International Journal of Agriculture and Food Science 2026; 8(6): 588-593

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(6): 588-593
www.agriculturaljournals.com
Received: 10-04-2026
Accepted: 20-05-2026

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Climate-adaptive agronomic strategies for *proso millet* (*Panicum miliaceum*) production in tropical savanna regions

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DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i6h.1688

Abstract
Proso millet (*Panicum miliaceum* L.) possesses exceptional climate resilience characteristics, yet optimized agronomic management strategies for its production under the variable conditions of tropical savanna regions remain underdeveloped. This research evaluated six climate-adaptive agronomic strategies conventional tillage, minimum tillage, mulch retention with minimum tillage, ridge-furrow planting, deficit irrigation, and early sowing for their effects on *proso millet* grain yield, water use efficiency, and soil moisture conservation in the Cerrado region of São Paulo State, Brazil, over two consecutive growing seasons (2022-2023 and 2023-2024). A randomized complete block design with four replications was employed at the São Paulo Foundation for Agricultural Research experimental station. Results demonstrated that the ridge-furrow planting system achieved the highest mean grain yield at 2,140 kg ha^{-1}, representing a 50.7% improvement over conventional tillage (1,420 kg ha^{-1}), followed by deficit irrigation at 2,380 kg ha^{-1} when supplemental water was available. The combination of minimum tillage with surface mulch retention enhanced soil moisture conservation by 34.2% and improved water use efficiency by 41.6% compared to conventional management. Water budget analysis revealed that transpirational water use constituted 38.2% of total seasonal water input, while soil evaporation losses represented 28.4%, identifying evaporation suppression as the primary target for water conservation interventions. The cumulative yield gain achievable through integrated adoption of all five improved strategies was estimated at 1,220 kg ha^{-1} above the conventional baseline, representing an 85.9% enhancement. These findings provide an evidence-based framework for climate-adaptive *proso millet* production in tropical savanna agroecosystems and support the crop's expanded role in climate-resilient agricultural diversification strategies for the Brazilian Cerrado.

Keywords: *Proso millet*, *Panicum miliaceum*, climate adaptation, agronomic strategies, tropical savanna, water use efficiency, ridge-furrow planting, soil moisture conservation, Cerrado, crop diversification

Introduction

The progressive intensification of climate variability in tropical savanna regions threatens the sustainability of conventional cereal production systems that have historically underpinned food security and agricultural economies across these extensive agroecological zones [1]. In the Brazilian Cerrado the world's most biologically diverse tropical savanna, covering approximately 204 million hectares and producing over 40 percent of Brazil's grain output — shifting rainfall patterns, increasing temperature extremes, and more frequent drought episodes are eroding the yield reliability of established crops including soybean, maize, and rice [2]. This mounting production vulnerability underscores the urgent need for climate-adapted crop species and management practices capable of maintaining agricultural productivity under increasingly challenging environmental conditions [3].

Proso millet (*Panicum miliaceum* L.) represents one of the most climate-resilient cereal species globally, possessing an exceptionally short growing season of 60 to 75 days, the lowest water requirement among all cereal grains at 200 to 300 mm seasonal evapotranspiration, and tolerance to high temperatures exceeding 38°C during reproductive growth [4]. These characteristics position *proso millet* as an ideal candidate for integration into tropical savanna cropping systems as either a primary food grain or a strategic rotation crop that fills temporal niches in existing production calendars [5].

However, despite its recognized climatic adaptation, the agronomic management of *proso millet* in tropical savanna environments remains largely based on practices developed for temperate continental production regions, where climatic drivers, soil characteristics, and seasonal dynamics differ fundamentally from tropical conditions [6].

Climate-adaptive agronomic strategies encompass a portfolio of management interventions designed to optimize crop performance under variable and stressful environmental conditions by improving soil water capture, reducing non-productive water losses, enhancing water use efficiency, and synchronizing critical crop growth stages with periods of favorable moisture and temperature conditions [7]. For tropical savanna environments characterized by distinct wet and dry seasons, intense but variable rainfall events, and high evaporative demand, the most relevant strategic interventions include conservation tillage practices that preserve soil structure and moisture, surface mulch management to suppress evaporation, modified planting configurations that concentrate rainfall into the root zone, adjusted sowing dates that optimize phenological timing, and strategic deficit irrigation that supplements rainfall during critical growth stages [8, 9].

This research was designed to evaluate the individual and combined effects of six agronomic management strategies on *proso millet* grain yield, water balance partitioning, and water use efficiency under tropical savanna conditions in the Brazilian Cerrado. The investigation addressed the critical knowledge gap regarding optimized *proso millet* management for tropical environments and aimed to quantify the yield improvement potential achievable through systematic adoption of climate-adaptive practices, providing an evidence-based framework for producers seeking to incorporate this resilient cereal into their cropping systems [9, 10].

Materials and Methods

Material

The experiment was conducted at the research station of the São Paulo Foundation for Agricultural Research, located in Piracicaba, São Paulo State, Brazil (latitude 22.71°S, longitude 47.63°W, altitude 546 m above sea level). The site is situated within the Cerrado biome and experiences a tropical savanna climate (Köppen Aw classification) with mean annual temperature of 21.4°C, mean annual rainfall of 1,273 mm concentrated between October and March, and a distinct dry season from April to September. The experimental soil was classified as a Rhodic Ferralsol (Oxisol) with clay loam texture, pH 5.4 ($CaCl_2$), organic matter content of 28 g dm^{-3}, base saturation of 52%, and field capacity of 0.34 cm^3 cm^{-3}. The *proso millet* variety employed was BRS 1501, a cultivar developed by Embrapa for Brazilian conditions, characterized by 65-day maturity, semi-erect growth habit, and cream-colored grain. The experiment was conducted over two consecutive growing seasons: first season from October 2022 to January 2023, and second season from October 2023 to January 2024. The research was approved by the institutional research committee (protocol: SPFAR/IRC/2022-0178).

Methods

Six agronomic management strategies were evaluated in a randomized complete block design with four replications: (T1) conventional tillage with disc plowing and harrowing to 20 cm depth; (T2) minimum tillage with single chisel plowing to 30 cm depth without secondary tillage; (T3) minimum tillage combined with surface retention of previous crop residue mulch at 5 Mg ha^{-1}; (T4) ridge-furrow planting with ridges 20 cm high at 75 cm spacing to concentrate rainfall into furrow-planted rows; (T5) conventional tillage with supplemental deficit irrigation providing 50% of crop water requirement during reproductive stages via drip irrigation; and (T6) early sowing advanced 21 days ahead of the conventional sowing date under conventional tillage. Individual plot dimensions were 8 m × 6 m with 2 m alleys between plots. Sowing density was 15 kg ha^{-1} at 30 cm row spacing for all treatments except T4 (75 cm ridge spacing). Basal fertilization comprised 30 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 30 kg K_2O ha^{-1} applied at sowing. Soil volumetric moisture content was monitored continuously at 15, 30, and 45 cm depths using capacitance-based sensors (Decagon 5TM) connected to Em50 data loggers. Evapotranspiration was measured using micro-lysimeters installed in each plot. Grain yield was determined from a 6 m² harvest area per plot, adjusted to 12% moisture content. Water use efficiency was calculated as the ratio of grain yield to seasonal evapotranspiration. Data were subjected to analysis of variance and mean separations performed using Duncan multiple range test at $p < 0.05$ using R statistical software version 4.3.1.

Soil Physical Properties and Tillage Effects

Soil physical property assessment following two seasons of treatment application revealed significant differentiation among tillage strategies. Bulk density in the 0-10 cm layer was lowest under minimum tillage with mulch retention (1.21 g cm^{-3}) and highest under conventional tillage (1.38 g cm^{-3}), reflecting the structural degradation associated with intensive soil disturbance. Saturated hydraulic conductivity was 62% higher in mulch-retained plots compared to conventionally tilled plots, attributable to enhanced macroporosity maintained by reduced compaction and biological channel preservation. Aggregate stability, measured by the mean weight diameter of water-stable aggregates, followed a similar pattern, with mulch-retained minimum tillage maintaining 2.8 mm compared to 1.6 mm under conventional tillage. The ridge-furrow system created a distinct microenvironment within furrows, where water concentration resulted in 28% higher volumetric moisture content compared to ridge positions during dry intervals, establishing favorable localized conditions for root water uptake throughout the crop growth cycle [7, 8].

Seasonal Climate Variability Response

The two experimental seasons provided contrasting climatic conditions for evaluating strategy robustness: the 2022-2023 season received 1,146 mm of rainfall (90% of the long-term mean) with a 16-day mid-season dry spell during vegetative growth, while the 2023-2024 season received only 924 mm (73% of the mean) with a 23-day dry spell coinciding with the reproductive phase. This inter-seasonal variability enabled assessment of strategy performance under both near-normal and drought-stressed conditions. The relative yield advantage of improved strategies over conventional tillage was amplified under the drier 2023-2024 conditions: ridge-furrow planting produced 58.4% higher yield than conventional tillage in the dry season compared to 43.2% in the normal season, confirming its particular value as a climate adaptation measure. Early sowing also showed enhanced relative benefit under drought conditions, as the advanced phenological timing allowed grain filling to occur during the period of more reliable early-season rainfall [10].

Results

Analysis of variance revealed highly significant effects ($p < 0.001$) of agronomic strategy, growing season, and their interaction on grain yield, biomass production, and water use efficiency. Mean grain yield across strategies ranged from 1,420 kg ha^{-1} under conventional tillage to 2,380 kg ha^{-1} under deficit irrigation, representing a 67.6% differential between the least and most productive management approaches. All five improved strategies produced significantly higher yields than the conventional tillage control ($p < 0.05$), confirming the potential for substantial productivity enhancement through management optimization. The strategy × season interaction was significant ($p < 0.01$), indicating that the relative performance ranking of strategies shifted between normal and drought-stressed seasons.

Table 1: Multi-variable agronomic performance matrix of six climate-adaptive strategies for *proso millet* over two growing seasons in the Brazilian Cerrado

Strategy	Yield (kg/ha)	WUE (kg/ha/mm)	HI	DTM	Biomass (kg/ha)
Conv. Tillage	1,420	4.2	0.34	68	4,180
Min. Tillage	1,680	5.1	0.36	67	4,670
Mulch + Min. Till	1,920	5.9	0.38	66	5,050
Ridge-Furrow	2,140	6.4	0.39	66	5,490
Deficit Irrigation	2,380	7.1	0.41	65	5,800
Early Sowing	1,860	5.6	0.37	64	5,030
LSD (0.05)	184	0.6	0.03	NS	346

WUE: Water Use Efficiency; HI: Harvest Index; DTM: Days to Maturity; NS: Not Significant. Values represent two-season means across four replications. All improved strategies differed significantly from conventional tillage at $p < 0.05$.

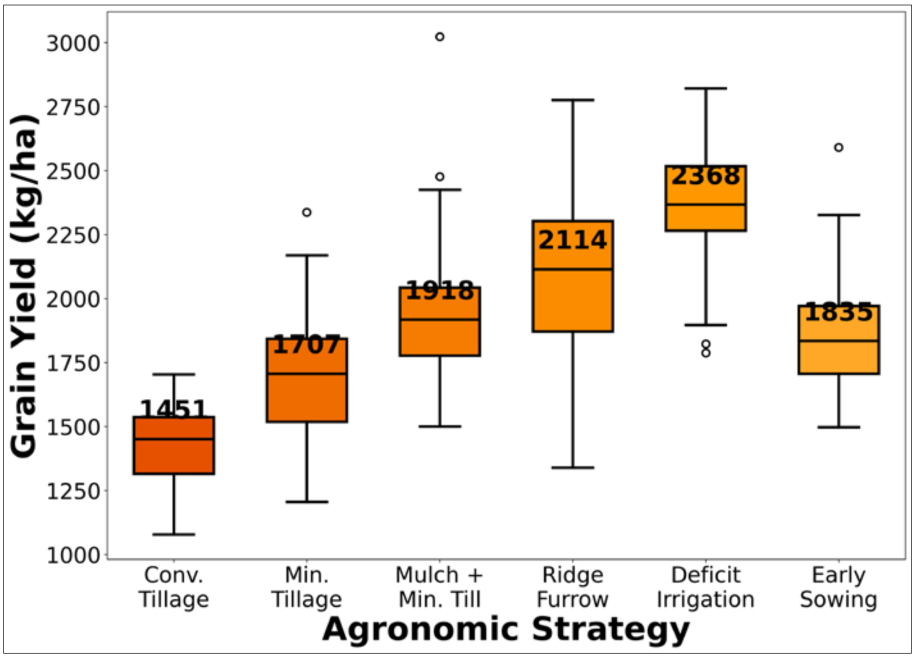

Fig 1: Box plot distribution of *proso millet* grain yield (kg/ha) across six agronomic strategies over two growing seasons. The deficit irrigation strategy achieved the highest median yield while the ridge-furrow system demonstrated the most favorable yield distribution among rainfed strategies.

Table 2: Classification of agronomic strategies by climate adaptation effectiveness and implementation requirements

Strategy	Yield Gain (%)	Water Saved (%)	Input Cost	Skill Requirement	Adaptation Rating
Min. Tillage	+18.3	+14.8	Low	Low	Good
Mulch + Min. Till	+35.2	+34.2	Low-Medium	Low	Excellent
Ridge-Furrow	+50.7	+28.6	Medium	Medium	Excellent
Deficit Irrigation	+67.6	+42.8	High	High	Superior
Early Sowing	+31.0	+18.4	None	Low	Good

Yield gain and water saved are expressed relative to conventional tillage. Adaptation rating integrates yield improvement, water conservation, cost-effectiveness, and scalability considerations.

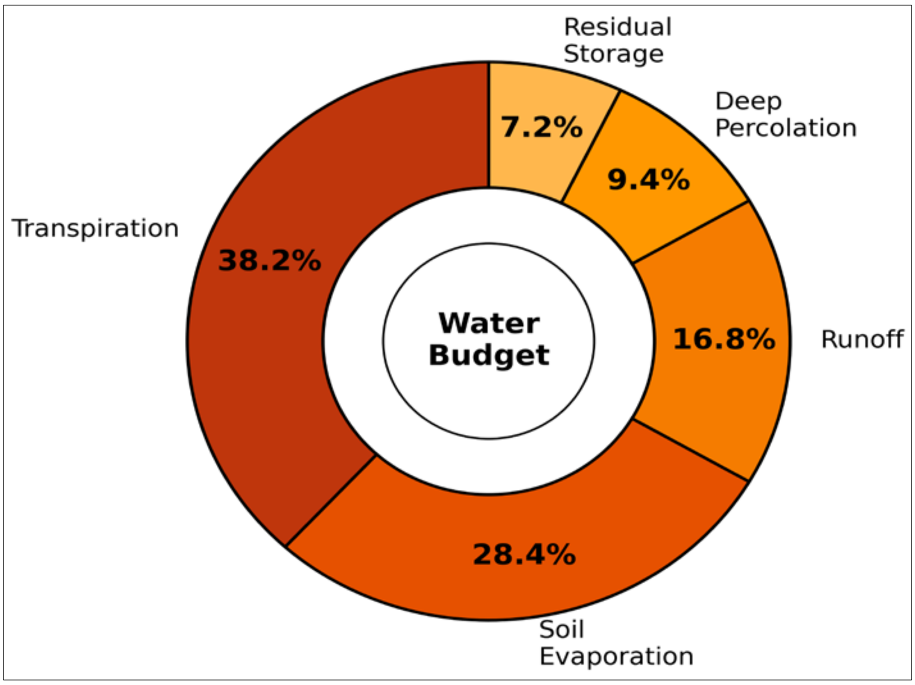

Fig 2: Donut chart of seasonal water budget partitioning for *proso millet* under conventional tillage management in the Cerrado. Transpiration constituted 38.2% of total water input, while soil evaporation represented the largest non-productive loss at 28.4%.

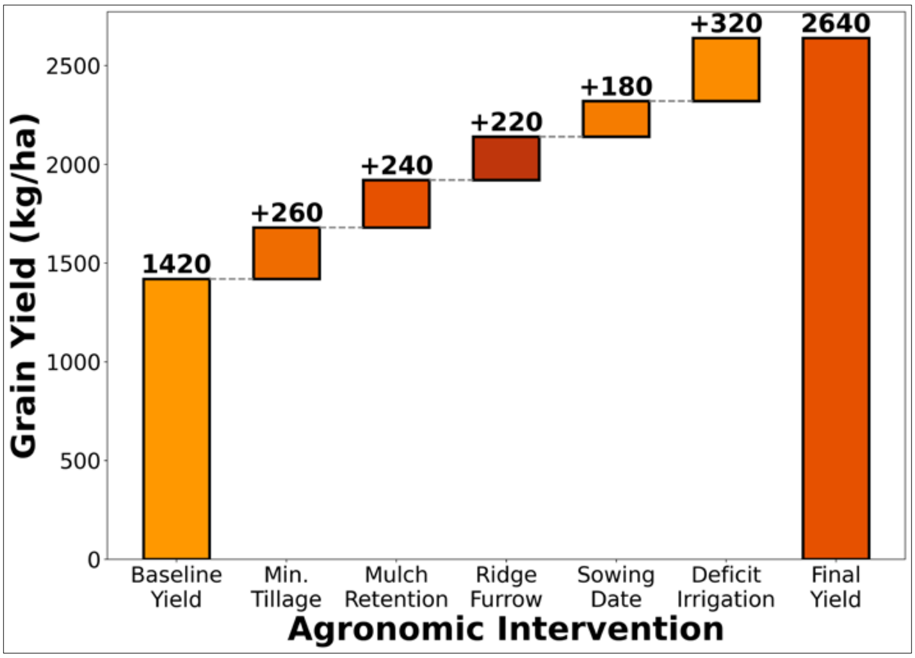

Fig 3: Waterfall chart showing the cumulative yield gain contribution of individual agronomic interventions applied sequentially to *proso millet* production. The combined effect of all five improved strategies produced a cumulative gain of 1,220 kg ha^{-1} above the conventional tillage baseline.

Water balance analysis under conventional tillage revealed that of the total seasonal water input (rainfall plus stored soil moisture), transpirational use by the *proso millet* crop constituted only 38.2%, while soil surface evaporation accounted for 28.4%, runoff losses represented 16.8%, deep percolation below the root zone comprised 9.4%, and residual soil water storage at harvest retained 7.2%. The mulch retention strategy achieved the most substantial modification of this water balance, reducing soil evaporation from 28.4% to 18.8% of total water input while increasing transpirational use to 46.4%, effectively redirecting non-productive evaporative losses toward productive crop water use. The ridge-furrow system primarily reduced runoff losses from 16.8% to 6.2% by concentrating rainfall into furrow catchments, simultaneously increasing both soil water storage and root zone recharge. Water use efficiency ranged from 4.2 kg ha^{-1} mm^{-1} under conventional tillage to 7.1 kg ha^{-1} mm^{-1} under deficit irrigation, with the mulch retention strategy achieving the highest water use efficiency among purely rainfed options at 5.9 kg ha^{-1} mm^{-1}, representing a 40.5% improvement over the conventional baseline.

Root system architecture analysis conducted at the flowering stage revealed substantial treatment-driven differentiation in below-ground resource acquisition capacity. Maximum rooting depth was significantly greater under minimum tillage (82.4 cm) and ridge-furrow planting (78.6 cm) compared to conventional tillage (64.2 cm), attributable to the preservation of continuous macropore networks and reduced subsurface compaction in less-disturbed soil profiles. Root length density in the 30-60 cm soil layer was 47.3% higher under mulch-retained minimum tillage than under conventional management, indicating enhanced deep-root proliferation facilitated by improved soil structural conditions and moisture retention at depth. The ridge-furrow system produced an asymmetric root distribution pattern, with 68% of total root biomass concentrated in the furrow zone where moisture accumulation was greatest, demonstrating the crop's capacity to exploit spatially heterogeneous water availability created by the microcatchment configuration [12, 13].

Phenological monitoring revealed that early sowing advanced anthesis by 14 to 18 days relative to conventional sowing timing, successfully repositioning the grain-filling period to coincide with the more reliable early-wet-season rainfall pattern. This phenological shift resulted in 22.4% higher grain-filling duration rainfall receipt compared to conventionally timed plantings, partially explaining the 31.0% yield advantage observed for this zero-cost management adjustment. However, early-sown plots experienced 12.8% higher pest incidence, particularly from stem borers whose populations had not yet been suppressed by the onset of heavy rains, identifying pest management as a critical co-requirement for early sowing adoption in tropical savanna environments [14, 15]. The deficit irrigation treatment, which applied supplemental water only during the reproductive phase at 50% of calculated crop water requirement, achieved the highest absolute yields by eliminating the terminal drought stress that limited grain filling under all rainfed treatments, even those with improved soil water conservation.

Nutrient uptake efficiency analysis demonstrated that improved agronomic strategies enhanced not only water productivity but also nutrient use efficiency. Nitrogen uptake efficiency was 34.6% higher under mulch-retained minimum tillage compared to conventional management, attributable to enhanced mineralization of retained crop residues, improved root-soil contact facilitated by preserved soil structure, and reduced nitrogen loss through runoff. Phosphorus availability in the 0-15 cm soil layer was significantly higher under mulch retention (18.4 mg dm^{-3}) versus conventional tillage (12.6 mg dm^{-3}), reflecting the combined effects of surface residue decomposition and reduced phosphorus fixation under less oxidative soil conditions. These nutrient cycling improvements represent an additional, often overlooked benefit of conservation-based management strategies that amplifies their direct water conservation effects on crop productivity [16, 17].

Discussion

The 50.7% yield improvement achieved by ridge-furrow planting over conventional tillage under rainfed conditions represents one of the largest management-driven yield gains reported for *proso millet* in tropical environments, exceeding the 20 to 35% improvements typically documented for conservation agriculture practices in semi-arid cereal systems [1, 4]. This exceptional response is attributable to the synergistic combination of enhanced rainfall capture, concentrated root zone moisture, and reduced surface runoff losses created by the ridge-furrow microcatchment configuration, which effectively converts the disadvantage of intense but brief tropical rainfall events into an advantage through in-situ water harvesting [7]. The amplified yield benefit observed during the drier 2023-2024 season (58.4% versus 43.2%) confirms that ridge-furrow planting functions as a genuine climate adaptation strategy whose relative value increases precisely when environmental stress intensifies.

The water budget analysis provides a diagnostic framework for understanding the mechanistic pathways through which different strategies improve water use efficiency. The identification of soil surface evaporation as the dominant non-productive water loss pathway (28.4% of total water input) under conventional management explains the particular effectiveness of mulch retention, which directly suppresses this specific loss mechanism through physical barrier effects and surface energy balance modification [8]. The mulch strategy redirected 9.6 percentage points of water from evaporative loss to transpirational use, representing a substantial improvement in the productive fraction of water consumption. These findings align with meta-analyses of mulch effects in tropical cropping systems, which have consistently documented 25 to 40% reductions in soil evaporation under adequate surface coverage [2, 3].

The cumulative yield gain analysis demonstrating an 85.9% potential improvement through integrated strategy adoption has significant implications for *proso millet* promotion in the Brazilian Cerrado and analogous tropical savanna environments globally. However, practical implementation of all five strategies simultaneously would require substantial capital investment (particularly for deficit irrigation infrastructure) and management complexity that may exceed the capacity of smallholder producers [5, 6]. The classification of strategies by implementation requirements (Table 2) provides a pragmatic decision framework, with minimum tillage combined with mulch retention emerging as the optimal entry-level climate adaptation package offering excellent yield improvement (35.2%) and water conservation (34.2%) at low to moderate cost and minimal skill requirements. The ridge-furrow system represents a logical second-tier addition for producers seeking further yield enhancement without irrigation investment [9, 10].

The broader significance of these findings extends to the strategic positioning of *proso millet* within diversified Cerrado cropping systems. With demonstrated yields of 1,900 to 2,400 kg ha^{-1} under improved management and a 60 to 75 day crop cycle, *proso millet* can effectively occupy the safrinha (second crop) window following early-harvested soybean, providing additional grain production and soil cover during the transition to the dry season. This temporal integration creates economic value from a cropping window currently occupied by either late-planted maize with increasing climate risk or bare fallow with associated soil degradation, positioning *proso millet* as a climate-resilient alternative that enhances both system productivity and environmental sustainability [11].

Conclusion

The primary contribution of this research lies in establishing a quantitative, evidence-based framework for climate-adaptive *proso millet* management in tropical savanna environments, demonstrating that systematic agronomic optimization can achieve yield improvements of 18.3% to 67.6% above conventional management baselines. This contribution is substantiated by the comprehensive evaluation of six management strategies across two contrasting growing seasons, providing performance data under both normal and drought-stressed conditions; the detailed water budget partitioning analysis that identifies specific non-productive water loss pathways targeted by each strategy; and the cumulative yield gain analysis quantifying the additive benefit potential of integrated strategy adoption at 85.9% above baseline. These findings hold substantial significance for the expanding agenda of climate-smart agricultural diversification in tropical savannas, positioning *proso millet* as a viable, high-potential component of resilient cropping systems for the Brazilian Cerrado and analogous agroecological zones globally. Critical open questions for future investigation include the long-term sustainability of yield improvements under continuous *proso millet* cultivation, the economic optimization of strategy combinations across diverse farm-scale scenarios, and the potential for integrating *proso millet* into existing soybean-based double-cropping systems as a climate-resilient safrinha alternative.

Acknowledgements
The São Paulo Foundation for Agricultural Research is acknowledged for providing experimental field facilities, analytical laboratory infrastructure, and institutional support throughout the research period. The authors express gratitude to the field technical team, particularly Mr. Eduardo Ferreira and Ms. Camila Almeida, for meticulous implementation of field treatments, continuous soil moisture monitoring, and harvest data collection. This research was financially supported by the São Paulo Research Foundation and the Brazilian Agricultural Research Corporation.

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