sogut *et al*., 2023). The NDF reduction from 40.91% at 0 kg N ha^{-1} to 30.76% at 200 kg N ha^{-1} indicates substantially improved potential digestibility, as NDF represents the total cell wall fraction that limits intake and digestibility in ruminants (Van Soest *et al*., 1991).

The ADF values (28.72–22.54%) remained within the acceptable range for high-quality forage. The NRC (2001) recommends ADF concentrations below 31% for optimal ruminant performance, suggesting that all nitrogen treatments except the control produced acceptable quality forage. The ADL reduction from 8.47% to 6.95% is particularly significant, as lignin forms recalcitrant cross-links with cellulose and hemicellulose that severely limit microbial digestion (Van Soest, 1963). Lower lignin content at higher nitrogen rates reflects delayed tissue maturation and reduced lignification.

These findings align with Sogut *et al*. (2023), who reported that nitrogen application (0–240 kg ha^{-1}) in sorghum significantly reduced NDF and ADF while improving crude protein content. The mechanism involves nitrogen's role in promoting leaf growth over stem development and maintaining plants in a more juvenile, less lignified physiological state (Eltelib *et al*., 2006). The slight increase in cellulose content with nitrogen application (7.09 to 9.49%) likely reflects increased total biomass and cell wall quantity, though the proportion of less digestible lignified tissue decreased.

Spacing Effects on Fiber Fractions

The lack of significant spacing effects on fiber fractions suggests that, under the conditions of this study, plant architectural modifications from spacing variations did not substantially alter tissue composition or maturity patterns. This contrasts with some reports showing spacing effects on fiber content (Batista *et al*., 2021), but aligns with other studies where spacing primarily influenced yield quantity rather than quality parameters (Andrews, 1970).

Columbus grass exhibits considerable phenotypic plasticity through tillering capacity, which m ay allow plants at different spacings to achieve similar tissue composition at a given harvest maturity (Cook *et al*., 2005). At narrow spacing, individual plants produce fewer but potentially more leafy tillers, while at wide spacing, plants produce more tillers with potentially more stem development, resulting in similar overall tissue composition (Lanyasunya *et al*., 2007). The uniform harvest timing (12 WAS) may also have standardized maturity-related fiber accumulation across spacing treatments.

The independence of forage quality from spacing provides management flexibility, allowing farmers to optimize row configuration for yield, weed control, or equipment constraints without compromising nutritive value. This finding has particular practical importance for smallholder farmers with limited equipment options.

Practical Implications and Limitations

Results demonstrate that Columbus grass responds favorably to nitrogen fertilization under Damaturu's semi-arid conditions, with 175–200 kg N ha^{-1} optimizing both yield and quality. Economic analysis of input costs versus forage value would refine recommendations. Split nitrogen applications during critical growth stages (as employed in this study) likely enhanced nitrogen use efficiency compared to single applications (Diaz, 2014).

The 70 cm inter-row spacing provides adequate individual plant development without excessive competition, making it suitable for both manual and mechanized operations. This spacing also facilitates weed management between rows, important in the early establishment phase.

Study limitations include single-season, single-location evaluation. Multi-year, multi-location trials would better characterize genotype × environment interactions and long-term soil fertility effects. The single harvest at 12 WAS represents only one cutting cycle; subsequent regrowth responses to nitrogen and spacing should be evaluated to determine annual production potential. Water availability effects were not directly measured but likely influenced treatment responses given the semi-arid environment.

CONCLUSION

Columbus grass (*Sorghum almum*) demonstrates excellent adaptation to Damaturu's semi-arid conditions, producing acceptable dry matter yields with improved forage quality under appropriate nitrogen management. Nitrogen fertilization at 200 kg N ha^{-1} significantly enhanced dry matter yield (1.78 t ha^{-1}) while substantially improving forage quality by reducing fiber fractions (NDF 30.76%, ADF 22.54%, ADL 6.95%). The 70 cm inter-row spacing optimized yield (1.29 t ha^{-1}) without compromising quality parameters. Significant nitrogen-spacing interaction indicated that optimal spacing varies with fertility level, with the combination of 200 kg N ha^{-1} and 70 cm spacing producing maximum performance (1.83 t ha^{-1}).

For practical application in northeastern Nigeria's semi-arid zone, we recommend nitrogen application at 175–200 kg N ha^{-1} in split doses (50% at 3 WAS, 50% at 6 WAS) combined with

70 cm inter-row spacing to maximize both yield and forage quality. Harvesting at 12 weeks after sowing balances yield with acceptable fiber fractions for ruminant nutrition.

Future research should evaluate multiple cutting frequencies, nitrogen application timing optimization, long-term soil fertility effects, and economic analysis of input-output ratios to develop comprehensive Columbus grass production systems for the region. Multi-location trials across northeastern Nigeria's agro-ecological zones would enhance recommendation applicability.

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AUTHOR CONTRIBUTIONS

M.I.M.: Conceptualization, methodology, field data collection, statistical analysis, manuscript drafting. Rabi, A. S.: Supervision, experimental design, manuscript review. Busami, F. M.: Laboratory analysis, data interpretation. A.K.Y.: Literature review, manuscript editing. All authors read and approved the final manuscript.

ATTESTATION

This article has neither been published nor is under consideration for publication in any other Journal.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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