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Performance and feed intake of *Nellore* steers in extensive, intensive, and integrated pasture-based beef cattle production systems

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HIGHLITGHS

- We evaluated *Nellore* steers' performance and feed intake traits during backgrounding-finishing phase.
- Five tropical pasture-based beef cattle production systems were analyzed.
- Well-managed intensified systems have the potential to avoid the effects of seasonality and pasture degradation processes.
- This increased efficiency allows less time and reduced area to obtain the final product, enhancing the land-use efficiency.

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ABSTRACT

This study evaluated the effects of five pasture-based production systems on the backgrounding-finishing phase performance and feed intake traits of *Nellore* steers. Over two years (2019–2021), steers (three/year/experimental unit) were randomly assigned to five treatments (with two replicates): 1) degraded pasture without nitrogen (N) fertilization (DP0); 2) silvopastoral with 200 kg N ha^{-1} (SP200); 3) rainfed pasture with 200 kg N ha^{-1} (RP200); 4) rainfed pasture with 400 kg N ha^{-1} (RP400); and 5) irrigated pasture with 600 kg N ha^{-1} (IP600). Animals grazed exclusively, receiving water and mineral-protein supplement ad libitum. IP600, RP400, and RP200 resulted in the highest Forage and Total Dry Matter Intake (DMI), correlating to superior performance. Supplement DMI was highest in DP0 and lowest in IP600. Considering the seasons, higher stocking rates [expressed in Animal Units (AU) and Equivalents (AE)] were observed in IP600 compared with SP200 (spring and winter), and with RP200, DP0 and SP200 (summer and autumn). Forage allowance and feed efficiency varied seasonally across treatments, influenced by defoliation frequency, intake patterns, and leaf preference during grazing intensity adjustments. During the dry period, performance declined across most treatments due to reduced pasture production, except for IP600, RP400, and RP200, which demonstrated resilience to drought and seasonal variability. Intensified and well-managed systems (IP600, RP400, and RP200) enhanced animal performance and feed intake, suggesting their potential as sustainable pasture management strategies. SP200 and DP0, however, may require tailored management strategies to optimize their benefits.

1. Introduction

Brazil's pasture-based livestock production has experienced significant growth between 1996 to 2017, with a 48 % increase in productivity from 147 to 218 million cattle, while reducing pastureland area by 18 million ha from 177.9 to 159.5 million ha (Landau et al., 2020; Silvestre and Millen, 2021; ABIEC, 2023). This progress is attributed to the adoption of effective pasture management and strategic intensification technologies, including basic practices like liming and fertilization, improved forage species adapted to tropical conditions [e.g., *Urochloa*

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(*syn. Brachiaria*) and *Megathyrsus* (*syn. Panicum*)], irrigation and C_3 forage overseeding [e.g., oat (*Avena* spp.) and annual ryegrass (*Lolium multiflorum* Lam.)] to ameliorate the 6-month period of cool and dry weather. Additionally, implementing stocking methods (including rotational grazing) and integration systems (e.g., silvopastoral) leverages the benefits of diversified land use (Oliveira et al., 2018; Sakamoto et al., 2020; Pasquini Neto et al., 2024). These practices enhanced forage productivity and nutritive value, boosting animal performance, system efficiency, and economic returns (Greenwood, 2021), while also potentially reducing greenhouse gas (GHG) emissions through shorter animal life cycles (Boval; Dixon, 2012; Oliveira, et al., 2020; Cardoso et al., 2020a).

Pasture intensification involves increasing production efficiency and output per unit of land area through enhanced management practices, enabling sustained or improved productivity while reducing land use (Palermo et al., 2014; Cardoso et al., 2020b). This approach maximizes the productivity of the soil-plant-animal interface by employing techniques like appropriate stocking rates, managing grazing pressures, maintaining a minimum residual mass height to ensure pasture persistence year-round (Petersen, 1994), and providing targeted mineral and protein-energy supplementation to address nutritional deficiencies of tropical pastures (Torrecilhas et al., 2021). Such supplementation is often combined with the strategic use of minerals throughout the year, while protein-energy supplements are provided during dry seasons and transitional periods when forage quality and availability are most limited (Cardoso et al., 2020b).

Optimizing pasture management strategies is crucial for maximizing productivity and minimizing the negative environmental impacts of livestock activities. In this context, intensification strategies—such as increased stocking rates, rotational grazing, and silvopastoral systems—offers potential for simultaneously enhancing animal productivity and sustainability. Additionally, integrating well-managed silvopastoral systems, where livestock and forestry activities coexist, diverse benefits can be offered to improve animal welfare due to the thermal comfort provided by the tree shade, including biodiversity, carbon sequestration, and enhanced land use efficiency through potential synergistic effects between system components (Pezzopane et al., 2019).

Given the growing global demand for sustainable meat production, understanding how intensified pasture-based systems improve resource efficiency while minimizing environmental impacts is critical. Well-managed systems, that employ improved pasture practices and enhance animal productivity contribute to broader sustainability goals by reducing GHG emissions and promoting biodiversity through integrated land use. This study proposes that intensifying pasture-based systems enhances animal productivity and efficiency, thereby supporting sustainable livestock production. Our primary objective was to evaluate the effects of different levels of intensification in pasture management, including silvopastoral integration, on *Nellore* steers' performance, feed intake, and feed efficiency during the backgrounding-finishing phase, as well assess the grazing systems' carrying capacity in Southeast Brazil. Insights into these variables are critical for advancing sustainable and efficient resource use in meat production.

2. Material & methods

The study was approved and conducted in accordance with the guidelines of the Committee for Ethics in the Use of Animals—CEUA [n° 04/2019 of the Brazilian Agricultural Research Corporation—Embrapa, Brazil; n° 08/2020 of the Faculty of Veterinary Medicine and Animal Science/ University of São Paulo—FMVZ/USP, Brazil], being carried out at Embrapa Southeast Livestock, São Carlos, São Paulo State, Brazil (21°57′ S, 47°50′ W, 860 m asl.) during two periods: a) from September 2019 to September 2020 (Period 1); b) from September 2020 to September 2021 (Period 2).

2.1. Treatments and management

The experiment consisted of five pasture-based production systems, with two replicates per system, arranged in a split-block design, providing 20 experimental spatial units across two years. These systems, comprising different levels of pasture intensification (detailed in Tables 1 and 2), were: 1) extensively managed rainfed degraded pasture with a mix of *Urochloa* (syn. *Brachiaria*) *brizantha* (Hochst ex A. Rich) cv. Marandu and *U. decumbens* Stapf cv. Basilisk without lime or fertilization (DP0); 2) integrated managed silvopastoral system with Brazilian native trees (312 trees ha^{-1}) and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1} (SP200); 3) intensively managed rainfed mixture of *U. decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1} (RP200); 4) intensively managed rainfed *M. maximus* (syn. *Panicum maximum*) Jacques cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea ha^{-1} year^{-1} (RP400); and 5) intensively managed and irrigated *M. maximus* cv. Tanzânia pasture, overseeded in the dry season with oat (*Avena byzantina* C. Koch cv. São Carlos) and annual ryegrass (*Lolium multiflorum* Lam. cv. BRS Ponteio) limed, fertilization with macro and microminerals and 600 kg N-urea ha^{-1} year^{-1} (IP600). Liming was not performed when the base saturation of systems was greater than 70 %.

The pasture-based production systems adopted in this study were structured and managed in accordance with the varying levels of pasture management intensification previously described by Pasquini Neto et al. (2024), who evaluated their effect on pasture production and nutritional value for beef cattle production systems in the Southeast region of Brazil. The IP600 and RP400 pastures were divided into 12 paddocks (0.15 ha each) and managed under rotational stocking with 3 days of occupation and 33 days of resting period. The RP200 and SP200 pastures were divided into six paddocks (0.52 and 0.60 ha each, respectively) and managed under rotational stocking with 6 days of occupation and 30 days of rest. The DP0 pasture was managed under continuous stocking in two single paddocks (2.0 ha each).

2.2. Animal management and performance

For each experimental period, thirty *Nellore* steers ("testers" with a mean initial live weight of 375 ± 30 kg and age of 22 ± 1 months old in Period 1, and 285 ± 21 kg and 13 ± 1 months old in Period 2) were selected within a homogenous (live weight, age, and genetic composition) group and randomly assigned to the treatments (three per experimental spatial unit). The animals remained exclusively on pasture, with ad libitum access to water and a mineral-protein supplement (Table 3) formulated for an estimated daily intake of 0.1 % of the animal's live weight.

The stocking rate of all treatments was adjusted using "regulator" *Canchim* steers (3/8 *Nellore* +5/8 *Charolais* steers), adopting the "put and take" technique (Mott and Lucas, 1952). This approach maintained the grazing pressure close to the carrying capacity of the pastures during the trial (Petersen, 1994). To adjust the stocking rate, the height of the grass stubble was monitored (35 cm for IP600 and RP400, 20 cm for RP200, and 15 cm for SP200), according to Costa & Queiroz (2013). In the DP0 treatment, the stocking rate was adjusted only in the periods of greater forage availability, while in the drought periods, only the "testers" were kept in the treatment, even if the grass stubble heights fell below the levels recommended by Costa & Queiroz (2013). However, due to a substantial soil water deficit during a significant part of the experimental periods (Fig. 1) and considering that the stubble heights in the pastures (Supplementary Tables S1 and 2) were limited by the apprehension of the animals in the drought periods of the years (Carvalho et al., 2007), the animals in the SP200 and DP0 treatments had to be relocated to nearby pastures with similar characteristics to avoid starvation during part of the drought seasons. These

Table 1
Pasture characteristics according to different levels of intensification of pasture-based systems during the experimental period.

Item	Treatments				
	IP600	RP400	RP200	SP200	DP0
C_4 Forage Grasses	*M. maximus (Panicum) maximum cv. Tanzânia*	*M. maximus (Panicum) maximum cv. Tanzânia*	*Mix of U. (Brachiaria) decumbens cv. Basilisk and U. (Brachiaria) brizantha cv. Marandu*	*U. (Brachiaria) decumbens cv. Basilisk*	*Mix of U. (Brachiaria) decumbens cv. Basilisk and U. (Brachiaria) brizantha cv. Marandu*
Overseeding (Dry Period)	Yes	No	No	No	No
C_3 Forage Grasses	*Avena byzantina* cv. São Carlos and *Lolium multiflorum* Lan. Cv. BRS Ponteio	–	–	–	–
Management Time (Years)*	20	20	25	15	25
Grazing Management (Days)	Rotational (3d of Occupation and 33d of Rest)	Rotational (3d of Occupation and 33d of Rest)	Rotational (6d of Occupation and 30d of Rest)	Rotational (6d of Occupation and 30d of Rest)	Continuous

Adapted from Pasquini Neto et al. (2024). *Relative to the date that forage samples were collected.
Treatments: DP0, extensively managed rainfed degraded mixture of *Urochloa brizantha* cv. Marandu and *Urochloa decumbens* cv. Basilisk pasture without lime or fertilization; SP200, integrated managed silvopastoral system with Brazilian native trees and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} $year^{-1}$; RP200, intensively managed rainfed mixture of *Urochloa decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} $year^{-1}$; RP400, intensively managed rainfed *Megathyrsus maximus* cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea ha^{-1} $year^{-1}$; IP600, intensively managed and irrigated *M. maximus* cv. Tanzania pasture, overseeded in the dry season with oat and ryegrass limed, fertilized with macro and microminerals and 600 kg N-urea ha^{-1} $year^{-1}$.

supplementary areas were considered in the calculations. Details of the climate profile during the experimental periods, including a breakdown of rainfall and temperature data, have been described by Pasquini Neto et al. (2024).

At the beginning and end of each experimental period, the "tester" animals were weighed after 16 h of fasting from solid food to determine the initial live weight (LW_i, kg) and final live weight (LW_f, kg), respectively. Intermediate weightings were conducted every 28 days without fasting, allowing stocking rates to be adjusted by weighing and inserting or removing a variable number of "regular" animals. The study lasted 730 days, with 366 days in Period 1 and 364 days in Period 2.

To determine the individual performance of the animals, the average daily gain (ADG, kg $animal^{-1}$ day^{-1}) of each animal was calculated as the difference between the final and initial weights, divided by the number of days of each period. The live weight at the end of seasons (LW_{eos}, kg) was obtained according to the adjustment of the last weighing of seasons until the last day of each season. The stocking rates were calculated as the number of animal units (AU, bovine with 450 kg) per ha (SRAU) and the number of animal equivalent (AE, the average weight of the tester animals present in a pasture) per ha (SRAE). Additionally, the average live weight gain per ha (LWG_{ha}, kg $animal^{-1}$ day^{-1} ha^{-1}) was calculated multiplying ADG per SRAE.

At the end of each experimental period, the tester's animals were transported by truck to the FMVZ/USP slaughterhouse, located 87 km from Embrapa Southeast Livestock. Upon arrival, the animals were euthanized using the Brazilian-approved stunning technique, followed by exsanguination via severance of the jugular vein. The slaughtering process was conducted in accordance with the Brazilian law on the Regulation of Industrial and Sanitary Inspection of Animal Products (RIISPOA) and the São Paulo State Inspection Service (S.I.S.P—0830) of the Pirassununga Campus of the University of São Paulo. The carcasses were hung by the Achilles tendon without electrical stimulation. The heads, feet, hide, and visceral organs were removed, and the carcasses were split into two sides for weighing to obtain the final hot carcass weight (HCW_f, kg $carcass^{-1}$) before being stored in a cold chamber (at −30°C). The initial hot carcass weight (HCW_i, kg $carcass^{-1}$) was estimated using linear regression analysis conducted with SAS *Software* PROC REG (SAS Institute Inc., Cary, North Carolina, USA), following a similar approach described by Tedeschi et al. (2002). The prediction equation, derived from a linear regression between LW_f and HCW_f of the animals was $HCW_i = -45.43441 + (0.60695 \times LW_i)$, resulting in a high coefficient of determination (R^2 of 0.95). The carcass yield (CY, %) was calculated as the ratio of HCW_f and LW_f multiplied by 100.

The carcass gain per ha (CG_{ha}, kg $carcass^{-1}$ ha^{-1}) was determined by multiplying CY by average live weight gain per ha (LWG_{ha}, kg ha^{-1}), dividing by 100, and then multiplying by the number of days in each experimental period. In addition, the carcass gain yield (CGY, %) was calculated to assess how much of the weight gain was converted into carcass, using the equation:

$$CGY = \left(\frac{HCW_f - HCW_i}{LW_f - LW_i}\right) \times 100$$

where: HCW_f: final hot carcass weight (kg $carcass^{-1}$); HCW_i: initial hot carcass weight (kg $carcass^{-1}$); LW_f: final live weight (kg); LW_i: initial live weight (kg).

2.3. Supplement and forage intake

The total dry matter intake (DMI_t, kg DMI day^{-1}) of the animals in each treatment was calculated as the sum of mineral-protein supplement intake (DMI_s) and forage intake (DMI_f).

The mineral-protein supplement intake (DMI_s, kg DMI day^{-1}) was calculated monthly for each treatment, using the following the equation:

Table 2
Pasture liming, fertilization, and irrigation according to different levels of intensification of pasture-based beef cattle production systems during the experimental period.

Item	Years	Treatments				
		IP600	RP400	RP200	SP200	DP0
Liming		Yes	Yes	Yes	Yes	No
Dolomitic limestone (EVN 70)	Year 1	640	820	0*	670	–
($kg\ ha^{-1}\ year^{-1}$)	Year 2	0*	0*	0*	0*	–
Number of applications		1	1	1	1	–
N fertilization		Yes	Yes	Yes	Yes	No
N-urea ($kg\ ha^{-1}\ year^{-1}$)		600	400	200	200	–
Number of applications		10	5	5	5	–
P_2O_5 fertilization		Yes	Yes	Yes	Yes	No
P_2O_5	Year 1	175	375	75	404	–
($kg\ ha^{-1}\ year^{-1}$)	Year 2	75	175	75	125	–
Number of applications		1	1	1	1	–
K_2O fertilization		Yes	Yes	Yes	Yes	No
K_2O	Year 1	197	194	311	144	–
($kg\ ha^{-1}\ year^{-1}$)	Year 2	133	119	0	344	–
Number of applications		1	1	1	1	–
Irrigation		Yes	No	No	No	No
Irrigation ($mm\ ha^{-1}$)	Year 1	493	–	–	–	–
	Year 2	565	–	–	–	–

Adapted from Pasquini Neto et al. (2024). EVN, Effective Neutralizing Value. N, nitrogen. P_2O_5, Ordinary superphosphate. K_2O, Potassium chloride.
Treatments: DP0, extensively managed rainfed degraded mixture of *Urochloa brizantha* cv. Marandu and *Urochloa decumbens* cv. Basilisk pasture without lime or fertilization; SP200, integrated managed silvopastoral system with Brazilian native trees and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea $ha^{-1}\ year^{-1}$; RP200, intensively managed rainfed mixture of *Urochloa decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea $ha^{-1}\ year^{-1}$; RP400, intensively managed rainfed *Megathyrsus maximus* cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea $ha^{-1}\ year^{-1}$; IP600, intensively managed and irrigated *M. maximus* cv. Tanzania pasture, overseeded in the dry season with oat and ryegrass limed, fertilized with macro and microminerals and 600 kg N-urea $ha^{-1}\ year^{-1}$.
* Liming was not performed when base saturation was greater than 70 %.

$$DMI_s = \left(\frac{DMI_s\ \text{Supplied} - DMI_s\ \text{Surplus}}{\text{days}}\right)$$

where: DMI_s Supplied: mineral-protein supplement provided (kg); DMI_s Surplus: mineral-protein supplement surplus in the trough after five days (kg).

The forage intake (DMI_f, kg DMI day^{-1}) was determined using indirect methods, specifically external [titanium dioxide (TiO_2)] and internal [indigestible neutral detergent fiber (iNDF)] markers. During both experimental periods, measurements were carried out in the middle of each season. For ten consecutive days, the three tester animals of each pasture (replicate) received 15 g of TiO_2 wrapped in Kraft paper with the aid of an oral applicator. In the last five days of TiO_2 dosing, individual feces samples were collected once a day directly from the animals' rectum and stored in a freezer (at −20°C). After the 5-day feces collection period, the individual samples were defrosted, homogenized to obtain a pooled sample per animal, then dried in a forced-air oven (55°C–72 h) and, finally, the dried samples were ground (1 mm sieve) in a Willey-type knife mill before being sent for TiO_2 and iNDF analysis.

The analysis of TiO_2 was performed as described by Myers et al. (2004) and adapted to Inductively Coupled Plasma Optical Emission Spectrometry ICP-OES model Thermo iCAP 6000 series—Dual View (Thermo Fisher Scientific, Waltham, Massachusetts, United States, USA) in radial mode and λ 334.941 nm.

To determine the iNDF content of the forages consumed by the animals, samples from all treatments were hand-plucked for three consecutive days in each season during both experimental periods (Table 3), simulating the grazing behavior of the animals (Sollenberger and Cherney, 1995). At the end of the 3-day collection period, the samples were homogenized to create a pooled sample, then dried in a forced-air oven (55°C–72 h). After drying, the samples were ground (2 mm sieve) in a Willey-type knife mill, placed into 100 g m^{-2} non-woven fabric filter bags and incubated (288 h) in the rumen of cannulated *Nellore* steers. After incubation, the bags were collected, washed in running water until completely clear and whitened, and then dried again in the forced-air oven (55°C–72 h) before being sent to determine the NDF analysis, according to the method of Goering and Van Soest (1970), without sodium sulfite and using a filter bag. The remaining residue was considered as the iNDF content.

The calculation of DMI_f followed the equation:

$$DMI_f = \frac{\left[iNDF_{feces} \times \left(\frac{TiO_2\ \text{supplied}}{TiO_2\ \text{recovered in feces}}\right)\right]}{iNDF_{forages}}$$

where: $iNDF_{feces}$: fecal content of indigestible neutral detergent fiber (%); TiO_2 supplied: TiO_2 content supplied to the animals (%); TiO_2 recovered in feces: TiO_2 content recovered in feces (%); $iNDF_{forages}$: forage content of indigestible neutral detergent fiber (%).

Additionally, auxiliary variables were assessed to elucidate the relationships between forage characteristics and animal performance. The forage allowance (FA, kg DM ha^{-1} of Forage kg^{-1} LW ha^{-1}) was calculated according to Sollenberger et al. (2005), based on the DM of live forage mass (leaf and stem fractions) obtained from Pasquini Neto et al. (2024). The feed efficiency (FE, g ADG kg^{-1} DMI_t) was calculated as the ratio of ADG and DMI_t.

2.4. Statistical analysis

Data were statistically analyzed using SAS *Software* (SAS Institute Inc., Cary, North Carolina, USA), with the animal as the experimental unit for the variables examined. The data were first submitted to PROC UNIVARIATE to test the normality of the residues (Shapiro–Wilk) and to identify the presence of "outliers". If the data were not normally distributed, a logarithmic transformation was applied before analysis. The data were then analyzed using PROC MIXED, testing different covariance structures and considering the effects of treatments and seasons of the year as fixed effects, while experimental spatial units and years were considered random effects. The analysis used a split-plot approach to account for repeated measures over time. The covariance structures that presented the lowest value of the corrected Akaike Information Criterion (AICC) were selected for use in the analysis (Wang and Goonewardene, 2004). The interaction between treatments ×

Table 3
Chemical composition of diets according to different levels of intensification of pasture-based beef cattle production systems during the experimental period.

Item/ treatments/ seasons		DM	CP	TDN	NFC	NDF	ADF	Lig	MM	EE	GE
		($g\ kg^{-1}$)	($g\ kg^{-1}$ DM)								($MJ\ kg^{-1}$ DM)
Mineral-protein supplement[a]		905.5	508.8	609.0	173.7	60.5	26.8	7.9	246.1	11.8	8.8
Available forages of the treatments in seasons											
DP0	Spring	297.1	110.2	645.9	123.2	656.4	315.0	30.9	91.9	36.4	18.4
	Summer	262.3	122.4	652.5	120.7	644.1	328.8	25.6	86.8	26.9	17.5
	Autumn	356.4	95.5	602.3	106.7	688.0	378.0	40.5	84.6	18.0	17.2
	Winter	638.7	55.4	557.3	110.8	737.5	462.2	56.6	82.7	13.9	16.6
SP200	Spring	319.0	126.9	641.9	139.2	609.1	313.8	31.0	94.5	30.7	18.4
	Summer	179.4	160.5	633.6	122.5	618.6	325.1	29.5	95.2	22.7	17.4
	Autumn	330.7	122.5	615.9	117.3	647.3	367.9	42.7	88.6	17.2	17.3
	Winter	670.1	39.7	555.7	114.6	767.8	481.9	62.4	65.6	11.9	17.0
RP200	Spring	335.7	94.0	615.4	110.2	682.0	328.4	38.3	86.9	28.9	18.2
	Summer	219.0	124.4	644.1	108.1	653.7	334.4	24.1	88.2	25.0	17.3
	Autumn	286.8	101.6	620.8	93.6	700.1	361.3	32.7	82.2	21.7	17.0
	Winter	475.2	65.8	616.2	107.4	732.7	412.2	37.6	72.5	22.9	16.8
RP400	Spring	307.7	112.2	582.2	98.3	656.8	339.3	41.6	103.8	15.8	17.0
	Summer	258.6	104.1	584.1	153.3	649.8	401.2	44.9	88.8	9.2	16.3
	Autumn	265.0	91.2	576.8	152.2	660.9	395.4	49.6	87.7	11.3	16.1
	Winter	399.2	64.8	552.0	137.2	699.0	446.2	56.9	90.1	9.9	15.7
IP600	Spring	248.1	146.3	599.5	108.8	646.7	339.0	39.7	87.0	12.6	17.2
	Summer	241.6	133.2	593.7	138.6	638.7	408.5	40.1	87.8	7.4	16.4
	Autumn	217.7	120.8	584.7	131.5	654.2	388.4	43.6	88.9	9.1	16.2
	Winter	181.0	187.3	595.8	103.9	592.0	351.4	38.9	115.5	25.4	16.7

DM: Dry matter; CP: Crude protein; TDN: Total Digestible Nutrients; NFC: No-Fiber Carbohydrates; NDF: Neuter detergent in fiber; ADF: Acid Detergent Fiber; Lig: Lignin MM: Mineral Matter; EE: Ethereal Extract; GE: Gross Energy.

[a] Ingredients (% of the mineral-protein supplement by DM): 45 % of Crushed Corn; 10 % of Sodium Chloride; 15 % of Mineral Premixes [quantity per kg: 240.0 g of Ca (max), 160.0 g of P; 60.0 g of S, 200.0 mg of Co, 2500.0 mg of Cu, 125.0 mg of I, 2250.0 mg of Mn, 50.0 mg of Se, 7500.0 mg of Zn, 1600.0 mg of F]; 30 % of Ammonium Nitrate [fertilizer containing the source of N (33.5 a 34.5 %)].

Treatments: DP0, extensively managed rainfed degraded mixture of *Urochloa brizantha* cv. Marandu and *Urochloa decumbens* cv. Basilisk pasture without lime or fertilization; SP200, integrated managed silvopastoral system with Brazilian native trees and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} $year^{-1}$; RP200, intensively managed rainfed mixture of *Urochloa decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} $year^{-1}$; RP400, intensively managed rainfed *Megathyrsus maximus* cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea ha^{-1} $year^{-1}$; IP600, intensively managed and irrigated *M. maximus* cv. Tanzania pasture, overseeded in the dry season with oat and ryegrass limed, fertilized with macro and microminerals and 600 kg N-urea ha^{-1} $year^{-1}$.

seasons was evaluated by using the SLICE command of PROC MIXED. Finally, estimated means were determined using the least squares means test (LSMEANS) with the Fisher's test applied, and a significance level of 5 % was considered.

3. Results

3.1. Supplement and forage intake

A significant interaction effect was observed between treatments × seasons for both forage (DMI_f) and total intake (DMI_t), when expressed in kg $animal^{-1}$ day^{-1} ($P = 0.0027$ and $P = 0.0036$, respectively), and as percentage (%) of live weight (LW) ($P = 0.0017$ and $P = 0.0003$, respectively). The effects of treatment and seasons of the year were also significant for supplement intake (DMI_s) in both kg $animal^{-1}$ day^{-1} ($P < 0.0001$ for treatment, and $P = 0.0039$ for seasons, respectively), and % LW ($P < 0.0001$ for treatment, and $P = 0.0045$ for seasons, respectively) (Table 4, Fig. 2 and Supplementary Tables S3, 4).

For DMI_s expressed as kg $animal^{-1}$ day^{-1}, the highest values were observed in the DP0 system, followed by SP200, then IP600, which showed the lowest. The DMI_s in RP200 were similar to those in SP200 and RP400, while RP400 were to IP600. When considering the seasons, the highest DMI_s were observed in the summer, autumn, and winter seasons, regardless of treatment. For DMI_s expressed as % LW, the results followed a similar pattern. The highest DMI_s were observed in DP0, followed by SP200 and then IP600, with RP200 and RP400 showing values similar to SP200 and IP600. Seasonal differences were also evident, with summer showing the highest DMI_s, followed by autumn, while spring had the lowest value. In addition, winter was similar to autumn and spring.

For DMI_f expressed as kg $animal^{-1}$ day^{-1} and as % LW, similar results were observed among treatments during the spring, summer, and autumn seasons. During spring, IP600 had the highest DMI_f, while during summer and autumn, IP600, RP200, and RP400 exhibited the highest DMI_f, and SP200 and DP0 showed the lowest values, respectively. In winter, when expressed as kg $animal^{-1}$ day^{-1}, IP600 showed the highest DMI_f, followed by RP200, RP400 and SP200, while DP0 had the lowest value. When expressed as % LW, the highest DMI_f was observed in IP600, followed by RP200 and RP400, and then DP0, with SP200 not differing significantly from IP600, RP200 and RP400 (Fig. 2a. and c.).

For DMI_t expressed as kg $animal^{-1}$ day^{-1}, similar results were observed for DMI_f across all seasons (Fig. 2b.). When expressed as % LW, the patterns were similar to those observed for DMI_f in the spring, summer, and autumn. In the winter, IP600 and SP200 had the highest DMI_t, while DP0 showed the lowest value. DMI_t in RP200 was similar to IP600 and RP400, while RP400 was similar to DP0 (Fig. 2d).

3.2. Performance

Treatment had a significant effect on LW_f ($P < 0.0001$), while treatment × season interactions affected ADG, LW_{eos} and LWG_{ha} ($P < 0.0001$), FA ($P = 0.0007$), and FE ($P = 0.0013$) across the systems (Table 5, Figs. 3, 4, and Supplementary Table S5).

The highest LW_f were observed in IP600, followed by RP200 and RP400, while SP200 and DP0 presented the lowest values.

During spring and autumn, the highest ADG were found in IP600, RP400 and RP200, with DP0 and SP200 exhibiting the lowest values. In

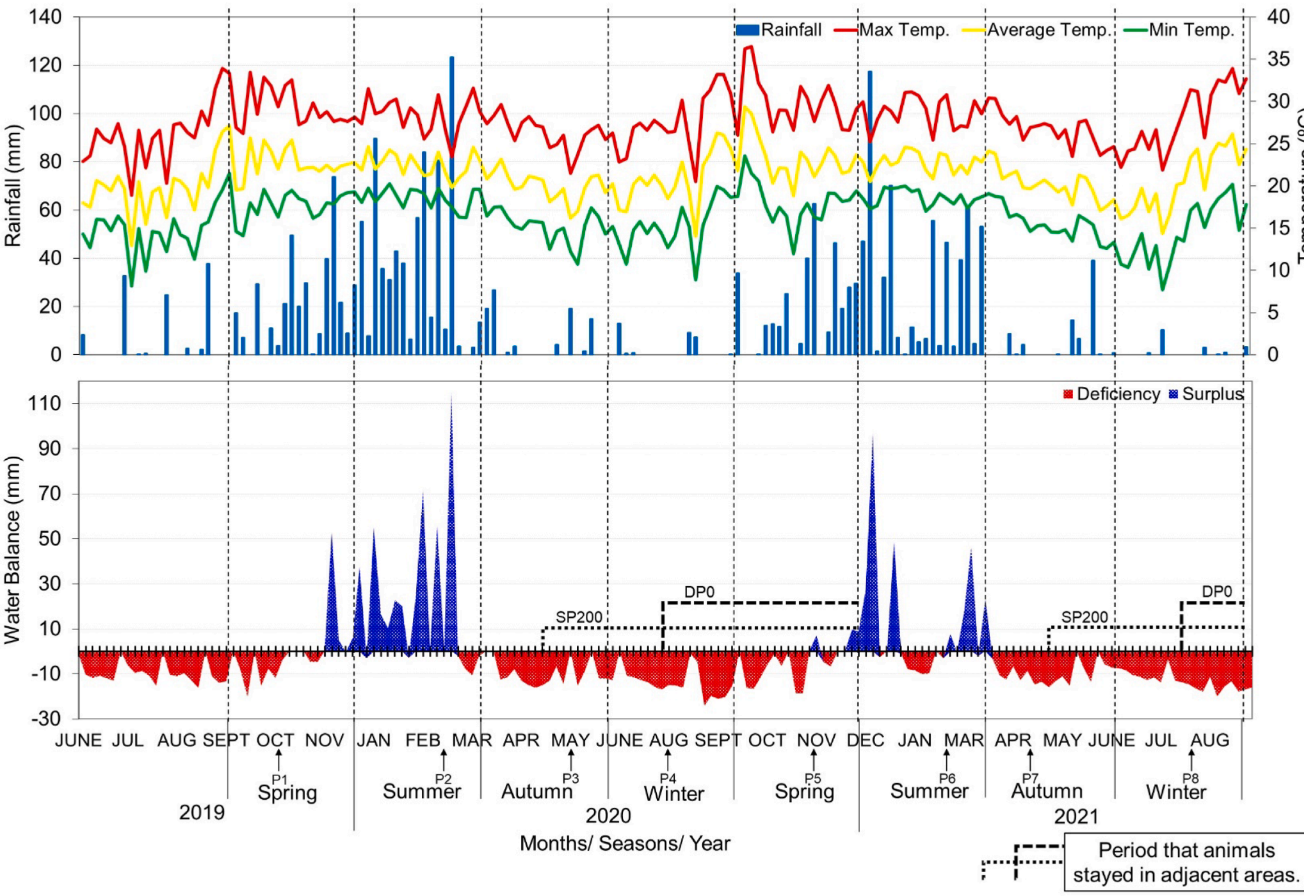

Fig. 1. Water balance, rainfall (mm), average temperature (°C) during the experimental period (September 2019 to 2021).

Table 4
Intake variables at different levels of intensification of pasture-based beef cattle production systems in Southeast Brazil (means of two years).

Variables	Treatments					Seasons				Statistical probabilities (*P*value)			
	DP0	SP200	RP200	RP400	IP600	Spring	Summer	Autumn	Winter	SEM	T	S	T × S
Forage DMI													
kg animal^{-1} day^{-1}	5.11	5.72	7.50	7.76	9.22	6.70	7.57	8.22	5.75	0.263	**<0.0001**	**<0.0001**	**0.0027**
% LW	1.28	1.39	1.68	1.71	2.10	1.88	1.80	1.74	1.11	0.071	**0.0002**	**<0.0001**	**0.0017**
Supplement DMI													
kg animal^{-1} day^{-1}	0.60^{A}	0.39^{B}	0.37^{BC}	0.30^{CD}	0.24^{D}	0.22^{B}	0.49^{A}	0.42^{A}	0.40^{A}	0.029	**<0.0001**	**0.0039**	0.8735
% LW	0.15^{A}	0.10^{B}	0.08^{BC}	0.06^{BC}	0.05^{C}	0.06^{C}	0.12^{A}	0.09^{B}	0.08^{BC}	0.007	**<0.0001**	**0.0045**	0.7410
Total DMI													
kg animal^{-1} day^{-1}	5.71	5.97	7.9	8.05	9.45	6.92	7.95	8.65	6.15	0.264	**<0.0001**	**<0.0001**	**0.0036**
% LW	1.43	1.46	1.77	1.77	2.15	1.94	1.89	1.85	1.19	0.071	**0.0033**	**<0.0001**	**0.0003**

Means followed by the same letter in the line do not differ by Fisher's test ($P < 0.05$).
DMI: Dry matter intake; LW: Live weight.
SEM: Standard error; T: Treatments; S: Seasons; T × S: Interaction between Treatments and Seasons.
Treatments: DP0, extensively managed rainfed degraded mixture of *Urochloa brizantha* cv. Marandu and *Urochloa decumbens* cv. Basilisk pasture without lime or fertilization; SP200, integrated managed silvopastoral system with Brazilian native trees and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1}; RP200, intensively managed rainfed mixture of *Urochloa decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1}; RP400, intensively managed rainfed *Megathyrsus maximus* cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea ha^{-1} year^{-1}; IP600, intensively managed and irrigated *M. maximus* cv. Tanzania pasture, overseeded in the dry season with oat and ryegrass limed, fertilized with macro and microminerals and 600 kg N-urea ha^{-1} year^{-1}.

summer, RP400 showed the highest ADG, followed by RP200 and SP200, with IP600 and DP0 showing values similar to RP400 and RP200. In winter, IP600 had the highest ADG, followed by RP200, RP400, SP200 and DP0 (Fig. 3a.).

In spring, RP400 and RP200 exhibited the highest LW_{eos} when compared to DP0. Values for IP600 were similar to those of RP400 and RP200, while SP200 had similar values to IP600 and DP0. During summer and autumn, RP400, RP200, and IP600 had the highest LW_{eos}, while DP0 and SP200 had the lowest values. In winter, IP600 showed the highest LW_{eos}, followed by RP200 and RP400, with SP200 and DP0 showing the lowest values (Fig. 3b.).

In spring, autumn, and winter, IP600 showed higher LWG_{ha}, followed by RP400 and RP200, with DP0 and SP200 exhibiting the lowest values. During summer, IP600 presented the highest LWG_{ha}, followed by RP400, then RP200, and finally SP200 and DP0, which presented the lowest values (Fig. 3c.).

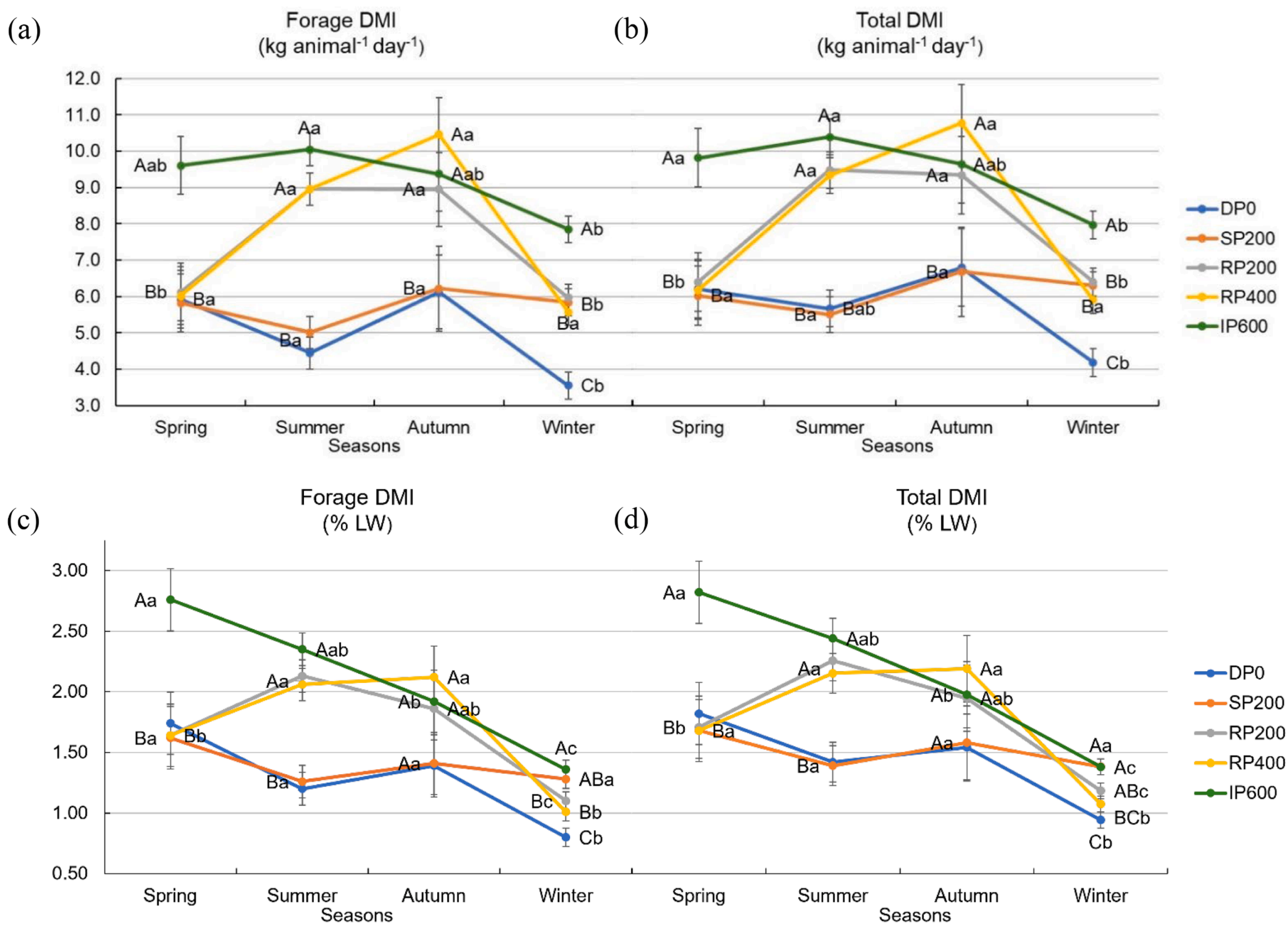

Fig. 2. Treatments × seasons interaction on the intake variables at different levels of intensification of pastoral systems for beef cattle production (DP0, SP200, RP200, RP400 and IP600). Means followed by the same capital letter for the production system factor within the same season and lowercase for the season factor within the same production system do not differ by Fisher's test ($P < 0.05$).

Table 5
Animal performance variables and feed efficiency at different levels of intensification of pasture-based beef cattle production systems in different seasons in Southeast Brazil (means of two years).

Variables	Treatments					Seasons				Statistical probabilities (*P*value)			
	DP0	SP200	RP200	RP400	IP600	Spring	Summer	Autumn	Winter	SEM	T	S	T × S
LW_f kg	441^C	458^C	564^B	562^B	621^A	*	*	*	*	11.82	**<0.0001**	*	*
ADG kg animal^{-1} day^{-1}	0.303	0.344	0.621	0.619	0.800	0.642	0.724	0.518	0.267	0.02	**<0.0001**	**<0.0001**	**<0.0001**
LW_{eos} Kg	427	433	491	498	504	391	456	505	530	5.70	**<0.0001**	**<0.0001**	**<0.0001**
LWG_{ha} kg ha^{-1} seasons^{-1}	60	57	195	285	432	101	378	265	78	24.11	**<0.0001**	**<0.0001**	**<0.0001**
FA kg DM ha^{-1} kg^{-1} LW ha^{-1}	0.84	1.51	1.94	3.38	2.88	2.31	2.01	1.91	2.21	0.160	**<0.0001**	**0.3756**	**0.0007**
FE g ADG kg^{-1} DMI_t	44.66	51.82	81.36	69.92	86.28	93.39	92.11	53.44	38.18	1.083	**0.0129**	**<0.0001**	**0.0013**

Means followed by the same letter in the line do not differ by Fisher's test ($P < 0.05$). *Data do not present by season.
LW_f: Final live weight; ADG: Average daily gain; LW_{eos}: Average live weight at the end of each season; LWG_{ha}: Average live weight gain per hectare; FA: Forage allowance; FE: Feed efficiency; ha: hectare; DMI: Dry matter intake.
SEM: Standard error; T: Treatments; S: Seasons; T × S: Interaction between Treatments and Seasons.
Treatments: DP0, extensively managed rainfed degraded mixture of *Urochloa brizantha* cv. Marandu and *Urochloa decumbens* cv. Basilisk pasture without lime or fertilization; SP200, integrated managed silvopastoral system with Brazilian native trees and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1}; RP200, intensively managed rainfed mixture of *Urochloa decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1}; RP400, intensively managed rainfed *Megathyrsus maximus* cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea ha^{-1} year^{-1}; IP600, intensively managed and irrigated *M. maximus* cv. Tanzania pasture, overseeded in the dry season with oat and ryegrass limed, fertilized with macro and microminerals and 600 kg N-urea ha^{-1} year^{-1}.

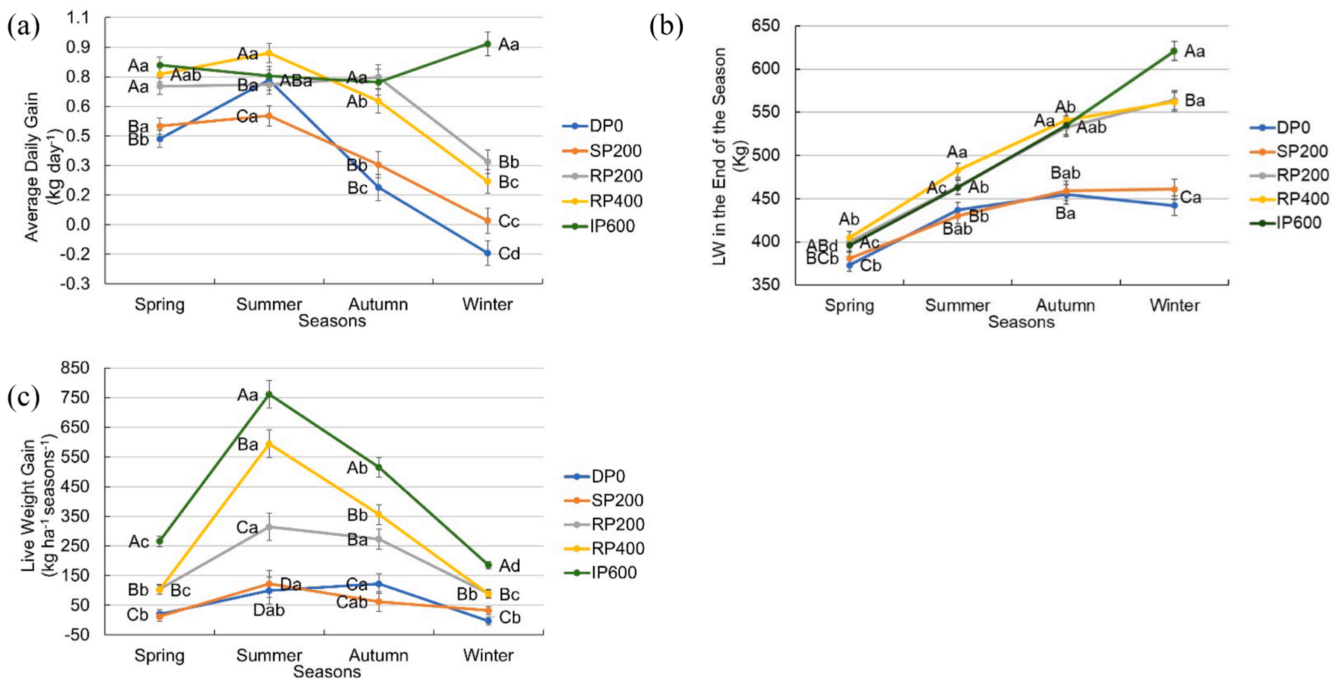

Fig. 3. Treatments × seasons interaction on animal performance variables at different levels of intensification of pastoral systems for beef cattle production (DP0, SP200, RP200, RP400 and IP600). Means followed by the same capital letter for the production system factor within the same season and lowercase for the season factor within the same production system do not differ by Fisher's test ($P < 0.05$).

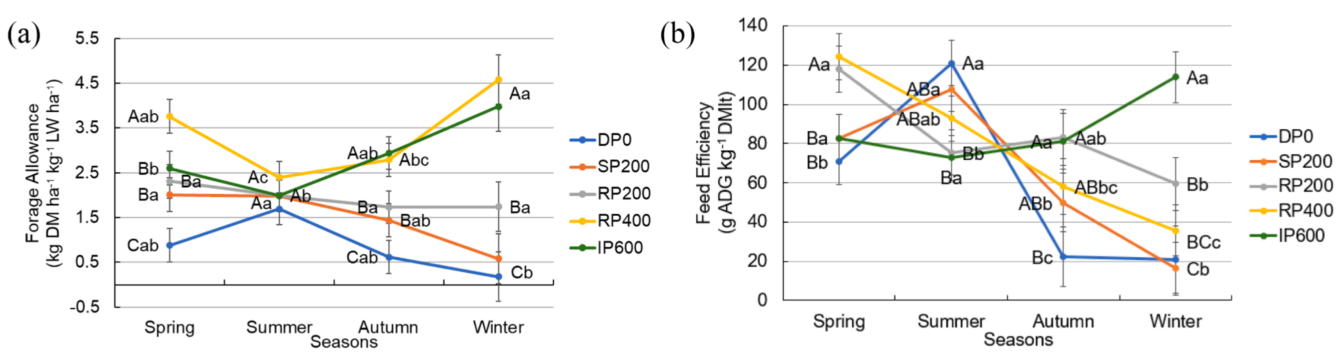

Fig. 4. Treatments × seasons interaction on auxiliary variables (FA and FE) at different levels of intensification of pastoral systems for beef cattle production (DP0, SP200, RP200, RP400 and IP600). Means followed by the same capital letter for the production system factor within the same season and lowercase for the season factor within the same production system do not differ by Fisher's test ($P < 0.05$).

Considering forage allowance (FA), in spring, RP400 had the highest value, followed by IP600, RP200 and SP200, with DP0 exhibiting the lowest value. During summer, similar values were observed across all treatments. In autumn, IP600 and RP400 showed the highest FA, followed by RP200 and SP200, then DP0. In winter, IP600 and RP400 showed the highest FA, followed by RP200, while SP200 and DP0 showed the lowest values (Fig. 4a.).

For feed efficiency (FE), during the spring, RP400 and RP200 had the highest values compared to SP200, IP600 and DP0. In summer, DP0 had the highest FE compared to RP200 and IP600. In addition, SP200 and RP400 presented values similar to DP0 and to RP200 and IP600. During autumn, the highest FE were observed in RP200 and IP600 compared to DP0, with SP200 and RP400 showing values similar to RP200 and IP600, and to DP0. In winter, IP600 exhibited the highest FE, followed by RP200, and then SP200. Additionally, RP400 and DP0 presented values similar to RP200 and to SP200 (Fig. 4b.).

3.3. Stocking rates and carcass variables

Treatment significantly affected HCW_f, CY, CG_{ha} and CGY ($P < 0.0001$), but did not affect HCW_i ($P = 0.7864$) (Table 6).

The highest values of HCW_f and CY were observed in IP600, followed by RP200 an RP400, while SP200 and DP0 had the lowest values. For CG_{ha}, IP600 exhibited the highest value, followed by RP400 an RP200, then DP0 and SP200. Finally, for CGY, IP600 showed the highest value, followed by RP200, and finally SP200 and DP0, which presented the lowest values. Values for RP400 were similar to RP200 and those for SP200 and DP0.

Treatment × season interactions affected stocking rates expressed as both animal units (AU) and animal equivalent (AE) ($P < 0.0001$) (Fig. 5 and Supplementary Table S6).

In spring, SRAU was higher in IP600, followed by RP200, RP400 and DP0, then with SP200 exhibiting the lowest value. In summer and autumn, IP600 had the highest SRAU, followed by RP400, then RP200, while DP0 and SP200 showed the lowest values. In winter, the highest SRAU was observed in IP600, followed by RP400, then DP0 and RP200,

Table 6
Stocking rates and carcass variables at different levels of intensification of pasture-based beef cattle production systems in different seasons in Southeast Brazil (means of two years).

Variables	Treatments					Seasons				Statistical probabilities (*P*value)			
	DP0	SP200	RP200	RP400	IP600	Spring	Summer	Autumn	Winter	SEM	T	S	T × S
Stocking rates													
AU ha^{-1}	1.89	1.24	2.56	3.90	5.68	1.69	4.63	3.9	1.99	0.25	**<0.0001**	**<0.0001**	**<0.0001**
AE ha^{-1}	2.03	1.34	2.58	3.84	5.89	2.14	5.02	3.67	1.72	0.27	**<0.0001**	**<0.0001**	**<0.0001**
HCW$_i$													
kg carcass^{-1}	158	159	157	162	157	*	*	*	*	4.60	0.7864	*	*
HCW$_f$													
kg carcass^{-1}	218^C	230^C	299^B	290^B	340^A	*	*	*	*	7.37	**<0.0001**	*	*
CY													
%	49.7^C	50.3^C	52.8^B	51.5^B	55.5^A	*	*	*	*	0.36	**<0.0001**	*	*
CG$_{ha}$													
kg carcass^{-1} ha^{-1}	120^D	117^D	418^C	600^B	989^A	*	*	*	*	75.88	**<0.0001**	*	*
CGY													
%	56.4^C	57.8^C	60.9^B	58.3^{BC}	65.5^A	*	*	*	*	0.82	**0.0006**	*	*

Means followed by the same letter in the line do not differ by Fisher's test ($P < 0.05$). *Data do not present by season.
AU: Animal unit (bovine with 450 kg of live weight); AE: Animal equivalent (AE: the average weight of the tester animals used in each treatment); HCW$_i$: Initial hot carcass weight, estimated by regression; HCW$_f$: Final hot carcass weight; CY: Carcass yield; CG$_{ha}$: Carcass gain per hectare; CGY: Carcass gain yield; ha: hectare.
SEM: Standard error; T: Treatments; S: Seasons; T × S: Interaction between Treatments and Seasons.
Treatments: DP0, extensively managed rainfed degraded mixture of *Urochloa brizantha* cv. Marandu and *Urochloa decumbens* cv. Basilisk pasture without lime or fertilization; SP200, integrated managed silvopastoral system with Brazilian native trees and rainfed *U. decumbens* cv. Basilisk pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1}; RP200, intensively managed rainfed mixture of *Urochloa decumbens* cv. Basilisk and *U. brizantha* cv. Marandu pasture limed, fertilized with macro and microminerals and 200 kg N-urea ha^{-1} year^{-1}; RP400, intensively managed rainfed *Megathyrsus maximus* cv. Tanzânia pasture limed, fertilized with macro and microminerals and 400 kg N-urea ha^{-1} year^{-1}; IP600, intensively managed and irrigated *M. maximus* cv. Tanzania pasture, overseeded in the dry season with oat and ryegrass limed, fertilized with macro and microminerals and 600 kg N-urea ha^{-1} year^{-1}.

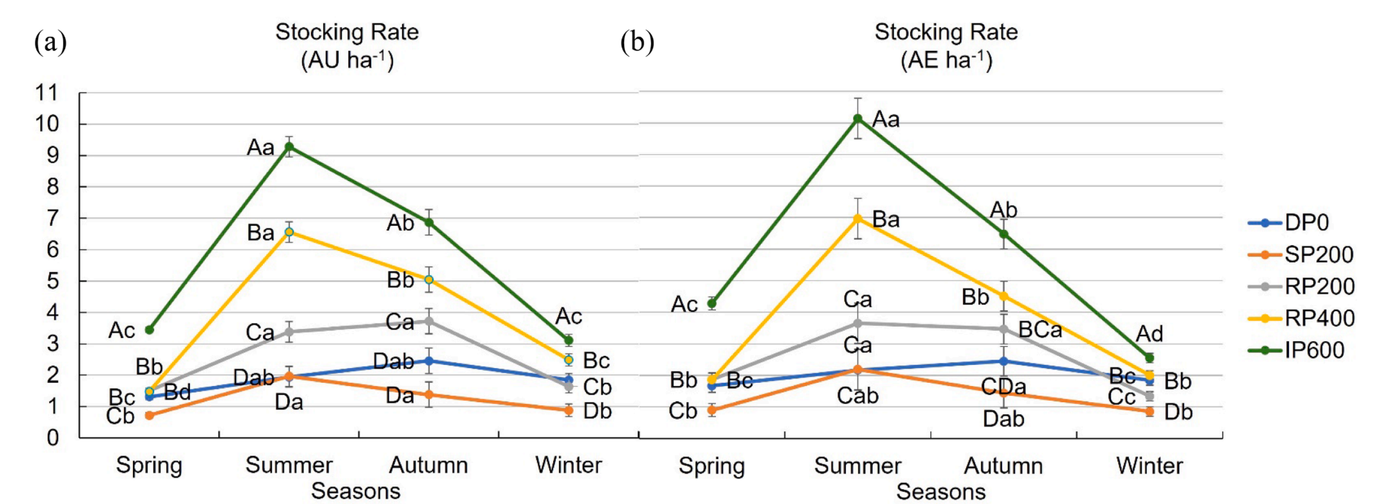

Fig. 5. Treatments × seasons interaction on stocking rates variables at different levels of intensification of pastoral systems for beef cattle production (DP0, SP200, RP200, RP400 and IP600). Means followed by the same capital letter for the production system factor within the same season and lowercase for the season factor within the same production system do not differ by Fisher's test ($P < 0.05$).

with SP200 showing the lowest value (Fig. 5a).

For SRAE, during spring, IP600 presented the highest value, followed by RP200, RP400 and DP0, while SP200 had the lowest value. In summer, IP600 presented the highest SRAE, followed by RP400, with RP200, SP200 and DP0 exhibiting the lowest values. In autumn, the highest SRAE was observed in IP600, followed by RP400, and then DP0. In addition, RP200 presented values similar to RP400 and DP0, while DP0 also showed values similar to SP200. In winter, IP600 presented a higher SRAE, followed by RP400 and DP0, RP200, and then SP200, which had the lowest value (Fig. 5b).

4. Discussion

To discuss the animals' performance and intake responses across systems, it is essential to assess the efficiency of grazing, which is influenced by the climate conditions, management strategies, and pasture productivity during the experimental period (Coleman and Moore et al., 2003; Sollenberger and Vanzant, 2011). Notably, both experimental periods included phases of severe water deficits, which significantly restricted pasture productivity, as previously reported by Pasquini Neto et al. (2024). During these drought periods of both years, animal performance was negatively affected. Consequently, treatments (e. g. IP600, RP400, and RP200) which provided more forage with improved nutritional quality, resulted in more favorable defoliation frequencies and better animal performance. Among the aerial parts of available forage of the pastures (Supplementary Tables S1 and 2), leaves hold the highest nutritional value, with a high protein content and lower levels of fibrous fractions (Table 3). This nutritional superiority influences the selectivity by grazing animals (Carvalho et al., 2007; Euclides et al., 2021). Consequently, examining the results in light of the two-year average of the forage mass accumulation, the composition of pasture components (leaf, stem, and dead material), and pasture nutritional values reported by Pasquini Neto et al. (2024), it's worthwhile for understanding the grazing efficiency and animal response within each system.

4.1. Supplement and pasture intake

The highest forage (DMI_f) and total intake (DMI_t) observed in IP600 during spring compared to other treatments can be attributed to the growth curve of the animals and the positive effects of pasture management practices, such as irrigation, which reduced the water deficit and improves DM accumulation and quality for animals' intake (Sakamoto et al., 2020). During summer, as rainfall accumulated, the higher DMI_f and DMI_t values in IP600, RP400, and RP200 reflect the efficient use of the productivity potential of the *Megathyrsus* spp. and *Urochloa* spp. cultivars due to N-fertilization and grazing management, which maintained a favorable FA with adequate leaf: stem ratio. Conversely, animals in DP0 and SP200 presented the lowest intakes, even after being relocated to the areas with stockpiled forage-grown (Fig. 1) (Euclides et al., 2007). This was due to the lack of N-fertilization in DP0 and lower leaf: stem ratios in SP200, which reduced animal defoliation frequencies and intake patterns in response by leaf's preference during grazing intensity (Carvalho et al., 2007; Cardoso et al., 2020a). In the SP200, this was due to the intense shading by the trees and the competition for nutrients between the trees and the pasture, increasing the proportion of stems (Lopes et al., 2017). In autumn, both DMI_f and DMI_t by the animals increased in function to the adjustments of the stocking rates to optimize grazing. However, in winter, as pasture production was severely reduced due to the climatic conditions, DMI_f and DMI_t decreased across all treatments except for IP600, possibly due to positive effects of pasture management, such as overseeding with oat and ryegrass, which provided better FA and high-quality. Furthermore, despite inclusion of non-protein nitrogen (NNP) source in the mineral-protein supplement, which helps ensure the critical crude protein (CP) level in the diet that would otherwise impair intake (Velazco et al., 2014), the high neutral detergent fiber (NDF) levels and limitations on leaf: stem ratio and FA led to reduce DMI_f in the other treatments, thereby limiting animal performance (Souza et al., 2010; Detmann et al., 2014b).

Additionally, the higher intake of mineral supplement (DMI_s) by the animals in DP0 and SP200 may be attributed to the inferior pasture conditions during the period, compensating for the lack of nutrients (Souza et al., 2010; Detmann et al., 2014b). Detmann et al. (2014a), state that forages must contain levels above the critical threshold of 6.0 to 7.0 % CP to support optimal animal performance. The efficiency of forage conversion into animal products is determined by the proportion of potentially digestible fraction ingested, with NDF being its main component (Table 3). Tropical forages with high NDF levels (above 600 g kg^{-1} of DM) may lead to reductions in DMI_t because animals cannot fully utilize fiber due to its lower degradation rate and the consequent slower passage through the rumen (Moot and Moore, 1985).

The nutritional composition of forages, particularly their NDF content, varies with levels of pasture intensification and thus affects individual feed intake by cattle and consequent enteric CH_4 emissions (Sakamoto et al., 2020). Improving the nutritional quality of pastures (e.g., increasing digestibility of fibrous fractions) can reduce the need for supplementation, improve animal performance, reduce the intensity of enteric CH_4 emissions (kg of CH_4/kg food ingested), and optimize resource utilization (Berchielli, et al., 2012; Guyader et al., 2016; Beauchemin et al., 2020). These findings highlight the importance of investigating the relationship between the chemical composition of cattle diets and the intensity of enteric CH_4 emissions relative to ADG, which could contribute to more sustainable and efficient beef production systems.

To evaluate and validate the DMI_t data obtained using markers, we compared the observed values with predictions from an equation specifically developed for animals in tropical pasture-based systems in Brazil (Azevêdo et al.,2010). For the DP0 and SP200, the equation overestimated intake by 13.1 % and 13.6 %, respectively. In the case of RP200 and RP400, estimates were close, with only a 6.2 % and 4.9 % overestimation, respectively. In contrast, for IP600, the equation underestimated intake by 5.0 %. Sakamoto et al. (2020) also applied this equation to estimate DMI_t and obtained expected results consistent with expectations for this experimental context. However, for DP0, the average DMI_t over the two years studied was approximately 19.3 % higher than we found. Notably, the equation estimates DMI_t based on the animals' physiological characteristics and forage chemical compositions, but it does not account variations due to abiotic factors (e.g., precipitation, temperature, and solar radiation), such as dry season restrictions (Detmann et al., 2014a) or animals selective grazing behavior influenced by leaf preference under different grazing intensities (Carvalho et al., 2007). Overall, the observed values align strongly with expected outcomes based on the animals' physiological and forage characteristics, despite environmental challenges imposed by seasonal FA. This alignment serves as a robust validation of our understanding and the rigor of our research.

4.2. Performance and stocking rates

At the end of the experimental periods, the tester animals were 34 ± 1 and 24 ± 1 months old in Periods 1 and 2, respectively. Due to the severe water deficit during the spring, autumn, and winter seasons in both periods, differences in performance and stocking rates between treatments were expected. Oliveira et al. (2018) and Sakamoto et al. (2020) have previously reported some of these findings.

The animal's higher final live weight (LW_f) in IP600 can be attributed again to the positive effects of pasture management, which resulted in higher forage productivity and quality for animals. On the other hand, the competition between the trees and the pasture in SP200 and the lack of fertilization in DP0 impaired the pastures and the LW_f of the animals in these treatments. Animals in SP200 and DP0 had final live weights (averaging 450 kg) 170 and 113 kg lower than observed in IP600 and the average in RP200 and RP400, respectively. Consequently, the highest values of HCW_f, CY, and CGY observed in IP600, followed by RP200 and RP400, are consistent with the findings of Oliveira et al. (2018), where the CY were similar in the same treatments, averaging 55.8 %, while for DP0, the CY was 53.3 %, approximately 7.2 % higher than what was observed in this study. The lower LW_f in SP200 may again be attributed to the tree's intense shading and competition for natural resources, which led to reduced FA over time due to insufficient pasture growth. This is further aggravated by shorter daylight hours and lower temperatures in winter. For DP0, due to the lack of soil correction, fertilization, and the presence of Al^{3+}, the quality of the pasture was significantly reduced compared to all other treatments (Pasquini Neto et al., 2024). Consequently, animal performance in DP0 was negatively affected, with significantly worse results than to other treatments.

The higher ADG and LW_{eos} values observed for IP600, RP400, and RP200 during spring indicate that grazing management positively affects animal growth rates, enhancing FE due to high-quality forages and FA. Animals in RP400 and RP200 had higher FE than IP600 due to the lower stoking rates, resulting in less competition per ha and high leaf selectivity (Carvalho et al., 2007; Euclides et al., 2021). Conversely, despite high CP levels in forages in SP200 and DP0, the restricted FA and intake patterns resulted in the lowest values of ADG and LW_{eos} (Carvalho et al., 2007). Furthermore, according to Detmann et al. (2014b), there is a nutritional imbalance during the growth of tropical forages in the rainy season characterized by a relative excess of energy in relation to available CP to animal requirements. Under these conditions, an unbalanced protein-to-energy ratio (P: E) possibly reduced the utilization of metabolizable energy and limited animals' DMI_f through metabolic mechanisms, impacting the performance of the animals. These factors support the necessity of specific supplementation programs for all rainy phases (dry-to-rainy, rainy, and rainy-to-dry). During summer, RP400, RP200, and IP600 achieved higher ADG and LW_{eos}, reflecting the animals' potential to perform better when provided with adequate FA with improved quality. This encouraged DMI_f of animals, avoiding excess residual forages. The ADG and FE values observed for DP0 and SP200 in the second year were influenced by the FA of the stockpiled forage growth from spring (Euclides et al., 2007) and the animals' compensatory weight gain by the DMI_t of high-quality diet. Compensatory weight gain occurs when animals that experience weight loss due to dietary restrictions subsequently exhibit accelerated growth upon returning to better nutritional conditions. The FA values observed in treatments reflect how grazing management can affect the relationship between animals' performance and forage accumulation (Sollenberger et al., 2005). When well-adjusted, the height of the grass stubble and the fixed days of grazing and rest periods allow for maximizing land use and animal productivity (Costa and Queiroz, 2013). However, maintaining an ideal ratio throughout the seasons for animal's needs requires continuous monitoring of other factors, such as pasture structure, quality, and spatial variability to ensure the benefits of treatments to dynamic responses to climatic conditions and soil fertility to pastures through seasons (Carvalho et al., 2007; Rouquette, 2016). Considering these factors, Detmann et al. (2014b) emphasize that when the relationship between FA and animals' DMI_t is not limited, the nutritional aspects of forage utilization will become predominant for animals' performance. Therefore, in tropical pasture-based production systems, an integrated approach is needed; FA and quality must be strategically managed to maximize treatment efficiency. During the autumn, there was a decline in accumulation and quality levels in the forages of all treatments, which extended into winter, reflecting the effect of drought on the senescence of pastures, resulting in decreased forage digestibility (Souza et al., 2010; Detmann et al., 2014b; Pasquini Neto et al., 2024). The reduced CP and increased NDF levels in autumn and winter further decreased ADG, $LW_{eos,}$ and FE values, particularly in SP200 and DP0, due to the more significant DMI_f restrictions imposed by the lower pasture heights, leaf: stem ratios, and FA. In winter, only animals in IP600 maintained high ADG, $LW_{eos,}$ and FE due to intercropping, irrigation, grazing management, and better nutritional quality of the forage (Pasquini Neto et al., 2024). This underscores the impact of climatic conditions on tropical pasture productivity and nutritive value when rainfed (DaMatta et al., 2010; Santos et al., 2013). In this aspect, FE is directly related to diet quality, grazing management, and environmental conditions (Carvalho et al., 2007; Euclides et al., 2021), being very limited to adequate FA intensity and often insufficient to maintain productive performance when the balance between intake and the animal's ability to convert feed into body weight gain is inefficient (Rouquette, 2016). These performance results are in line with the findings of Sakamoto et al. (2020). Additionally, the higher FA value observed for RP400 is a direct result of the adjustments in the stocking rates, an essential aspect of grazing management that ensures animals have enough pasture access (Carvalho et al., 2007). However, severe weather conditions negatively affected the leaf: stem ratio and the forage quality, which affected the animals' growth requirements (Viciedo et al., 2019).

Considering animal efficiency per unit area, higher LWG_{ha} and stocking rates were consistently obtained in IP600, attributed to the adoption of intensive management. During spring, RP200, RP400, and DP0 achieved similar results, likely due to the adjustments in stocking rates to grazing management and availability of quality forages. In the summer, RP400 and RP200 presented increased stocking rates and LWG_{ha}, due to N-fertilization, which significantly boosted forage production during the rainy season. Conversely, SP200 and DP0 presented lower LWG_{ha} and stocking rates due to insufficient forage accumulation (Pasquini Neto et al., 2024) and relocation to supplementary areas. During autumn and winter, the dynamic responses to climatic conditions reduced the pasture structures, leading to stocking rates adjustments. Increased grazing pressure negatively affected all treatments that lacked technologies to reduce seasonal effects, such as irrigation and overseeding in IP600. Depletion of the forages in RP400, RP200, DP0 and SP200 resulted in lower pasture heights, leaf: stem ratios, and, consequently, stocking rates and LWG_{ha} losses during the end of the dry period due to competition and selectivity by the animals (Carvalho et al., 2007; Cardoso et al., 2020).

In this regard, considering the influence of increased performance on GHG mitigation efforts, animals in DP0 and SP200 may contribute to larger emissions of enteric CH_4 without proportional production (Oliveira et al., 2020; Sakamoto et al., 2020). However, through the efficient management of pastures, it's possible to reduce enteric CH_4 emissions while simultaneously increasing carcass gain per area (CG_{ha}); reducing the slaughter age of the animals; ensuring efficiency, economic profitability, and sustainability (Palermo et al., 2014; Oliveira et al., 2018; Cardoso et al., 2020a). The CG_{ha} obtained confirms that intensive management can increase efficiency and profitability, as IP600 had the highest CGha, followed by RP400 and RP200. Sakamoto et al. (2020), in a study carried out in the same experimental area, demonstrated reductions in CH_4 emission intensity per kg of carcass per ha in RP400 compared with DP0. According to Koscheck et al. (2020), maintaining pastures at a low to moderate grazing height (0.15 to 0.25 m) with supplementation (protein + energy) levels between medium to high (0.3 to 0.6 % LW) can effectively improve animal performance, reduce age at slaughter, and enhance sustainability, while reducing CH_4 emissions/kg of carcass produced.

5. Conclusion

Intensive pasture-based production systems, whether rainfed or irrigated (IP600, RP400, and RP200), enhance productivity and land-use efficiency, enabling animals to reach their targets weight faster compared to extensively conventional systems (DP0). However, intensification often involves higher costs, and their feasibility is influenced by regional environmental and socioeconomic factors. The silvopastoral system (SP200) exhibited lower animal performance, potentially due to competition between pasture and trees, as well as adverse seasonal conditions, underscoring the need for careful management. Degraded pastures are undesirable due to resource depletion and increase land requirements. This study reinforces the importance of avoiding systems prone to degradation, as they fail to deliver essential ecosystem services. Intensively managed, recovered pastures offer potential for mitigating GHG emissions through soil carbon sequestration and increased meat production efficiency. Adoption of these practices depends on economic viability, suggesting a role for supportive public policies. Further economic studies are necessary to assess the feasibility of intensified systems in tropical pasture-based livestock production.

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CRediT authorship contribution statement

Rolando Pasquini Neto: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Althieres José Furtado:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Gabriele Voltareli da Silva:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Annelise Aila Gomes Lobo:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adibe Luiz Abdalla Filho:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Flavio Perna Junior:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexandre Berndt:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Sérgio Raposo de Medeiros:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **André de Faria Pedroso:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patrícia Perondi Anchão de Oliveira:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paulo Henrique Mazza Rodrigues:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.livsci.2025.105667.

Data availability

Data supporting the findings of this study are available within the article and its supplementary material.

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