

Intercropping rice with forage plants as a pathway for sustainable intensification and pasture recovery in tropical upland systems¹

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ABSTRACT

Management decisions regarding the choice of forage species and sowing timing may affect crop and pasture establishment and overall system efficiency. This study aimed to evaluate the agronomic performance, yield, and land-use efficiency of upland rice intercropped with *Urochloa brizantha* cv. Marandu under sowing strategies in tropical conditions. Field experiments were conducted to assess rice yield, forage biomass production, and the efficiency of the intercropping system compared to monoculture. The treatments included forage sowing times in relation to the establishment of the rice crop. Indicators of sustainable intensification, including the land equivalent ratio (LER), resource-use efficiency, and system resilience, were also evaluated. Rice yields ranged from 2.4 to 3.3 Mg ha⁻¹ and were not reduced by intercropping, when compared with monocropping. The simultaneous forage sowing produced up to 6.8 Mg ha⁻¹ of forage dry matter, whereas delayed sowing at 45 days after emergence increased the rice yield and resulted in LER values above 2.0. The integration strategy improved the land-use efficiency and contributed to pasture recovery, supporting intercropping agricultural systems.

KEYWORDS: *Urochloa brizantha*, crop-livestock integration, forage grass establishment, rice-forage intercropping.

RESUMO

Consórcio de arroz com plantas forrageiras como via para a intensificação sustentável e a recuperação de pastagens em sistemas de terras altas tropicais

Decisões de manejo relacionadas à escolha de espécies forrageiras e ao momento de semeadura podem influenciar no estabelecimento de culturas e pastagens, bem como na eficiência global do sistema. Objetivou-se avaliar o desempenho agrônomo, produtividade e eficiência do uso da terra de arroz de terras altas consorciado com *Urochloa brizantha* cv. Marandu sob estratégias de semeadura em condições tropicais. Experimentos de campo foram conduzidos para avaliar a produtividade do arroz, produção de biomassa forrageira e eficiência do consórcio em relação ao monocultivo. Os tratamentos incluíram épocas de semeadura da forrageira em relação ao estabelecimento da cultura do arroz. Também foram avaliados indicadores de intensificação sustentável, incluindo o índice de equivalência de área (IEA), eficiência no uso de recursos e resiliência do sistema. As produtividades do arroz variaram de 2,4 a 3,3 Mg ha⁻¹ e não foram reduzidas pelo cultivo consorciado, em comparação ao monocultivo. A semeadura simultânea das forrageiras proporcionou produção de até 6,8 Mg ha⁻¹ de matéria seca, enquanto a semeadura aos 45 dias após a emergência aumentou a produtividade do arroz e resultou em valores de IEA superiores a 2,0. A estratégia de integração melhorou a eficiência do uso da terra e contribuiu para a recuperação das pastagens, favorecendo sistemas agrícolas consorciados.

PALAVRAS-CHAVE: *Urochloa brizantha*, integração lavoura-pecuária, estabelecimento de gramíneas forrageiras, consórcio arroz-forrageira.

INTRODUCTION

Agriculture in tropical regions plays a strategic role in global food security. However, production systems face increasing pressures from climate variability, land degradation, and competition for

land resources (Adami et al. 2020). In many tropical countries, including Brazil, yield gaps remain substantial due to soil fertility constraints, irregular rainfall, and the limited adoption of integrated management practices (Oliveira et al. 2024). These challenges reinforce the need for sustainable

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intensification strategies capable of increasing yield while reducing pressure for agricultural expansion into native ecosystems (Yuan et al. 2024).

Pasture degradation represents a major limitation to livestock production and system sustainability in tropical agroecosystems. In Brazil, more than half of the pasture area exhibits some degree of degradation, resulting in low animal productivity and inefficient land use (LAPIG 2018). Recovering pasture productivity through integrated crop-livestock systems has been identified as a key pathway for increasing meat and milk production, improving soil quality, and enhancing farm resilience under climate variability (Dias-Filho 2016, Oliveira et al. 2024).

Crop-forage intercropping systems have gained attention because of their ability to combine grain production with pasture establishment within the same season. These systems provide continuous soil cover, improve nutrient cycling, reduce weed pressure, and enhance water-use efficiency, thereby supporting conservation agriculture and no-tillage systems (Crusciol et al. 2012, Andrade et al. 2020). In addition, integrated systems contribute to soil carbon accumulation and biological activity, strengthening long-term sustainability and ecosystem services (Vieira et al. 2024).

Although intercropping systems involving maize, sorghum, and soybean have been widely studied, rice-forage intercropping remains less explored, particularly in tropical upland systems. The rapid early growth of tropical forage grasses may increase competition for light, water, and nutrients, potentially reducing rice yield and harvestability, if not properly managed (Silva et al. 2004, Oliveira et al. 2009). Therefore, management strategies that regulate crop-forage competition are essential to ensure system feasibility and productivity.

The introduction of the Clearfield® technology has created new opportunities for rice-based integrated systems. The use of imidazolinone herbicides, such as imazapyr and imazapic, allows the selective suppression of early forage growth, enabling a better coexistence between crop and forage components (Castro et al. 2018, Santos et al. 2021, Santos et al. 2024). However, despite the widespread adoption of *Urochloa brizantha* in tropical pastures, limited information is available on how forage sowing time affects crop performance, pasture establishment, and system-level outcomes in upland rice systems.

Thus, this study evaluated the effects of forage sowing time and establishment method on rice yield, forage productivity, and economic performance, in a tropical rice-forage intercropping system. We hypothesized that: delayed forage sowing would reduce interspecific competition and preserve rice yield; simultaneous sowing would enhance forage biomass production and accelerate pasture establishment; and intercropping would improve land-use efficiency and overall system productivity, when compared with rice monocropping.

MATERIAL AND METHODS

The study was conducted at the Embrapa Arroz e Feijão, in Santo Antônio de Goiás, Goiás state, Brazil (16°28'00"S, 49°17'00"W, and 823 m of altitude), during the 2017/2018 and 2018/2019 growing seasons. According to the Köppen climate classification, the region has an Aw climate (tropical Savanna), with mean annual rainfall of 1,505 mm and average annual temperature of 22.9 °C. Monthly rainfall and maximum and minimum air temperatures recorded during the growing seasons are presented in Figure 1.

The soil was classified as a clay-textured Latossolo Vermelho Acriférico típico (Santos et al. 2025), equivalent to a Typic Acrustox (USDA 2014). Prior to the establishment of the experiment, soil samples collected from the 0-20 cm layer showed a pH of 5.6 and an organic matter content of 38 g kg⁻¹. The concentrations of P, K, Cu, Zn, Fe, and Mn were 22.3, 147, 0.8, 7.8, 19.8, and 8.0 mg dm⁻³, respectively, whereas those of Ca, Mg, Al, and potential acidity (H+Al) were 26.4, 17.2, 1.0, and 20 mmol_c dm⁻³, respectively. Chemical analyses were performed according to the methodology described by Donagema et al. (2011).

The experiment was arranged in a randomized complete block design with four replicates in each growing season. The treatments were organized in a 2 × 3 + 7 factorial scheme. Intercropping treatments consisted of the combination of two sowing methods for *Urochloa brizantha* cv. Marandu (broadcast or soil incorporation) and three forage sowing times relative to upland rice establishment: at rice sowing, 20 days after emergence (DAE), and 45 DAE. Seven additional treatments consisted of rice and forage monocultures established using the same sowing times and methods, allowing comparisons between

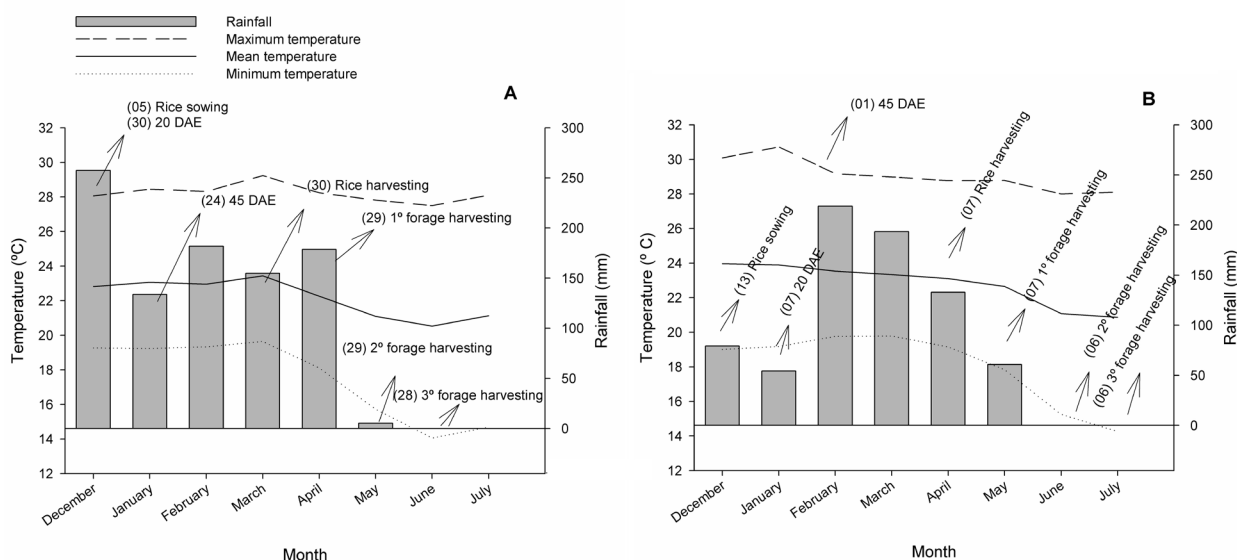


Figure 1. Rainfall and maximum, mean, and minimum air temperatures recorded during the upland rice-forage grass intercropping experiment in Santo Antônio de Goiás, Goiás state, Brazil, during the 2017/2018 (A) and 2018/2019 (B) growing seasons.

integrated and sole-crop systems. Each plot measured 3.5×10 m, and the central four rice rows were used as the harvest area.

The imidazolinone-tolerant upland rice cultivar BRS A501 CL was sown at a density of 100 seeds m^{-2} , with a row spacing of 0.35 m. Prior to sowing, the area was desiccated with glyphosate (2,400 g a.e. ha^{-1}). Forage was sown at 15 kg ha^{-1} (crop value = 50 %) when incorporated into the soil, and at 30 kg ha^{-1} when broadcast, due to the lower emergence of broadcast-sown plants (Santos et al. 2015). In the incorporation method, the seeds were placed at an approximate depth of 2-3 cm. Fertilization followed regional recommendations for the Cerrado (Brazilian Savannah) (Sousa & Lobato 2004), consisting of 200 kg ha^{-1} of monoammonium phosphate at sowing and 100 kg ha^{-1} of N as urea, split between tillering and panicle initiation.

Weed control and regulation of early forage growth were performed using imazapyr + imazapic (Kifix®, BASF), applied at a spray volume of 200 L ha^{-1} . Herbicide doses and application timings were adjusted according to the duration of crop-forage coexistence in each treatment (Table 1).

The rice was harvested at 115 days after sowing, using a combine harvester adjusted to a cutting height of 0.15 m. Rice agronomic traits were evaluated at physiological maturity using 10 plants $plot^{-1}$, including panicle density, number of grains per panicle, and

1,000-grain weight. Grain yield was determined by harvesting the effective area, threshing the grains, and adjusting the grain moisture content to 13 %.

Forage dry matter yield was assessed at 30, 60, and 90 days after rice harvest (DAH) using quadrat sampling (0.25 m^2 ; 4 subsamples $plot^{-1}$). The samples were dried in a forced-air oven at 65 °C until constant weight, and subsequently weighed to determine the dry matter yield. The crude protein content (CP) was determined at 90 DAH, using the equation: $CP = N (\%) \times 6.25$, where N is the nitrogen concentration determined in the samples by the Kjeldahl method (Malavolta et al. 1997).

Intercropping performance was evaluated using the land equivalent ratio (LER), crowding coefficient (K), and aggressivity index (A), following the methodologies proposed by Mead & Willey (1980) and Agegnehu et al. (2006). The competitive interactions between the intercropped species were assessed through LER, K, and A, according to

Table 1. Herbicide (imazapyr + imazapic) doses and application timings used in the intercropping system between upland rice cultivar BRS A501 CL and *Urochloa brizantha* cv. Marandu under forage sowing times.

Grass sowing time	Dosage and time of herbicide applying
0 DAE of the rice	70 + 70 g c.p. ha^{-1} at 20 and 45 DAE
20 DAE of the rice	100 + 75 g c.p. ha^{-1} at 0 and 45 DAE
45 DAE of the rice	70 + 70 g c.p. ha^{-1} at 0 and 20 DAE

DAE: days after emergence; c.p.: commercial product.

the equation proposed by Mead & Willey (1980): $LER = (Y_{1,2}/Y_{1,1}) + (Y_{2,2}/Y_{2,1})$.

The aggressivity index was calculated according to the methodology proposed by Agegnehu et al. (2006), using the following equation: $A_{rice} = [Y_{1,2}/(Y_{1,1} \times Y_{1,2})] - [(Y_{2,1})/(Y_{2,2} \times Y_{2,1})]$ or $A_{U.marandu} = [(Y_{2,1})/(Y_{2,2} \times Y_{2,1})] - [Y_{1,2}/(Y_{1,1} \times Y_{1,2})]$, where Y_1 and Y_2 represent the dry matter yields of the rice cultivar BRS A501 CL and *Urochloa brizantha* cv. Marandu, respectively. $Y_{1,1}$ represents the yield of BRS A501 CL under monoculture, and $Y_{1,2}$ the yield of rice intercropped with *Urochloa brizantha* cv. Marandu. Likewise, $Y_{2,1}$ and $Y_{2,2}$ represent the dry matter yield of *Urochloa brizantha* cv. Marandu under monoculture or intercropped with the rice cultivar BRS A501 CL, respectively (Baumann et al. 2001, Biabani et al. 2008).

The crowding coefficient (K) was determined according to the methodology proposed by Agegnehu et al. (2006), using the following equation: $K = (Y_{1,2} \times Z_{2,1})/[(Y_{1,1} - Y_{1,2}) \times Z_{1,2}]$ or $K = (Y_{2,1} \times Z_{1,2})/[(Y_{2,2} - Y_{2,1}) \times Z_{2,1}]$, where Y represents the dry matter yield of the rice cultivar BRS A501 CL (subscript 1) and *Urochloa brizantha* cv. Marandu (subscript 2), whereas $Z_{1,2}$ and $Z_{2,1}$ represent the sown proportions of rice and *Urochloa brizantha* cv. Marandu, respectively.

The economic performance was assessed based on production costs and revenues from grain yield and market prices (IFAG 2019, IPEA 2019). According to Borghi et al. (2013), crop-pasture systems allow gains per area of up to 5 kg ha⁻¹ day⁻¹, depending on forage allowance, and the crude protein content must be above 7 % (Van Soest 1994).

Meat yield per kilogram was estimated based on forage allowance per hectare in the two agricultural years. First year-broadcast sowing: 0 DAE = grazing days $\times$ 5.0 kg d⁻¹ ha⁻¹; 20 DAE = 4.4 kg d⁻¹ ha⁻¹; 45 DAE = 1.37 kg d⁻¹ ha⁻¹. Incorporation sowing: 0 DAE = grazing days $\times$ 5.0 kg d⁻¹ ha⁻¹; 20 DAE = 4.32 kg d⁻¹ ha⁻¹; 45 DAE = 1.56 kg d⁻¹ ha⁻¹. Second year-broadcast sowing: 0 DAE = grazing days $\times$ 4.89 kg d⁻¹ ha⁻¹; 20 DAE = 4.48 kg d⁻¹ ha⁻¹; 45 DAE = 5.0 kg d⁻¹ ha⁻¹. Incorporation sowing: 0 DAE = grazing days $\times$ 5.0 kg d⁻¹ ha⁻¹; 20 DAE = 3.51 kg d⁻¹ ha⁻¹; 45 DAE = 3.0 kg d⁻¹ ha⁻¹.

Thereafter, the grazing time was calculated according to Crusciol et al. (2012), considering 365 days per year and subtracting 115 days corresponding to the rice cultivar BRS A501 CL crop management, as well as 60 days corresponding to the rest period between rice harvest and the first grazing period.

Both Crusciol et al. (2012) and Borghi et al. (2013) emphasize that these rest periods are important for adequate pasture establishment. Therefore, these pastures were available for grazing for 190, 210, and 235 days, respectively for the sowing times of 0, 20, and 45 DAE.

Production data were used for the economic efficiency analysis of the rice-forage intercropping system, considering the sowing treatments and the economic efficiency indicators proposed by Guiducci et al. (2012). For this purpose, net income (NI), leveling point (LP), total productivity of factors (TPF), and rate of return on investment (RR) were calculated according to the following equations: Net income (NI) = total revenue - total cost; Leveling point (LP) = total cost/product price; Total productivity of factors (TPF) = total revenue/total cost; Return rate (RR) = TPF - 1.

Total revenue was calculated by multiplying the mean grain yield by the average price per kilogram of rice (Borghi et al. 2013). The forage component, in the economic viability analysis, was evaluated based on meat productivity per area (kg d⁻¹ ha⁻¹), according to Crusciol et al. (2012) and Borghi et al. (2013). For this purpose, the average price per kilogram of meat paid to farmers on the respective evaluation dates was considered.

Data were analyzed using the R software. Rice grain yield, forage dry matter yield, crude protein content, and efficiency indices were subjected to analysis of variance (Anova). Year, sowing time, and sowing method were considered as fixed effects, and blocks were treated as random effects nested within year. When significant effects were detected ($p \leq 0.05$), the intercropping treatments were compared with monocropping controls using the Dunnett's test, and comparisons among intercropping treatments were performed with the Tukey test at 5 % of significance. Model assumptions were evaluated through residual analysis, and data were transformed when necessary; however, original means are presented.

RESULTS AND DISCUSSION

A significant interaction between growing season and forage sowing management was observed for 1,000-grain weight (Table 2), whereas the number of grains per panicle was not affected by the treatments. Overall, intercropping with *Urochloa brizantha* cv. Marandu did not compromise the

rice agronomic performance when compared with monocropping, confirming the agronomic feasibility of integrating grain and forage production within the same production cycle.

Climatic variability strongly influenced the crop responses. Grain yield in 2017/2018 exceeded that of 2018/2019 by 36 % (Table 2), which coincided with a reduction of approximately 20 % in rainfall during the second season (Figure 1). These results reinforce the sensitivity of upland rice to water deficit during reproductive stages, when limitations in assimilate supply and spikelet fertility directly reduce yield (Bouman et al. 2007, Feng et al. 2007). Such interannual variability is characteristic of tropical Savanna environments and remains a major constraint to yield stability in rainfed systems (Ibrahim & Saito 2022, Yuan et al. 2024).

Panicle density showed contrasting responses between the seasons. In 2017/2018, the forage sowing time did not influence this variable; whereas, in 2018/2019, density declined as the coexistence period increased (Table 3). The most pronounced reduction occurred under simultaneous sowing (0 DAE), with a 29 % decrease relative to the previous season. These results indicate that climatic stress amplified competitive interactions, particularly when crop and forage were established simultaneously.

A year $\times$ sowing time interaction was also observed for 1,000-grain weight (Table 2). In 2017/2018, simultaneous sowing and delayed establishment at 45 DAE reduced grain weight (Table 4); whereas, in 2018/2019, no differences among treatments were detected. This suggests that environmental conditions modulated the ability of rice plants to compensate for competition through grain filling.

Despite these seasonal differences, rice grain yield was maintained under intercropping. The highest yields were observed when forage was established at 45 DAE, whereas the sowing method had no effect. Importantly, rice yields under all intercropping strategies remained statistically comparable to monocropping. These findings support the hypothesis

Table 3. Number of grains per panicle of Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under different sowing times.

Growing season	Grass sowing time		
	0 DAE	20 DAE	45 DAE
2017/2018	121 aA	98 aA	122 aA
2018/2019	86 bB	114 aAB	123 aA

Means followed by the same lowercase letter in the column, and the same uppercase letter in the rows do not differ from each other by the Tukey test ($p < 0.05$). DAE: days after emergence.

Table 2. Agronomic performance of Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under sowing times and management practices.

Sources of variation	NPM (unit)	NGP (unit)	Y1000 (g)	PROD (kg ha ⁻¹)
Growing season				
2017/2018	329	80	21.7	3,280 a
2018/2019	309	67	21.9	2,412 b
Grass sowing time				
0 DAE	297	58	21.4 b	2,575 b
20 DAE	303	69	21.6 ab	2,609 b
45 DAE	352	94	22.5 a	3,353 a
Grass sowing management				
Incorporation into the soil	303	85	21.8	2,836
Broadcast	332	62	21.8	2,855
Rice monocropping	309	63	21.9	3,176
Sources of variation	Analysis of variance - p-values			
Growing season (GS)	0.3819	0.5326	0.5336	0.0003
Grass sowing time (GST)	0.0831	0.3694	0.0098	0.0075
Grass sowing management (GSM)	0.1978	0.2857	0.8390	0.9302
GS $\times$ GST	0.0224	0.4231	0.0356	0.1556
GS $\times$ GSM	0.6046	0.2844	0.7651	0.5838
GST $\times$ GSM	0.7706	0.2190	0.8135	0.8082
GS $\times$ GST $\times$ GSM	0.6245	0.3084	0.6067	0.5915
CV (%)	22.740	9.6500	4.5300	26.0600

NPM: number of plants per square meter; NGP: number of grains per panicle; Y1000: 1,000-grain yield; PROD: production. Means followed by same letter in the column do not differ from each other by the Tukey test ($p < 0.05$). CV: coefficient of variation; DAE: days after emergence.

Table 4. One thousand-grain weight (g) of Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under different sowing times.

Growing season	Grass sowing time		
	0 DAE	20 DAE	45 DAE
2017/2018	20.84 bB	22.86 aA	21.49 aB
2018/2019	21.92 aA	22.06 aA	21.75 aA

Means followed by same lowercase letter in the column, and the same uppercase letter in the rows, do not differ from each other by the Tukey test ($p < 0.05$). DAE: days after emergence.

that temporal separation during establishment reduces interspecific competition and allows rice to develop canopy dominance, increasing light interception and reducing competition for nitrogen and water. Similar results have been reported in rice-forage systems in which excessive early forage growth negatively affected crop performance (Oliveira et al. 2009).

The use of imazapyr + imazapic was decisive in regulating competition, because the rice crop has low competitive ability in intercropping systems due to its C3 photosynthetic metabolism (Yin & Struik 2008, Chauhan et al. 2014). The selective suppression of early forage growth allowed Clearfield® rice to establish structural dominance without eliminating

the forage component. This temporary growth delay altered resource partitioning, enabling rice to maintain a competitive advantage during critical phenological stages and supporting previous evidence of improved productivity and environmental performance in Clearfield® intercropping systems (Santos et al. 2024).

Belowground interactions likely reinforced these responses. The rapid root proliferation and nutrient uptake capacity of *Urochloa brizantha* may intensify competition when establishment coincides with rice. However, herbicide-mediated growth delay reduced early root competition, improving crop access to soil water and nutrients. This temporal complementarity is a key mechanism explaining the resilience and resource-use efficiency of integrated systems (Oliveira et al. 2024).

Forage dry matter accumulation was strongly influenced by sowing time and growing season (Table 5). Intercropping reduced the forage biomass at 30 and 60 days after rice harvest (DAH), reflecting initial suppression during the coexistence period. However, differences diminished by 90 DAH, and intercropped systems achieved productivity comparable to monocropping, indicating a successful pasture establishment after the rice harvest.

Table 5. Forage dry matter yield and crude protein content of *Urochloa brizantha* cv. Marandu intercropped with Clearfield® rice (BRS A501 CL) under different sowing times and management practices, harvested at 30, 60, and 90 days after rice harvest.

Sources of variation	30 DAH (kg ha ⁻¹)	60 DAH (kg ha ⁻¹)	90 DAH (kg ha ⁻¹)	CP (g kg ⁻¹)
Growing season				
2017/2018	2,807 b	2,474 b	4,103 b	82.53 b
2018/2019	4,987 a	6,650 a	7,868 a	95.29 a
Grass sowing time				
0 DAE	4,550 a*	5,765 a*	7,684 a*	79.03 b
20 DAE	4,045 ab*	4,464 ab*	6,156 b*	93.01 a*
45 DAE	3,097 b	3,456 b	4,117 c	94.69 a*
Grass sowing management				
Incorporation into the soil	4,257 a	5,229 a	6,707 a	91.25 a
Broadcast	3,537 b	3,895 b	5,264 b	86.56 b
Forage monocropping	6,832	7,352	7,677	80.27
0 DAE	8,539	8,882	9,776	80.86
20 DAE	7,154	7,938	7,957	72.97
45 DAE	4,802	5,237	5,298	86.99
Sources of variation	Analysis of variance - p-values			
Growing season (GS)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Grass sowing time (GST)	0.0050	0.0031	< 0.0001	< 0.0001
Grass sowing management (GSM)	0.0433	0.0134	0.0005	0.0191
GS × GST	< 0.0001	0.3581	0.1229	0.0098
GS × GSM	0.9738	0.1130	0.2114	0.6072
GST × GSM	0.0004	0.9844	0.0157	0.0040
GS × GST × GSM	0.0057	0.9719	0.0661	0.0005
CV (%)	30.53	28.94	21.69	7.44

Means followed by the same letter in the column do not differ from each other by the Tukey test ($p < 0.05$). Means followed by asterisk differ from the control treatment (forage monocropping) by the Dunnett test ($p < 0.05$). DAH: days after rice harvest; DAE: days after emergence; CP: crude protein content; CV: coefficient of variation.

Simultaneous sowing consistently resulted in the highest forage biomass, whereas productivity decreased as sowing was delayed. At 90 DAE, a significant interaction between sowing time and method was observed, with seed incorporation increasing biomass under early establishment. Improved seed-soil contact under incorporation enhances germination and early seedling vigor while reducing desiccation risk (Foloni et al. 2009, Santos et al. 2015).

The higher forage productivity in 2018/2019 also demonstrated the ecological plasticity and drought tolerance of *Urochloa brizantha*, which can sustain growth under variable rainfall regimes (Paciullo et al. 2008). These results indicate that the forage component contributes to system stability under climatic variability.

The crude protein content was influenced by year, sowing time, and establishment method

(Table 6). Delayed sowing at 45 DAE resulted in the highest protein levels, likely due to younger plant tissue and lower structural carbohydrate accumulation. Although simultaneous sowing reduced the crude protein content, the values remained above the thresholds required for ruminant maintenance (Lana et al. 2016, Andrade et al. 2020). Thus, the early establishment maximized biomass without compromising forage quality from a livestock perspective. Integrated grain systems with *Urochloa* species also enhance soil microbial activity and sustainability indicators, reinforcing the multifunctional benefits of crop-forage integration (Vieira et al. 2024).

Agronomic efficiency indicators confirmed the superiority of intercropping relative to monocropping. The land equivalent ratio (LER) ranged from 1.19 to 2.17 (Table 7), demonstrating consistent land-use

Table 6. Crude protein content of *Urochloa brizantha* cv. Marandu intercropped with Clearfield® rice (BRS A501 CL) under different sowing times and management practices.

Grass sowing time	Crude protein (g kg ⁻¹)			
	Broadcast		Incorporation to soil	
	2017/2018	2018/2019	2017/2018	2018/2019
0 DAE of the rice	77.19 aB	79.38 aAB	84.85 aB	74.69 bB
20 DAE of the rice	100.63 aA	87.03 bA	102.50 aA	81.88 bB
45 DAE of the rice	102.50 aA	72.66 bB∅	104.06 aA	99.53 aA∅

Means followed by the same lowercase letter in the rows do not differ from each other, regarding the growing seasons. Means followed by the same uppercase letter in the columns do not differ from each other, regarding the grass sowing times. Means followed by "∅" in the rows do not differ from each other, regarding the grass sowing managements. All means were compared by the Tukey test ($p < 0.05$). DAE: days after emergence.

Table 7. Agronomic efficiency indices of Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under different sowing times and management practices.

Efficiency indexes of intercropping							
Grass sowing time	Growing season of 2017/2018						
	LER of rice	LER of forage	Total LER	A of rice	A of forage	K of rice	K of forage
Broadcast grass sowing							
0 DAE	0.86	0.51	1.37	0.00022852	-0.00022852	3.09	2.08
20 DAE	0.82	0.55	1.37	0.00021900	-0.00021900	2.17	2.44
45 DAE	0.96	0.86	1.82	-0.00000072	0.00000072	12.31	12.62
Grass sowing by incorporation							
0 DAE	0.77	0.53	1.3	0.000254	-0.000254	0.86	4.43
20 DAE	0.66	0.59	1.25	0.000178	-0.000178	0.48	5.70
45 DAE	0.82	0.37	1.19	0.000143	-0.000143	1.13	2.35
Growing season of 2018/2019							
Broadcast grass sowing							
0 DAE	0.81	0.72	1.53	0.000375	-0.000375	2.11	5.19
20 DAE	0.88	0.64	1.52	0.000376	-0.000376	3.48	3.66
45 DAE	1.41	0.76	2.17	0.000373	-0.000373	-1.70	6.57
Grass sowing by incorporation							
0 DAE	0.80	0.83	1.63	0.000427	-0.000427	0.99	20.23
20 DAE	1.10	0.73	1.83	0.000042	-0.000042	-2.71	10.73
45 DAE	1.31	0.78	2.09	0.000411	-0.000411	-1.07	13.84

LER: land equivalent ratio; A: aggressivity index; K: crowding coefficient; DAE: days after emergence.

advantages. Values above 2.0 under delayed sowing in the drier season indicate a strong complementarity in resource capture between system components. Negative aggressivity indices for *Urochloa brizantha* confirmed the rice dominance, contrasting with unmanaged systems in which forage grasses may suppress grain crops (Borghi et al. 2013).

Economic results reinforced the systemic advantages of intercropping. Although establishment costs increased by up to 19 % (Table 8), productivity gains offset these additional investments. All

intercropping systems generated a higher net income than monocropping (Table 9), with forage inclusion increasing the revenue by at least 118 %. These results demonstrate that diversification reduces production risks by combining grain and forage outputs.

All treatments operated above the break-even point (Table 10), and the total factor productivity ranged from 1.10 in monocropping to 2.85 under simultaneous sowing. Rates of return followed the same pattern, confirming the economic viability of Clearfield® rice forage intercropping. Simultaneous

Table 8. Average establishment cost of Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under different sowing times.

Establishment cost	Rice monocropping (US\$)	Grass sowing time		
		0 DAE (US\$)	20 DAE (US\$)	45 DAE (US\$)
Effective operation cost (EOC)	415.08	447.12	456.28	512.51
Total operation cost (TOC)	450.83	482.86	492.02	548.25
Total cost (TC)	517.56	549.60	558.75	614.99

EOC: costs of inputs, herbicides, mechanization (per hour), laboring, transportation, harvest, and financial expenses; TOC: depreciation of agricultural improvements and implements + EOC; TC: opportunity cost on fixed capital + TOC. US\$ 4.125 (IPEA 2019); DAE: days after emergence.

Table 9. Revenue from Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under different production systems.

Production system	Production				
	Growing season of 2017/2018				
	Grain yield (kg ha ⁻¹)	Income (US\$ ha ⁻¹)*	Meat yield (kg ha ⁻¹)**	Income (US\$ ha ⁻¹)**	Total Income (US\$)
Rice monocropping	4.055	727	-	-	727
	Broadcast grass sowing				
0 DAE	3.167	568	475	1.105	1.673
20 DAE	2.993	537	454	1.056	1.593
45 DAE	3.531	633	183	427	1.060
	Grass sowing by incorporation				
0 DAE	3.436	616	475	1.105	1.721
20 DAE	2.921	524	462	1.075	1.599
45 DAE	3.632	652	161	375	1.027
	Growing season of 2018/2019				
Rice monocropping	2.298	412	-	-	412
	Broadcast grass sowing				
0 DAE	1.949	350	475	1.105	1.455
20 DAE	2.106	378	369	858	1.236
45 DAE	3.387	608	352	812	1.420
	Grass sowing by incorporation				
0 DAE	1.751	314	465	1.081	1.395
20 DAE	2.416	433	470	1.094	1.527
45 DAE	2.863	514	588	1.368	1.882
	Sum of two growing seasons				
Rice monocropping		1.139			1.139
	Broadcast grass sowing				
0 DAE		918		2.211	3.129
20 DAE		915		1.914	2.829
45 DAE		1.241		1.247	2.488
	Grass sowing by incorporation				
0 DAE		931		2.187	3.118
20 DAE		958		2.169	3.127
45 DAE		1.165		1.743	2.908

All revenues were standardized to US Dollars (USD) according to the average exchange rate at the time of the study. DAE: days after emergence.

Table 10. Economic viability of Clearfield® rice (BRS A501 CL) intercropped with *Urochloa brizantha* cv. Marandu under different sowing times and management practices.

Production system	Broadcast grass sowing					
	TC (US\$ ha ⁻¹)	TR (US\$ ha ⁻¹)	LP (kg ha ⁻¹)	NI (US\$ ha ⁻¹)	TPF	RR
Rice monocropping	1.035	1.139	5.207	104	1.10	0.10
0 DAE	1.099	3.129	5.529	2.030	2.85	1.85
20 DAE	1.118	2.829	5.622	1.711	2.53	1.53
45 DAE	1.230	2.488	6.188	1.258	2.02	1.02
Grass sowing by incorporation						
Rice monocropping	1.035	1.139	5.207	104	1.10	0.10
0 DAE	1.099	3.118	5.529	2.019	2.84	1.84
20 DAE	1.118	3.127	5.622	2.009	2.80	1.80
45 DAE	1.230	2.908	6.188	1.678	2.36	1.36

TC: total cost of intercropping establishment; TR: total revenue; LP: leveling point; NI: net income; TPF: total productivity of factors; RR: rate of return; DAE: days after emergence. All monetary values are expressed in US Dollars (USD) per hectare, standardized to the average exchange rate at the time of the study.

sowing was the most profitable strategy, whereas delayed establishment provided greater yield stability. These trade-offs highlight the flexibility of the system and its potential to adapt to different farm objectives.

Overall, the results demonstrate that rice forage intercropping regulated through sowing time and selective herbicide management is a robust strategy for sustainable intensification, pasture recovery, and climate resilience in tropical upland systems.

CONCLUSIONS

1. Rice forage intercropping using Clearfield® upland rice and *Urochloa brizantha* proved to be an effective strategy for integrating grain production and pasture establishment;
2. Delaying forage sowing to 45 days after emergence favored the rice yield stability, whereas simultaneous sowing maximized forage production and economic returns;
3. The system improved the land-use efficiency and profitability while contributing to pasture recovery and sustainable intensification of tropical upland production systems.

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