



Sward structure, herbage mass and beef production of multispecies pastures across integrated and conventional livestock systems in the Brazilian subtropics

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ABSTRACT - This study evaluated animal and plant production in multispecies pastures across integrated crop-livestock systems (ICLS) during winter, spring, and summer in Paraná, Brazil. The treatments consisted of Crop-Livestock System (CL), Silvopastoral System (SS), Agroforestry System (AS), and Livestock System (LS). During winter, the unshaded systems (LS and CL) outperformed the systems with the a tree component (SS and AS) presenting a greater forage mass that was 770 kg DM ha⁻¹ higher ($P < 0.01$), and a total forage production that was 1574 kg DM ha⁻¹ higher ($P < 0.01$). Herbage allowance and leaf blade allowance were similar among systems (2.5 and 0.5 kg DM kg LW⁻¹, respectively). Individual animal performance did not differ among systems (0.857 kg animal⁻¹ day⁻¹); however, LS and CL showed higher stocking rates, with 262 kg more live weight (LW) ha⁻¹ during winter and spring ($P < 0.01$ and $P < 0.01$), and greater live weight gain (LWG), which was 1.44 kg LW ha⁻¹ day⁻¹ higher during winter ($P < 0.01$), compared with SS and AS. In subtropical environments, multispecies pastures managed under ICLS provide similar individual beef cattle performance compared with the Livestock System. During the winter, the presence of trees in the Silvopastoral and Agroforestry systems reduces herbage mass production and, consequently, beef production. However, the presence of the tree contributed to maintaining summer forage across seasons, thereby reducing the spring forage gap and sustaining forage availability and animal production.

Keywords: animal production, forage, livestock, silvopastoral system, tropical pasture, winter pasture

1. Introduction

The expanding agricultural frontiers globally are reaching saturation, causing environmental issues such as water contamination, erosion, and biodiversity loss (Balbino et al., 2011). With a global population of 9.1 billion by 2050 and 50% increase in food demand (FAO, 2017), Brazil, as a major player in the world market, largest beef exporter and second biggest producer (ABIEC, 2022), faces the challenge of balancing agricultural production and environmental preservation.

Integrated crop-livestock systems (ICLS) are characterized by temporal and spatial interactions at different scales, involving agriculture, livestock, and forestry. These systems provide diverse benefits, including cost and risk reduction for farmers, income enhancement and diversification (Barbosa et al., 2023), improved soil structure (Duan et al., 2019), increased organic matter content (Pardon et al., 2017), carbon sequestration (Shi et al., 2018), reduced disease and weed incidence, and improvements in the physical, chemical, and biological properties of the soil (Pimentel et al., 2023; Rego et al., 2023). Moreover, well-managed integrated systems are cited as a reliable option for climate-smart agriculture (Portugal et al., 2023) and can favor the inclusion of marginalized areas into production systems, thus reducing the need to convert new areas, supporting agricultural expansion while preserving existing biomes (Sgarbossa et al., 2020).

Silvopastoral systems integrates trees, forage and livestock into a single land area, enhancing production diversification with various ecosystem benefits (Amorim et al., 2023). However, these systems introduce complex temporal and spatial interaction conditions compared with traditional full-sun production systems. The coexistence of upper forest and lower annual plant species within the same production area can alter the interaction dynamics of the plant community, affecting the microclimate of the understory (Sgarbossa et al., 2018; Mayer et al., 2026). This integration leads to morphological adaptations and changes in sward structure, which can result in a direct reduction in forage production and grazing efficiency (Varella et al., 2019; Carvalho et al., 2009).

In ICLS, the influence of animals for the subsequent crop can be beneficial through the effects of grazing, as pasture consumption stimulates plant growth, root development, and increases soil nutrient absorption, in addition to direct effects on nutrient cycling, through the deposition of nutrients via animal feces and urine (Soares et al., 2024a).

While integrated systems may increase land-use efficiency, the proper arrangement of the system's components is fundamental for capitalizing on existing synergies and enabling an increase in animal productivity (Carvalho et al., 2019). In grazing-livestock farming, a key challenge is managing pasture and grazing techniques to balance plant growth, herbage consumption, and animal production (Costa et al., 2021). Portugal et al. (2023) assert that simply increasing the diversity of integrated crop-livestock systems (ICLSs) is not sufficient to enhance agricultural system functioning. They propose that setting moderate grazing intensities is crucial for this improvement, allowing grazers to selectively target and consume the most digestible plant parts, particularly leaves, due to the optimal sward structure provided by the system (Carvalho, 2013). Effective pasture management and grazing intensity adjustments influence pasture persistence, production levels per animal and per unit area, and the maintenance of high herbage intake rates and quality, which are crucial for optimal animal performance, as this depends on an optimal canopy structure (Euclides et al., 2014).

Despite advances in understanding ICLS (Fedrigo et al., 2019; Soares et al., 2024b; Mayer et al., 2026), there is still a lack of studies that comprehensively assess plant and animal production in ICLS in environmentally protected areas with continuous grazing and species diversity, which house both native and intercropped plant species.

Overseeding winter species, such as black oats, appears to be a promising strategy for mitigating forage gaps typical of the cold season in integrated systems, but its effects on pasture structure and animal performance remain poorly documented, especially when combined with different tree or crop arrangements.

Based on evidence that the integration of crops and/or trees into livestock systems can modify sward structure, this study hypothesized that a multispecies pasture under ICLS could improve herbage mass and beef cattle performance in the Brazilian subtropics. Our objective was to assess sward structure, herbage mass, and beef cattle production under different arrangements of integrated crop-livestock systems throughout winter, spring, and summer over two production cycles.

2. Material and methods

All procedures involving animals were approved by the Commission for Ethics in the use of animals of the agricultural sciences sector of the Universidade Federal do Paraná (014/2021).

2.1. Experimental area

The study was carried out from July 16, 2021, to April 15, 2023, as part of a long-term ICLS experiment initiated in 2013. The experimental site is located in Pinhais, Paraná, Brazil (25°23'30" S latitude, 49°07'30" W longitude, 900 m a.s.l.). According to the Köppen classification, the region's climate is Cfb, characterized by an average annual precipitation of 1400 mm, an average minimum temperature of 12.5 °C, and an average maximum temperature of 22.5 °C (Figure 1). The experimental area is part of the Environmental Protection Area of the Iraí River, a territorial unit created by State Decree No. 1.753/96, under Law 6.938/81, which prohibits the use of pesticides.

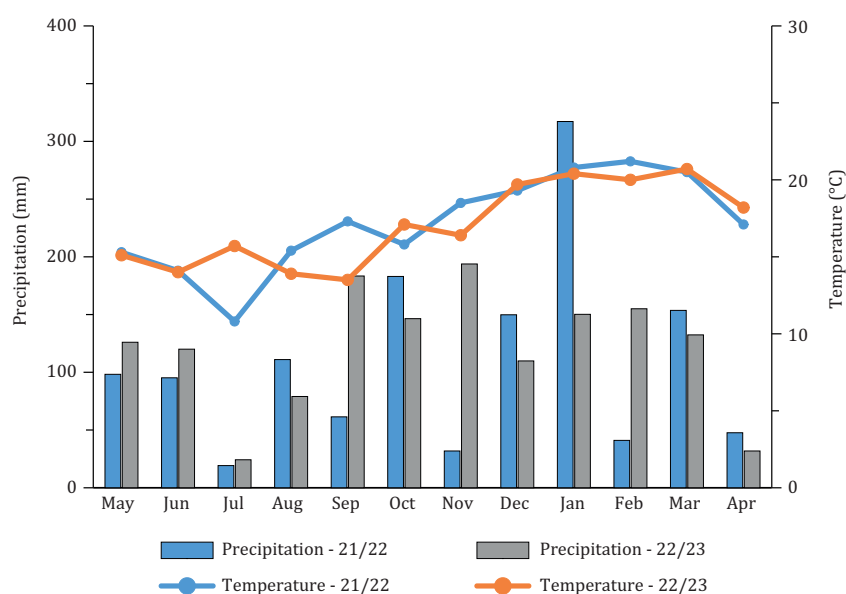


Figure 1 - Average temperature and monthly accumulated precipitation in the municipality of Pinhais, PR, in 2021-22 and 2022-23. Data obtained from SIMEPAR meteorological station (SIMEPAR, 2023).

The long-term experiment is characterized by different arrangements of pasture, crop, and forest components in ICLS. In 2013, a perennial pasture (Guinea grass - *Megathyrsus maximus* cv. Aries) was established, and Eucalyptus trees (*Eucalyptus benthamii*) were planted in the tree-integrated systems at an initial density of 357 trees ha⁻¹, arranged in single rows (14 m between rows and 2 m within trees) following contour lines. These lines were established by leveling the central tree line on the hillslope, with adjacent lines placed in parallel up and down the slope – a practice aimed at reducing runoff and promoting soil and water conservation (Kruchelski et al., 2021). The predominant row orientation was northwest to southeast, despite slight variations due to terrain curvature.

The lower branches of the eucalyptus trees were pruned in 2015, at 21 months, and in 2016, and at 33 months after planting to reduce shading. In 2017, a thinning operation was conducted, removing approximately 45% of the trees in the area, as described by Porfírio-da-Silva et al. (2018). In 2019, another tree row was removed, resulting in the current spacing of 28 m between rows and 11 m between plants. The forest component management followed the guidelines described by Kruchelski et al. (2021).

Pastures of all systems were sown and fertilized similarly each year. During the autumn, black oat (*Avena strigosa*) was overseeded using a no-till direct seed drill without desiccation of the perennial pasture. In 2021, the black oat cultivar EMBRAPA 139 was seeded on May 15th at a density of 80 kg ha⁻¹ of seed. In 2022, overseeding was performed on May 1st at a density of 90 kg ha⁻¹ of seed. In both years, seeding was done with a no-till seed drill with a 0.17-m row spacing. Winter pasture was fertilized in both cycles with 300 kg ha⁻¹ of urea during oat tillering. In 2021, natural phosphate was also applied at 200 kg ha⁻¹ and potassium chloride at 100 kg ha⁻¹. The chemical attributes of the 0.0 to 0.10 m layer were evaluated in 2021, before the experimental evaluations, were similar between the systems, with no limitations were observed (Table 1).

Table 1 - Soil chemical attributes of 0.0 to 0.10 m soil layer in the Livestock system (LS), Silvopastoral System (SS), Crop with Livestock (CL) and Agroforestry System (AS) systems in 2021

Attribute	Unit	Systems				Reference value ⁵	Interpretation ⁵
		LS	SS	CL	AS		
pH _{CaCl2}	-	5.1	5.1	5.0	5.1	5.0	High
Al ⁺³ *	cmol _c /dm ³	0	0	0	0	-	Very low
H+Al	cmol _c /dm ³	3.8	3.9	4.2	3.7	-	-
Ca ⁺² *	cmol _c /dm ³	4.6	4.7	4.9	4.6	2.1	High
Mg ⁺² *	cmol _c /dm ³	2.8	2.7	2.6	2.7	1.1	High
K ⁺ **	cmol _c /dm ³	0.50	0.30	0.60	0.40	0.22	High
P **	mg/dm ³	8.1	10.4	8.0	10.2	10	High
SB ¹	-	7.9	7.6	8.0	7.7	-	-
CEC ²	-	11.7	11.4	12.3	11.4	15	Medium
V ³	%	68	67	66	67	65	High
C ⁴	g/dm ³	27.7	27.8	26.8	27.5	15	High

* Al³⁺, Ca²⁺, and Mg²⁺ extracted by 1.0 mol KCl L⁻¹ (1:10, v/v).

** P and K available extracted by Mehlich-1.

¹ SB, Sum of bases = Ca²⁺ + Mg²⁺ + K⁺.

² CEC, Capacity to exchange cations in pH 7.0 calculated by the sum of H⁺, Al³⁺, Ca²⁺, Mg²⁺ and K⁺.

³ V, Base saturation = (Ca²⁺ + Mg²⁺ + K⁺) / (CTC_{pH7}) × 100.

⁴ C, Total organic carbon (Analyzed by dry combustion).

⁵ Pauletti and Motta (2019).

The cool season pasture primarily consisted of black oat accompanied by other spontaneous grasses, such as Italian ryegrass (*Lolium multiflorum*) and white clover (*Trifolium repens*). The warm season pasture primarily consisted of Guinea grass, accompanied by other spontaneous perennial species, such as alexandergrass (*Urochloa plantaginea*), giant star grass (*Cynodon plectostachyus*), limpograss (*Hemarthria altissima*), brachiaria (*Urochloa* spp.), Torpedograss (*Panicum repens*), Panic paspalum (*Paspalum paniculatum*), Dallisgrass (*Paspalum dilatatum*), Bahiagrass (*Paspalum notatum*), Kikuyu grass (*Pennisetum clandestinum*) in addition to other species weeds plants Billygoat-weed (*Ageratum conyzoides*), Wormwood (*Artemisia absinthum*), Beggarticks (*Bidens* spp.), Field mustard (*Brassica rapa*), Lovegrass (*Eragrostis plana*), Pink-sorrel (*Oxalis atifolia*), Woolly plantain (*Plantago tomentosa*), Wild radish (*Raphanus raphanistrum*), Brazilian pusley (*Richardia brasiliensis*), Common sowthistle (*Sonchus oleraceus*), Dandelion (*Taraxacum officinale*), Common cocklebur (*Xanthium strumarium*), among others.

2.2. Experimental design

The experiment was carried out using a randomized complete block design with three replicates. Treatments consisted of three ICLS combinations: Crop with Livestock (CL); Silvopastoral System (SS); Agroforestry System (AS), and one non-ICLS treatment that consisted of pure livestock production (LS). The evaluation period covered two grazing cycles, the first from July 16, 2021, to April 18, 2022 (276 grazing days), and the second from July 8, 2022, to April 15, 2023 (281 grazing days), spanning

three distinct seasons: winter, spring, and summer in both years. All evaluated systems had the same number of grazing days. The autumn season was not evaluated in this study, as the animals left the experimental area for black oat establishment (on April 18, 2022, and April 15, 2023). Because only 30 days remained in autumn, these days were incorporated into the summer season in both grazing cycles.

The total area of 20.9 ha was divided into 12 paddocks (experimental units) of 1.74 ± 0.30 ha each. The blocking factor was created based on the slope of the terrain and drainage patterns, with blocks divided by a divergent contour line.

All treatments were grazed by beef steers during the warm and the cool seasons. The SS system consisted of beef steers grazing warm-season perennial pastures and cool-season annual pastures, intercropped with eucalyptus tree alleys. The CL system involved a rotation of oat as cool-season cover crop, maize cultivation under no-tillage management, and steers grazing cool-season annual pastures and warm-season perennial pastures. The AS system consisted of a rotation of a cool-season cover crop, maize cultivation under no-tillage practice, and steers grazing cool-season annual pastures and warm-season perennial pastures, intercropped with tree alleys. Both CL and AS treatments used the ley farming technique, with three years of grazing and one year of maize cultivation during the warm season (Figure 2). In the winter preceding the sowing of agricultural crops, there was no grazing. To facilitate no-till planting without herbicides, both in winter and summer, the overseeding technique was used. In winter, frost acts as a natural desiccant during the sowing of black oats over the perennial summer pasture, while in summer, grain crops are sown after the black oat cycle (Dominschek et al., 2018).

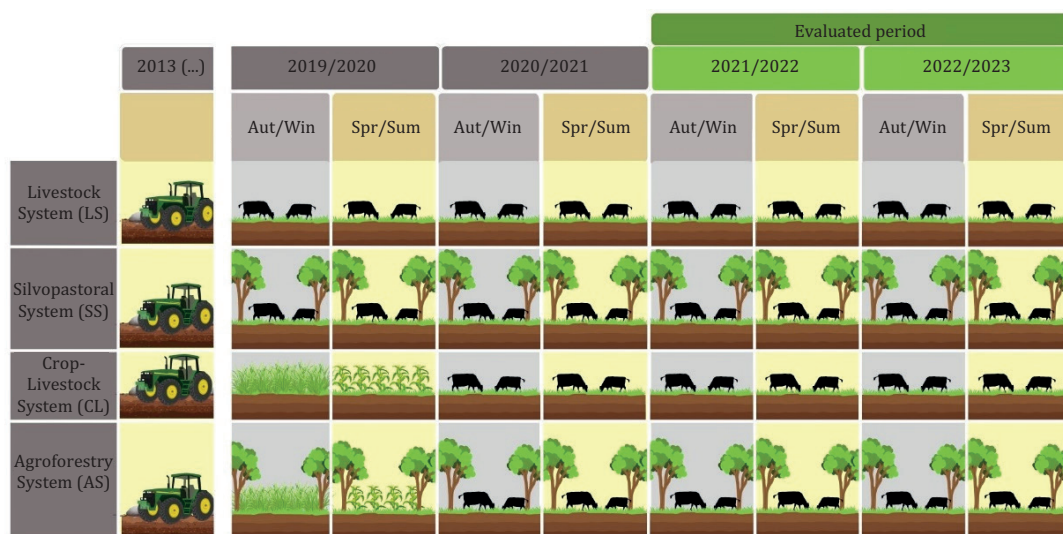


Figure 2 - Schematic representation of NITA experimental protocol arrangement for the evaluated treatments, in previous years, including 2013 with the beginning of the experiment, 2019 with the last maize crop in the CL and AS systems, and the evaluated period (2021/22 and 2022/23).

2.3. Grazing management

The pasture was managed using the continuous stocking method with variable stocking rate. The grazing management was based on the *Rotatinuous* stocking concept (Carvalho et al., 2016) and considered an average target sward height of 24 cm for both cool and warm season pastures. This approach aimed to maximize intake rates and, consequently, animal performance, as proposed by Carvalho (2013). During the stocking season, sward height was measured every 15 days using a sward stick (Barthram, 1985). The sward height was measured at 150 points following a pre-defined transect

in each paddock. At each point, the grass species touched by the stick was measured and identified. Afterward, frequency height distributions were calculated for each target species (*Avena strigosa* for cool season; *Megathyrus maximus* for the warm season and both species for the spring). Subsequently, adjustments to the stocking rate (SR) were implemented using the put-and-take method (Mott and Lucas, 1952), adding or removing animals from the paddocks as needed to maintain sward height as close as possible to the target.

Herbage mass (HM) and herbage accumulation rate (HAR) evaluations were conducted every 28 days. Herbage mass (kg ha^{-1} of dry matter [DM]) was estimated by placing three randomly located metal frames ($0.5 \times 0.5 \text{ m}$) in each paddock and cutting all the herbage inside each frame at ground level. Herbage accumulation rate (HAR) was determined using grazing exclusion cages (Klingman et al., 1943), with three cages per paddock placed in representative areas. In the AS and SS, the cages were placed between the tree rows at an average distance of six meters from the tree lines. Biomass cuts were conducted every 28 days at ground level within the area inside the cage using a metal frame measuring 0.25 m^2 . The collected herbage samples were oven-dried at 55°C for 72 hours and weighed on a precision scale (0.001 g) to determine DM. HAR was calculated as the difference between the mass inside the cage (on the 28th day) and the mass outside the cage (from the previous cut), divided by the number of days, and expressed as $\text{kg ha}^{-1} \text{ day}^{-1}$. Herbage density (HD) was obtained by dividing HM by sward height, with units adjusted to kg DM m^{-3} . Total herbage production (THP) was calculated by multiplying HAR by the number of days in each period and adding the initial HM (kg ha^{-1}). Herbage allowance (HA) was obtained as the ratio of average HM to the corresponding stocking rate (SR) of the paddock, expressed in kg DM per kg of live weight (LW) (Sollenberger et al., 2005). Leaf blade allowance was calculated as the ratio of leaf mass to the paddock's stocking rate (kg DM per kg LW).

Morphological separation was performed by collecting three biomass samples at ground level in each treatment using a metal frame with an area of 0.25 m^2 . Subsequently, the botanical and structural separation of the components of the target pastures was carried out, namely: leaf blades and stems of grasses, senescent material, and other species, whether forage or not, expressed in kg DM ha^{-1} . The leaf-to-stem ratio was calculated as the ratio between the dry mass of leaf blades and the dry mass of stems.

2.4. Livestock management

At the beginning of each stocking season, a new group of 36 steers with similar weight, breed, and age were randomly allocated to paddocks (7 ± 3 months of age; $156 \pm 30 \text{ kg}$ of live weight). The three test steers within each productive year (cool and warm seasons) remained in the same paddock throughout the stocking season. The animals had access to fresh water and *ad libitum* mineral salt in their paddocks, endo- and ectoparasite control was performed according to Molento et al. (2013).

From the beginning to the end of the two stocking periods of each productive year, the steers were weighed every 28 days. The average daily gain (ADG, $\text{kg animal}^{-1} \text{ day}^{-1}$) was calculated as the difference between the final and initial live weight (LW) of each test steer, divided by the number of grazing days in each stocking period. The stocking rate (SR, kg ha^{-1}) was determined by summing the live weight of the test and put-and-take steers, multiplying by the number of days each animal remained in the paddock, and dividing by the paddock area. Consequently, the live weight gain per area (LWG, $\text{kg ha}^{-1} \text{ day}^{-1}$) for each stocking period was derived from the stocking rate and the average ADG of the three test steers in that period.

2.5. Statistical analysis

All statistical analyses were performed using the software R version 4.2.0 package “Exp.Des”. The assumptions of normality were checked using the Shapiro-Wilk test, and variance homogeneity was assessed using the Bartlett test. When necessary, results were transformed by root square or logarithmic functions. The variables were subjected to analysis of variance following a two-factor model, considering system $\times$ season (Equation 1) with a significance level of 5% ($P < 0.05$). Systems and

seasons of the year were considered fixed effects. When significant differences were detected, means were compared using the Tukey test ($P < 0.05$).

$$Y_{ijk} = m + B_k + G_i + A_j + GA_{ij} + E_{ijk}, \quad (\text{Equation 1})$$

in which Y_{ijk} = observed value in the experimental plot; m = overall average of all measurements; B_k = effect of the block factor; G_i = effect of the system factor; A_j = effect of the season factor; GA_{ij} = effect of interaction between system (G) and season (A); and E_{ijk} = random error component.

3. Results

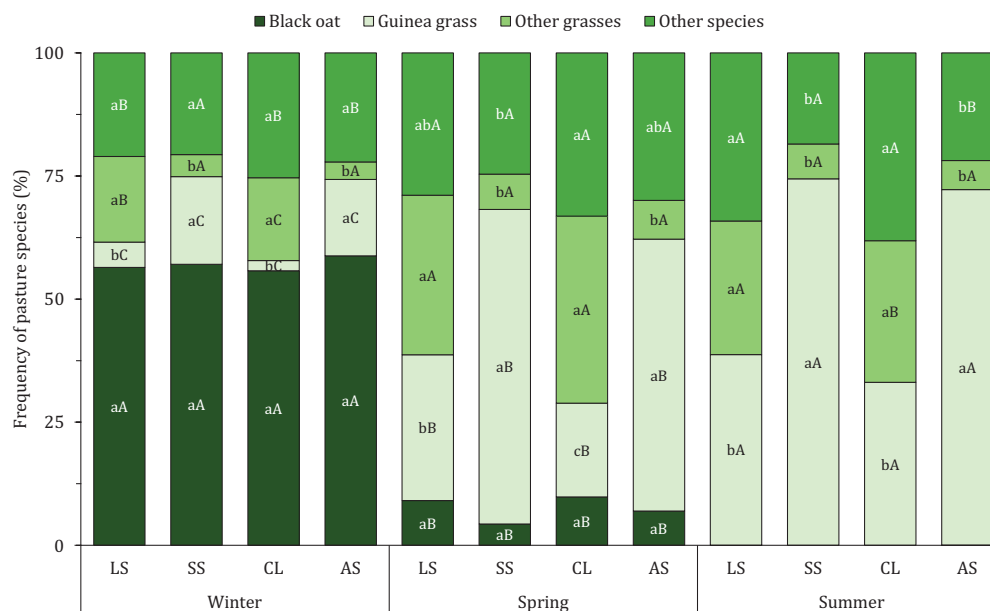
3.1. Sward structure and herbage production

Variables such as other material mass and leaf-to-stem ratio did not show significant interactions between systems and seasons ($P > 0.05$; Table 2). Herbage density was, on average, $0.61 \text{ kg DM m}^{-3}$ among systems. Across seasons, herbage density was 36% higher in spring and summer, compared with winter.

Herbage allowance was $2.5 \text{ kg DM kg LW}^{-1}$ similar across systems and was 0.8 and $1.4 \text{ kg DM kg LW}^{-1}$ higher in winter than in spring and summer, respectively. Leaf blade allowance was $0.5 \text{ kg DM kg LW}^{-1}$ and was similar across systems and seasons (Table 2).

On average across systems, herbage accumulation rate was 28% higher in LS compared with the average of the other systems. In spring, the herbage accumulation rate was 25% higher compared with summer. The total herbage production was $1,573.6 \text{ kg ha}^{-1}$ higher in LS and CL compared with SS and AS, and did not differ among seasons (Table 2).

During winter, black oat and other plant species (non-grasses) constituted, on average, 57% and 22% of the pasture across all systems, respectively (Figure 3). In winter, integrated systems with trees



Capital letters indicate significant differences between seasons for each treatment, lowercase letters represent significant differences between treatments for each season at $P < 0.05$.

Figure 3 - Frequency of Black oat, Guinea grass, other grasses and other species in Livestock System (LS); Silvopastoral System (SS); Crop-Livestock (CL) and Agroforestry System (AS) in winter, spring and summer season.

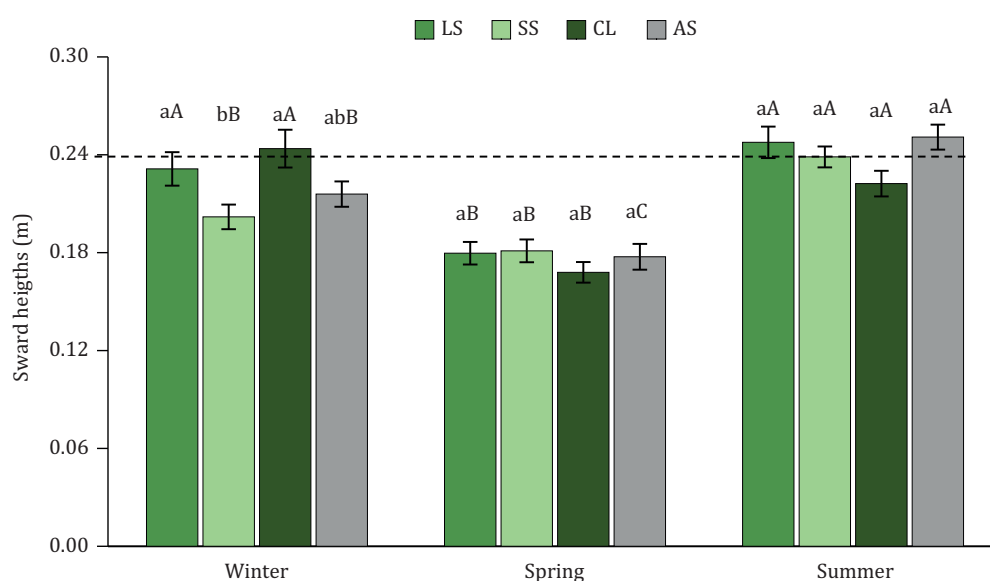
Table 2 - Average and SEM of herbage density (HD), leaf mass (LM), other materials mass (OMM), leaf:stem ratio (L:S ratio), herbage accumulation rate (HAR), herbage allowance (HA), leaf blade allowance (LBA), total herbage production (THP) and average daily gain (ADG) in livestock system (SS); silvopastoral system (LS); crop with livestock (CL); agroforestry system (AS) during the winter, spring and summer seasons

Item	Systems (Sy)				Seasons			P-value	
	LS	SS	CL	AS	Winter	Spring	Summer	Sy	Sy × S
HD (kg DM m ⁻³)	0.66 ± 0.07	0.57 ± 0.06	0.65 ± 0.06	0.54 ± 0.06	0.48 ± 0.04b	0.62 ± 0.06a	0.69 ± 0.06a	0.350	<0.001
LM (kg ha ⁻¹)	605 ± 43	542 ± 36	537 ± 43	509 ± 36	639 ± 44a	453 ± 26b	552 ± 30ab	0.472	0.008
OMM (kg ha ⁻¹)	419 ± 53	326 ± 46	649 ± 89	312 ± 45	407 ± 47	334 ± 35.60	510 ± 65	0.074	0.286
L:S ratio	1.1 ± 0.1	1.4 ± 0.1	1.1 ± 0.1	1.1 ± 0.08	1.1 ± 0.08	1.3 ± 0.09	1.1 ± 0.1	0.086	0.248
HA (kg DM kg LW ⁻¹)	2.5 ± 0.15	2.5 ± 0.23	2.7 ± 0.22	2.3 ± 0.21	3.3 ± 0.18a	2.5 ± 0.13b	1.9 ± 0.07c	0.392	<0.001
LBA (kg DM kg LW ⁻¹)	0.5 ± 0.1	0.6 ± 0.05	0.5 ± 0.06	0.5 ± 0.04	0.7 ± 0.04	0.5 ± 0.05	0.5 ± 0.05	0.807	0.105
HAR (kg ha ⁻¹ day ⁻¹)	63.7 ± 4.0a	43.7 ± 3.0c	58.7 ± 3.86ab	46.2 ± 2.96bc	55.3 ± 3.17ab	58.9 ± 3.58a	47.1 ± 2.71b	<0.001	0.014
THP (kg ha ⁻¹)	6317 ± 386a	4352 ± 232b	5801 ± 351a	4619 ± 194b	5449 ± 337	4977 ± 270	5391 ± 309	<0.001	0.287
ADG (kg day ⁻¹)	0.834 ± 0.1	0.857 ± 0.06	0.891 ± 0.06	0.847 ± 0.05	1.052 ± 0.06a	0.767 ± 0.04b	0.753 ± 0.03b	0.884	<0.001

Values with the same letter within the row do not differ at P<0.05.

exhibited a higher frequency of Guinea grass and a lower contribution of other grasses compared with systems without trees (LS and CL). In spring, the frequency of black oat was consistent at 7% across all systems, and the frequency of Guinea grass increased in all systems compared with winter, with SS and AS showing a frequency twice as high as that observed in the other systems. As there was no black oat in summer, the frequency of Guinea grass averaged 73% in SS and AS systems, while it was 36% in LS and CL systems.

In winter, the sward height in CL (0.24 m) was similar to that in LS and AS, and on average, was 4 cm higher than in SS (0.20 m). In spring and summer, average sward heights were 0.18 and 0.24 m, respectively, with no differences among systems (Figure 4).

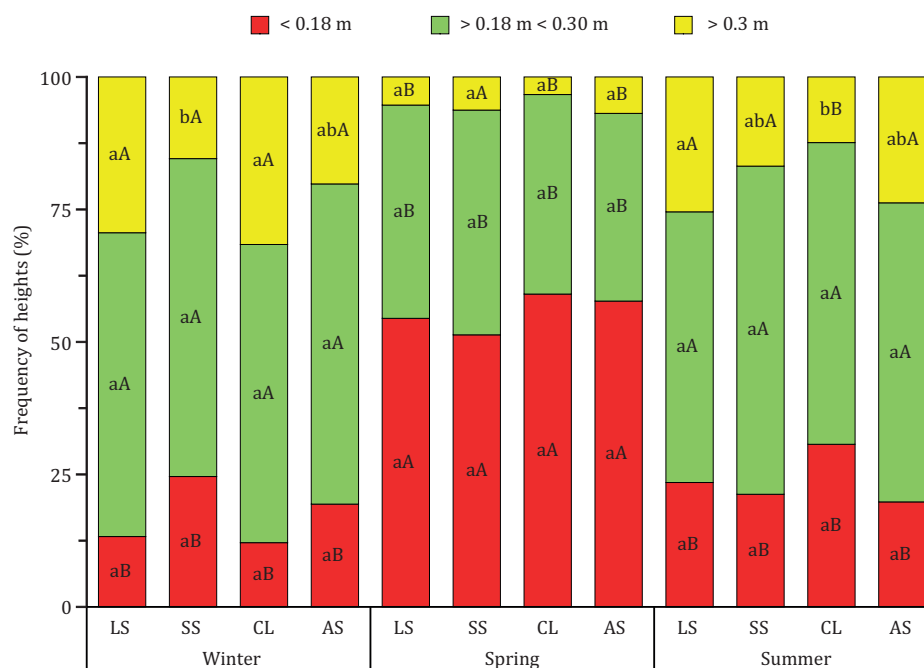


Capital letters indicate significant differences between seasons for each treatment, lowercase letters represent significant differences between treatments for each season at $P < 0.05$.

Figure 4 - Black Oat and Guinea grass heights in Livestock System (LS); Silvopastoral System (SS); Crop-Livestock (CL) and Agroforestry System (AS) in winter, spring and summer season.

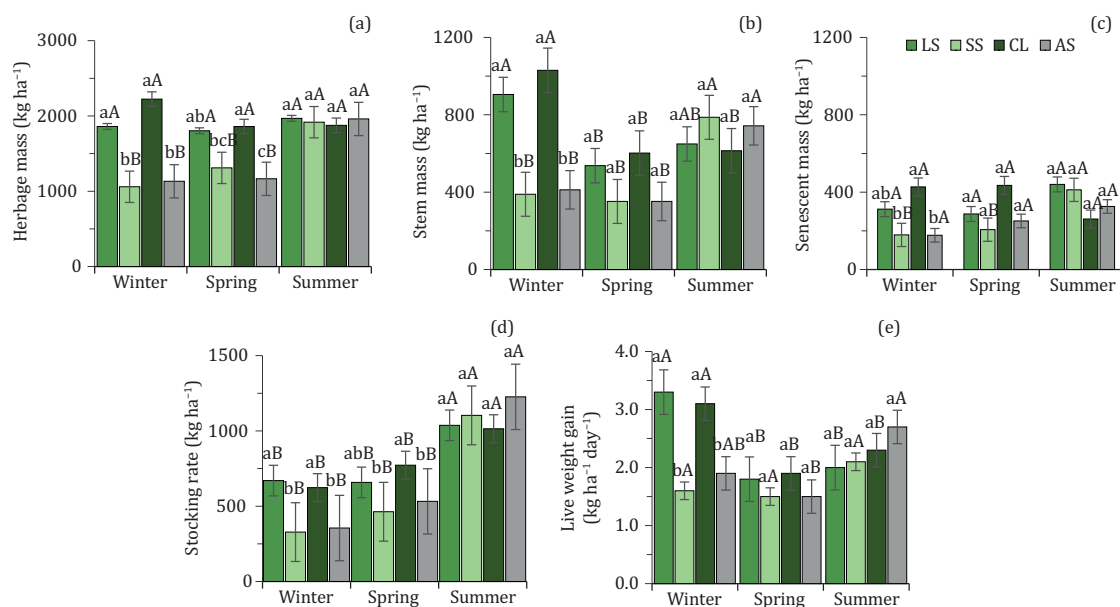
During winter and summer, 58% of height points of black oat and Guinea grass were within the 0.18 to 0.30 m management range, with no significant differences between systems. In spring, 39% of height points were within 0.18 to 0.30 m range. The frequency of height points < 0.18 m was 56% in spring and 21% on average in winter and summer (Figure 5).

In winter and spring, average herbage mass was 86% and 48% higher in LS and CL compared to SS and AS, respectively (Figure 6). In summer, herbage mass was $1,917 \text{ kg ha}^{-1}$ and was similar across all systems. On average, leaf mass was 548 kg ha^{-1} similar among systems. Leaf mass was 16% and 41% higher in winter compared with summer and spring, respectively (Table 2). In winter, average stem mass was 567 kg ha^{-1} higher in LS and CL than in SS and AS. In spring and summer, stem mass was similar among systems (Figure 6). In winter, on average across systems, senescent material was 191 kg ha^{-1} higher in LS and CL than in SS and AS. In winter and spring, senescent material mass was on average was, on average, 247 kg ha^{-1} lower in SS than in summer (Figure 6).



Capital letters indicate significant differences between seasons for each treatment, lowercase letters represent significant differences between treatments for each season at $P<0.05$.

Figure 5 - Frequency of heights of Black Oat and Guinea grass heights in Livestock System (LS); Silvopastoral System (SS); Crop-Livestock (CL) and Agroforestry System (AS) in winter, spring and summer season.



Capital letters indicate significant differences between seasons for each system, lowercase letters represent significant differences between systems for each season at $P<0.05$.

Figure 6 - Herbage mass (a), stem mass (b), senescent mass (c), stocking rate (d) and live weight gain (e) of steers in Livestock System (LS); Silvopastoral System (SS); Crop-Livestock (CL) and Agroforestry System (AS) systems in winter, spring and summer seasons.

3.2. Animal production

Average daily gain was $0.857 \text{ kg animal}^{-1} \text{ day}^{-1}$ and did not differ among systems. Average daily gain was 38% higher in winter ($1.05 \text{ kg animal}^{-1} \text{ day}^{-1}$) compared with the mean for spring and summer ($0.760 \text{ kg animal}^{-1} \text{ day}^{-1}$; Table 2).

During winter, average stocking rate was 89% lower in SS and AS compared with LS and CL, respectively (341.6 vs 646.6 kg ha^{-1}), and 44% lower during spring (497.2 vs 715.3 kg ha^{-1}). In summer, stocking rate was similar among all systems, with an average of $1,094.8 \text{ kg ha}^{-1}$ (Figure 6d).

In winter, live weight gain per area (LWG) was 81% greater in LS and CL compared with SS and AS (3.22 vs $1.77 \text{ kg ha}^{-1} \text{ day}^{-1}$). In spring and summer, LWG averaged $1.98 \text{ kg ha}^{-1} \text{ day}^{-1}$ and was similar among systems (Figure 6).

4. Discussion

4.1. Sward structure

The results indicate that the presence of trees in SS and AS contributes to the maintenance of guinea grass throughout the seasons. This effect is attributed to the microclimate created by the trees, which provides protection against winter frosts and favors faster regrowth in spring and summer (Mayer et al., 2026). The sensitivity of black oat to the presence of trees in winter, despite being a cool-season species, may be associated with shading during a period when solar radiation is already naturally reduced. The combination of a short photoperiod, a steeper solar angle, and competition for light with the tree canopy likely limited the rate of stem elongation and the emission of new leaves, negatively impacting canopy height and dry matter production (Ribeiro et al., 2020). The superior performance of guineagrass in tree systems during the summer may be related to its greater tolerance to partial shade (Lima et al., 2022), which allows it to maintain high photosynthetic efficiency under moderate shade levels, in addition to being in seasons with naturally longer photoperiods.

Spring forage scarcity is a challenge faced by Brazilian livestock. With winter forages decline in productivity and summer species not yet at their maximum productivity, forage supply and nutritional value decrease, reducing the availability of high-quality pasture for the animals (Malaguez et al., 2017). In this study, it was observed that the presence of trees contributed to maintaining the summer forage (Guinea grass) throughout the seasons, consequently reducing this spring forage gap and maintaining levels of forage and animal production during this period.

Across all systems, the majority of height measurements ranged between 0.18 and 0.30 meters (Figure 5). This optimal management height was determined by Mezzalira et al. (2014) for black oat in “Rotatinuous” stocking concept, aiming to maximize animal intake rate and consequently, performance, by allowing grazers to selectively target and consume the most digestible plant parts, particularly leaves, due to the optimal sward structure provided by the system (Carvalho, 2013). This illustrates the feasibility of implementing the “Rotatinuous” stocking in continuous grazing scenarios, with the development of a sward structure conducive to maintaining high ingestion rates. The higher frequency of lower heights ($<0.18 \text{ m}$) observed in the spring in all systems and lower frequency of points with optimal management heights (0.18 to 0.30 m) were probably due to the transition from the end of the black oat cycle to the start of guinea grass regrowth. Sward height, for grazing herbivores, represents the amount of available biomass, with opportunities for high intake and greater bite depths (Carvalho et al., 2001; Savian et al., 2018), and when grazing animals encounter sward structures that significantly restrict bite size, they struggle to maintain intake rates, leading to competition for time between grazing, rumination, and other activities, consequently reducing the daily intake (Hodgson et al., 1997). In spring, it was possible to observe a 38% lower average daily gain (ADG) (Figure 6) compared with winter, but similar to summer.

During the summer period, sward height (Figure 4) and herbage mass (Figure 6) were similar between systems. This indicates that trees did not restrict pasture growth. The high availability of light and water during this season minimized competition between trees and grasses, a pattern corroborated by studies showing that, under adequate water availability, trees have little effect on pasture productivity (Addo-Danso et al., 2025; Amorim et al., 2023). Baungratz et al. (2023) observed higher herbage mass under full-sun conditions compared with a Silvopastoral System (*Cordia trichotoma* and *Peltophorum dubium*) in Aruana guinea grass pasture (*Megathyrsus maximus* cv. Aruana), and higher sward heights in the Silvopastoral System.

4.2. Herbage production

Total herbage production was similar between seasons (Table 2) demonstrating the system's capacity to produce 15,817 kg DM ha⁻¹ throughout the year, but it was 36% higher in full sunlight systems (LS and CL) compared with ICLS designs with trees (Table 2). Taiz et al. (2015) reported that increased competition for water and radiation results in lower biomass in shaded environments, as observed in this study, especially during the winter period. In tree-integrated systems, there is a reduction in radiation intensity, especially in the photosynthetically active range, requiring plant adaptation to cope with changes in light quality, influencing morphological characteristics and forage production. Tolerance strategies include adjustments in leaf area, specific leaf weight, chlorophyll density, crude protein content, and leaf:stem ratio, as well as changes in reserve allocation and changes in leaf angle (Garcez Neto et al., 2010; Varella et al., 2019). Oliveira et al. (2022) in a meta-analysis including *Eucalyptus* spp. and *Urochloa* spp. showed lower forage mass and forage density in silvopastoral systems, compared with grass monoculture, as well as lower pasture heights in SPS with closer tree row spacing (1-14 m), likely due to reduced light availability and growth limitation. In contrast, silvopastoral systems with wider tree row spacing (>28 m) had greater pasture height, as plants could grow taller to reach higher strata and capture more light. Forage mass and forage allowance have a direct influence on stocking rate, which in turn influences average weight gain; lower values of these variables resulted in lower stocking rate and average weight gain, but similar average daily gain between systems in their meta-analysis.

Herbage allowance is described as an instantaneous measure of forage availability per unit of demand and is an important tool to explain differences in performance among treatments, as, given a certain amount of herbage mass per unit area, it has a direct influence on stocking rate (Moojen et al., 2022). In this study, HA was 0.8 and 1.4 kg DM kg LW⁻¹ higher in winter compared with spring and summer, respectively, with no statistically significant differences among systems. Leaf blade allowance was similar among systems and seasons (Table 2). Carvalho et al. (2001) state that forage allowance is directly related to animals' grazing selectivity, both in terms of plant species and plant parts consumed, allowing the ingestion of a diet richer in nutrients and with lower energy expenditure.

4.3. Animal production

With high herbage allowance values in all systems during the two grazing cycles (Table 2), steers had the opportunity to select and consume higher-quality strata, directly influencing average daily gain values, which also did not differ among systems, with an average of 0.857 kg animal⁻¹ day⁻¹. In a Brazilian context, meta-analysis data compiling 132 studies on beef cattle grazing tropical pastures reported average ADG values of 0.621 kg animal⁻¹ day⁻¹ in the rainy season and 0.361 kg animal⁻¹ day⁻¹ in the dry season (Tambara et al., 2021). This suggests that the average daily gain observed in our study was well above the national average, indicating favorable pasture and management conditions.

The average daily gain was directly affected by the seasons, with a 38% higher ADG in winter (1.05 kg animal⁻¹ day⁻¹) compared to spring and summer (Figure 6), similar to found by Kunrath et al. (2020). These results can be explained by the difference in the HA (Table 2) and composition of the animals' diet, with the majority consisting of C₃ plants in winter and C₄ plants in spring and summer (Portugal et al., 2023). In the same experimental area, Portugal et al. (2023) reported that the crude

protein content of pasture was 204 and 150 g kg⁻¹ DM in the cold and warm seasons, respectively. It is important to highlight that the metabolic pathway of C₄ plants often results in increased of lignin in plant tissues, and this alteration can significantly influence forage intake and digestion by ruminants (Archimède et al., 2011).

During winter, the stocking rate was higher in LS and CL (average 647 kg LW ha⁻¹) compared to the SS and AS (average 342 kg ha⁻¹; Figure 6). The stocking rate was adjusted to maintain sward height close to an average of 24 cm for black oats and Guinea grass in all systems, as presented previously in this study. The variations in stocking rates can be attributed to differences in HAR among the systems. Specifically, during the winter season, LS and CL systems exhibited a higher sward height (Figure 4), herbage mass (Figure 6), HAR and THP (Table 2) compared with SS and AS. The presence of trees in SS and AS systems likely contributed to a decrease in available sunlight, impacting the photosynthetic activity and overall productivity of the pasture, resulting in decreased height, forage mass, and total forage production in these systems.

Regarding LWG, Oliveira et al. (2022), in their meta-analysis, reported that live weight gain is directly affected by the stocking rate, which is, in turn, influenced by HAR. Therefore, with lower values of HAR and THP, animal production is consequently reduced. In this study, we observed the highest values of LWG and SR in the same systems and seasons where higher heights, forage mass, and THP were observed using sward height as the management criterion. Our results demonstrated an 81% higher LWG for LS and CL during the winter compared with SS and AS, but with no differences between systems in the spring and summer (Figure 6).

Therefore, this study showed that systems integrated with the forestry component generally exhibit lower herbage and beef production rates, especially during winter. However, in summer, these systems present production potential similar to those under full sun, demonstrating that, on farms in the Brazilian subtropics, different integration arrangements can be adopted, provided that forage production planning is adjusted to the seasonal conditions throughout the year. These findings also highlight the productive capacity and the reduced environmental impact of integrated crop–livestock systems with multispecies pastures and without the use of pesticides for pest, disease, or weed control.

Furthermore, assessing pastures and beef cattle responses alone provides only a partial understanding of the multifunctionality of ICLS. Although tree-based systems may depress forage mass production during winter, the combined production of grain, forage, and wood enhances system-level resilience and positions ICLS in subtropical regions as a strategic pathway for sustainable intensification. Although our study did not quantify economic outcomes, the productive advantages observed in multispecies pastures within the ICLS framework have clear implications for farm profitability. Evidence from temperate grasslands shows that increasing sward diversity (grass–legume–herb mixtures) enhances forage quality and animal performance while reducing nitrogen fertilizer requirements, resulting in equal or superior economic performance compared with monoculture swards (Jezequel et al., 2024; Taube et al., 2024). Likewise, long-term ley-farming and grassland studies show that plant diversity improves yield stability and resource-use efficiency, contributing to higher net returns (Vishwakarma, 2025). In tropical environments, economic evaluations of ICLS consistently report higher profitability, greater net present value, and lower financial risk relative to specialized crop or livestock enterprises (Reis et al., 2020; Simili et al., 2023; Pontes et al., 2021).

5. Conclusions

In subtropical environments, multispecies pastures can be managed under ICLS and provide similar beef cattle performance compared with the Livestock System. During the winter, the presence of trees in the Silvopastoral System and Agroforestry System reduce herbage mass production and, consequently, beef production. However, the presence of trees contributed to maintaining summer forage (Guinea grass) throughout the year, thereby reducing the spring forage gap and sustaining forage and animal production levels during this period.

Data availability

The data that support the results of this study are available from the corresponding author upon reasonable request.

Author contributions

Conceptualization: Crestani, C. and Oliveira, L. B. **Data curation:** Vacelik, B. A.; Corteze, A. P.; Mayer, M. A.; Moojen, F. G. and Oliveira, L. B. **Formal analysis:** Nunes, P. A. A. **Investigation:** Vacelik, B. A.; Crestani, C.; Corteze, A. P. and Moojen, F. G. **Methodology:** Vacelik, B. A.; Crestani, C.; Corteze, A. P.; Mayer, M. A.; Moojen, F. G.; Nunes, P. A. A. and Soares, A. B. **Supervision:** Moojen, F. G. and Oliveira, L. B. **Validation:** Vacelik, B. A.; Crestani, C.; Corteze, A. P. and Nunes, P. A. A. **Visualization:** Vacelik, B. A.; Mayer, M. A. and Soares, A. B. **Writing – original draft:** Vacelik, B. A.; Moojen, F. G. and Nunes, P. A. A. **Writing – review & editing:** Corteze, A. P.; Mayer, M. A. and Soares, A. B.

Conflict of interest

The authors declare no conflict of interest.

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