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Innovative improvements of silvopastoral systems applied to the *Brachiaria decumbens* yields in degraded areas – A case study in Orellana, Amazonian Ecuador

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Abstract: Climate change is a global, recurring phenomenon that is altering weather patterns around the world. The corresponding changes have significant implications for natural ecosystems, agriculture, and livestock. Based on this context, we realized a study, which assessed the effect of silvopastoral systems on *Brachiaria decumbens* yields. Therefore, we realized a completely randomized block design with three replications for each treatment. The treatments were of low density of trees/ha (138 ha^{-1}) named SPs1, a high density of trees/ha (312 ha^{-1}) named SPs2, as well as a monoculture system (no trees) only pasture named simply Control. The experimental variables evaluated were forage production, chemical composition and nutrient values. The results yielded variations in the agronomic data by treatment ($P < 0.05$) and season effects ($P = < 0.05$). Despite that, all chemical determinations did not change among treatments ($P = 0.11$ to 0.96) nor for the season effect ($P = 0.43$ to 0.98). Subsequently, all nutritional values (i.e., energy and protein values) lacked to vary by main effects ($P = 0.26$ to 0.92). In conclusion, the SPs improved the agronomic responses, which may allow a greater chemical composition and forage quality in the long term. Nevertheless, further long-term studies should be performed in order to confirm and improve the given results of the current study.

Keywords: Silvopastoral systems, livestock precision, Equator amazon, Small livestock

Introduction

Worldwide, but more specifically within tropical forests, there are increasing clearings in order to make space for cattle pastures (Buschbacher, 1986; Wright, 2010; Kaimowitz and Angelsen 2008; Griscom and Ashton 2011; Parsons, 1976). This involves cutting down trees and removing vegetation, leading to the loss of forest ecosystems (Phillips 1997; UNDP, 2017; Watson et al 2018; Jayasinghe et al., 2022). Besides the known negative effects of climate change and the herewith often associated global warming, deforestation disrupts the natural habitat of numerous plant and animal species, contributing to biodiversity loss (Bodo et al 2021; Kumar et al 2022; Hughes 2017; Habibullah et al 2022; Toulkeridis et al 2020; Bálint et al 2011). The process of converting forests to pastures often involves the use of unsustainable land management practices, such as slash-and-burn agriculture or improper grazing techniques (Mena et al 2006; Rojas-Downing et al 2017; Yadav 2013; Hohnwald et al 2006). These practices enable degradation of the soil, leading to erosion, nutrient depletion, and often also to the complete loss of soil fertility (Lal 2015; Lal 2009; Tan et al 2005). As a result, the land becomes less productive and subsequently can no longer support healthy ecosystems (DeFries et al 2004; Barrios 2007; Gomiero 2016). The destruction of tropical forests for cattle pastures releases significant amounts of greenhouse gases, primarily carbon dioxide (CO_2) and later, even worse, to a following increase of methane (CH_4) emissions to the atmosphere when cattle is introduced (Olivera et al 2021; Szymczak et al 2021; Houghton 2005; Bustamante et al 2012; Laurance et al 1998; Fearnside and Barbosa 1998). Trees store large amounts of carbon, and when forests are cleared, this carbon is released into the atmosphere (Lugo and Brown 1992; Malhi et al 2002). Additionally, burning of cleared vegetation contributes to further CO_2 emissions (Van der Werf et al 2010; Reyes et al 2019). These emissions contribute to and accelerate climate change processes as well as global warming (Cox et al 2000; Hansen et al 2000). Tropical forests are carbon sinks, which lead to the absorption and storage of large amounts of CO_2 from the atmosphere (Lugo and Brown 1992; Soepadmo 1993; Clark 2002). When forests are converted to pastures, the stored carbon is released into the atmosphere, accelerating the greenhouse effect (Lal 2003; do Carmo et al 2012; Nunes et al 2020). The loss of these carbon stocks reduces the forest's capacity to mitigate climate change (González et al 2021; Fuentes-Quisaguano et al 2023).

Silvopastoral systems (SP) refer to the integration of trees, forage crops, and livestock on the given land area (Alonso 2011; Jose and Dollinger 2019; González et al 2021; Gomes da Silva et al 2021). These systems have gained attention in recent years due to their potential to enhance productivity, sustainability, and environmental benefits compared to traditional agricultural practices (Nahed-Toral et al 2013; Hanisch et al 2019; Mauricio et al 2019). Hereby, *Brachiaria decumbens,* also known as signal grass, is a popular forage grass used in tropical and subtropical regions for livestock grazing (Olivera et al 2006; Ortega-Aguirre et al 2015; Lima et al 2019; Low 2015; Barbosa et al 2008). Additionally, B. *decumbens* is known for its C4 photosynthetic pathway, which enables it to efficiently utilize sunlight and carbon dioxide for growth, particularly under conditions of drought and high temperatures (Waller & Lewis, 1979; Ortega-Aguirre et al., 2015). This metabolic adaptation not only enhances its productivity but also allows it to thrive in environments with limited water availability. *B. decumbens* is a low-growing decumbent perennial grass with flowering stems up to 100 cm high originating from the prostrate, multi-nodded stems, while plants can spread by both rhizomes and stolons as well as through seed production (Low, 2015). The chemical composition of *Brachiaria decumbens* varies depending on factors such as growth stage, management, and environmental conditions (Do Nascimento et al. 2019). However, several studies have reported, where DM content ranges between 92.6 and 95.6%, CP content varies from 9.5% at three months of growth to 11.2% at one month. Whereas Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF) as essential indicators of digestibility range from 54 to 56% and 43% and 46%, respectively (Olivera, and Del Pozo 2006; Hare et al. 2014; Ortega-Aguirre et al. 2015; Lima et al. 2019). In Ecuador, *Brachiaria decumbens* is widely used by small livestock farming to raise cattle under extensive productive systems (Garay et al 2017; Reyes-Pérez et al 2019; Reyes-Pérez et al 2020; Fuentes-Quisaguano et al 2023; Fuentes et al 2023).

Based on the aforementioned, the predominant aim of the current case study has been to assess the *Brachiaria decumbens* in SP in an Amazonian environment in Eastern Ecuador.

Materials and Methods

Study Area

The Province of Orellana, located in the north of the Ecuadorian Amazon Region (AR), is territorially distributed in four cantons, being Francisco de Orellana, Loreto, Aguarico, and Joya de los Sachas (GADMO 2019; Figure 1). The geographical coordinate of the study area were 23‘ 34.33’ South Latitude and 77° 02′ 26.70’ West Longitude. The province covers an approximate area of 21,703 km^2, with an altitude of over 300 meters above sea level (m a.s.l.), including active volcanoes and a strong existing biodiversity (Toulkeridis and Zach, 2017; Lozano et al 2020; INAMHI 2021; Torres et al 2022). Based on meteorological data, in Orellana rule two well marked seasons, of which one is characterized by heavy rainfalls with a range > 2800 mm during the months of February to August, while the other reaches precipitations of < 1000 mm for the months of September to January (INAMHI 2021). The average annual temperature ranges from 18 to 32 ºC, with a relative humidity of ≤ 80% (Holdridge 1967).

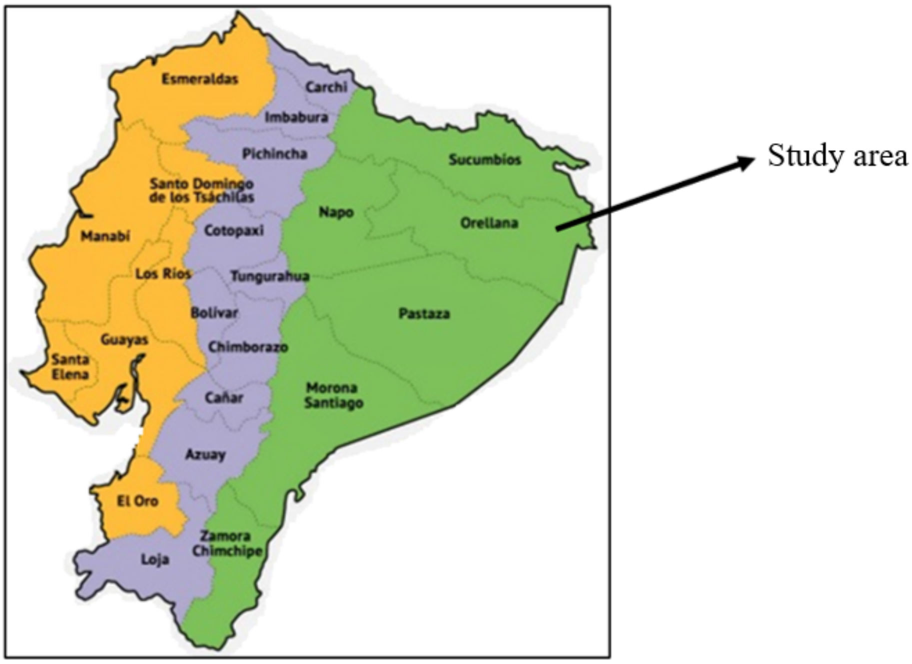

Figure 1: Location of the study area

Socio-productive characteristics have reported a population of 136,396 people, of which 64,266 are male and 72,130 are female (INEC 2019). The total area of 606,307 hectares is distributed, with 80% (485,039 ha) corresponding to forests and mountains, 7.2% (43,582 ha) of permanent crops, 4.6% (28,049 ha) for other uses, and 4.2% (25,162 ha) with cultivated pastures, while 3.1% (19,034 ha) are covered with natural pastures (Ríos et al 2016). On the other hand, 0.82% (4959 ha) are occupied with transitory crops and fallow land.

Experimental Design and Treatments

During 2017, some 9 ha of Dallis grass (*Brachiaria decumbens*) were established in silvopastoral systems (SPs), whose trees were in spatial arrangements as dispersed in paddocks, with distances between 6 × 6 and 4 × 4 between trees. Subsequently, they were divided into paddocks of 1 ha each. Therefore, during the whole experiment, no fertilizers of any kind were applied on the pastures.

In the present experiment, we applied a completely randomized block design with three replications for each of the three established treatments (Figure 2):

SPs1 = Low density of trees/ha (138 ha^{-1})

SPs2 = High density of trees/ha (312 ha^{-1})

Control = monoculture system (no trees) only pasture.

B1	B2	B3
Control	SPs1	SPs2
SPs2	Control	Control
SPs1	SPs2	SPs1

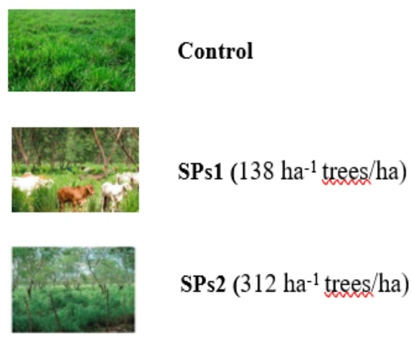

Figure 2: Scheme of the applied experimental design

Each pasture was cut every 35 days during the season of maximum precipitation (HP) from February to August, and every 45 days during the season of low precipitation (LP) from September to January.

Evaluation of variables and sample collection

Agronomic Measures

Agronomic variables were determined in each of the three treatments established according to the season, being either in high (HP, 10 cuts) or low rainfall (LP, 8 cuts). The plant height was determined using a flexometer expressed in cm, which was taken at several points in each of the replicates of every treatment before each harvest (Fahey et al 1994). Plant cover was measured as percentage to the squared meter (%/m^2) by

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direct observation and counting method, using a 1 × 0.25 cm metal square following the known methodology (de Lima Veras et al 2020; González Marcillo et al 2021).

Forage production

Fresh mass (FM) was assessed through the double sampling technique described by NRC (1962) and Hancock (2017). Therefore, for direct measurements, we used one 0.25 m^2 square to collect random samples in each treatment prior every grazing during periods of maximum and minimum rainfall, namely HP over 35 days and LP over 45 days, respectively. On the other hand, as an indirect method, the visual scale with ranges from 1 to 3, where 1 is the lowest zone and 3 is the highest in terms of forage production. Consequently, subsamples of 500 grams (g) were taken from each treatment in each season (HP and LP precipitation) and dried in a forced-air oven at 103°C for 72 hours to calculate the percentages of DM ha^{-1}.

Chemical Composition

Throughout the experimental period, being from March 2017 to March 2020, green forage samples were collected in duplicate and frozen at –20 °C for later determination of their chemical composition. Prior to analysis, the samples were thawed and conditioned in an oven at 60°C for 48 hours, after which they were passed through a 1 mm mesh grinder (Retsch SM2000, Retsch, Haan, Germany). All chemical determinations were performed in duplicate according to official reference methods (AOAC 2000). DM was determined in an oven at 103°C for 48 hours (Ref. 930.15), ash at 550°C for five hours (Ref. 942.05), whereas crude protein was calculated as percent N × 6.25 by Kjeldahl's method (Ref. 976.05), ether extract (Ref. 920.39), and crude fiber (Ref. 962.09). On the other hand, the determinations of neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) by means of the methodology described by Van Soest et al (1991), by adding α-amylase and sodium sulphite in an Ankom200 Fiber Analyzer (Ankom Technology, Fairport, Monroe, NY, USA).

Nutrient values

In addition, the feeding values of *Brachiaria decumbens* were estimated using the equations proposed by INRA (2018) and applied by Guamán-Rivera et al., 2023a; Guamán Rivera et al., 2023b). In this sense, all energy values such as gross energy (GE), digestible energy (DE), metabolizable energy (ME), and net energy for lactating (ENL; a conversion of 1 UFL = 1.76 Mcal/kg DM was used) were calculated and expressed in kcal/kg DM. Regarding to UFL, is a unit of energy measurement in the INRA feeding system used to evaluate the energy requirements of ruminants. It quantifies the energy value of feeds relative to their ability to support milk production in lactating cows. In the same way, the current study calculated protein digestible in the intestine from dietary origin (PDIA) (expressed as g/kg DM) and protein digestible in the intestines (PDI) as a sum of (PDIA + PDIM). In this case, PDIM is one of the components of the protein value system for ruminants and is calculated as part of the PDI. Finally, according to INRA (2018) rumen protein balance (RPB, g/kg DM) was estimated with the equation RPB = –84.5 + 0.61 × CP. The RPB is a new trait that reflects the difference between the microbial protein synthesis allowed by degraded proteins in the rumen and that allowed by the energy from fermentable organic matter (MOF) in the rumen.

Statistical analysis

All data were subjected to normality tests to proceed to parametric tests, using the statistical package SAS v. 9.4 (SAS Institute Inc., Cary, NC, USA). Productive responses, as well as chemical composition data and nutritive values, were analyzed as repeated measures with the MIXED procedure of SAS. The mixed model had as fixed effects treatments (SPs1, SPs2, and Control), rainfall regime (HP and LP), as well as their interaction, while blocks and residual error were considered as random effects. In order to establish correlations between chemical composition data and nutritive values, a CORR procedure was applied in the same statistical package. Means were expressed as least squares (LSM) separated by PDIFF and Dunnett's adjusted (Holtshausen et al. 2011). Statistical differences were declared at $P < 0.05$, while trends were at $P < 0.10$.

Results and discussion

The agronomic responses of *Brachiaria decumbens* in silvopastoral systems are listed in Table 1. Statistical differences among treatments were observed for plant height ($P = 0.004$) as well as crude protein ($P = 0.002$). The SP2 had greater plant height (59.30 ± 0.94 cm) than SPs1 and Control, although without differences between them (52.91 ± 0.94; $P = 0.34$). Lima et al. (2019) reported lower plant height than the studied items (34.6 cm), but with a strong influence by seasonal effect (Garay et al. 2017). Similar results have been observed in two recent studies in Orellana province, with results of 44.3 and 38 cm of the given plant heights (Guamán-Rivera et al. 2024a; 2024b) . Furthermore, contrary to these results, Ortega-Aguirre et al. (2015) reported a low plant height in *Brachiaria* spp (16.53 cm) and *Panicum* spp (21.06 cm). In this sense, Paciullo et al (2008) observed that *Brachiaria decumbens* exhibits phenotypic plasticity in response to seasonal variations in climatic conditions and shade, which gives this species great potential for use in silvopastoral systems (Olival et al 2021). Nevertheless, in the given conditions during the research period, the present study revealed that a low tree density allows for better responses than a high tree density. Therefore, it coincides to previous studies as plants grown in SPs tend to be physiologically younger, which extends the vegetative phase, reducing tissue death (Lima et al 2019a; Baldassini et al 2018). Based on our results, we hypothesized that *Brachiaria decumbens* has a low shade tolerance due to the SPs2 always indicating lower agronomic yields.

Table 1. Agronomic responses of Brachiaria decumbens evaluated under silvopastoral systems.

	Treatment			Season[1]		SEM	*P*-Value		
Item	Control	SPs1	SPs2	HP	LP		T	S	T×S
Plant height, cm	52.92^{b}	59.30^{a}	52.90^{b}	45.65^{k}	64.40^{j}	0.94	0.004	0.001	0.20
Plant coverage, %	67^{y}	81^{x}	60^{y}	68	70	4	0.06	0.64	0.53
Fresh mass, kg ha^{-1}	4834	7090	5845	5185^{k}	6662^{j}	1021	0.42	0.02	0.09
DM, kg ha−1	1492	2237	1896	1720^{y}	2030^{x}	295	0.21	0.09	0.14
CP, kg ha^{-1}	35.81^{c}	53.69^{a}	41.71^{b}	42.48	46.16	3.29	0.002	0.32	0.36

[1]Season; HP= rainy season; LP = dry season; SEM: standard error of the mean; $^{a\text{-}d}$ Different letters differ by treatment at P > 0.05; $^{j\text{-}k}$ Different letters differ by season at P < 0.05. $^{x\text{-}y}$ Indicates statistical tendencies at P < 0.10.

The crude protein (CP) values by ha were also greater in the SPs1 (53.69 ± 3.29) than SPs2 (41.71 ± 3.29), whereas the control had a lower CP value (35.81 ± 3.29) by ha when compared to those obtained in the SPs (*P* = 0.001 to 0.03). Scientific evidence stated that an increase in the CP content could be related to shaded environments and their photosynthesis and the effect of soil N dynamics (Lima et al 2019b). Despite that, plant coverage showed a statistical tendency among treatments (*P* = 0.06; Table 1), the fresh mass (5923 ± 1021, on average) and DM ha^{-1} (1875 ± 295, on average) did not vary among treatments, despite that Low (2015) observed that *B. decumbens* produces more during dry season. However, *Brachiaria decumbens* in our experimental work had a numerically greater fresh mass and DM (SPs1) due to it was impacted by a lower shade intensity, such as reported by Gomes et al (2019). In fact, according to Gómez et al (2013) the shadow intensity has been morphologically associated with thinner, longer, and wider leaves or cell walls than the *Brachiaria* is cultivated as a monoculture.

As for the seasonal effect, similar results were observed for plant height (P = 0.002) and CP (*P* = 0.002). Greater values were reported in the LP than HP, as listed in Table 1. González et al (2021) obtained for *Panicum maximum* in Orellana similar results to those of the current study in the LP season. In addition, it coincides that seasonal variations in temperature and water availability occur during the year (Pezzopane et al 2019). Consequently, this affects the annual forage production and should be considered in the planning of livestock farms (Silva-Olaya et al 2022). In fact, the fresh mass was significantly conditioned (P < 0.02; HP vs. LP; 5185 vs. 6662 ± 1021 kg ha), but the DM only had a slight tendency (P = 0.09; 1720 vs. 2023 ± 295 kg ha). On the contrary, no differences were observed in the T×S interaction (*P* = 0.9 to 0.53; Table 1). In this sense, the observation that season significantly affects fresh mass collected, but not dry matter may be explained by the influence of environmental factors such as rainfall, humidity, and temperature on the water content of plant tissues, while the actual biomass production (dry matter) remains relatively stable. This distinction has been widely documented in agronomic and ecological studies (McDonald et al. 2010). Therefore, dry matter production is primarily influenced by factors such as nutrient availability, photosynthesis, and growth stages rather than water content. Subsequently, given research indicates that while water availability can influence plant turgor and growth rates, the cumulative dry matter production over a season often remains stable if other growth conditions (e.g., soil fertility, temperature) are favorable (Larcher, 2003). Consequently, the seasonal variability in fresh mass but not in dry matter may be attributed to the dynamic influence of environmental conditions on plant water content, whereas dry matter reflects more stable biomass accumulation processes (Sarma et al., 2002). These findings align with previous studies, highlighting the importance of separating water content from structural biomass to accurately evaluate plant productivity (McDonald et al., 2010).

Table 2 lists and demonstrates the chemical composition among treatments and by season effect. No statistical differences were observed among treatments (*P* = 0.11 to 88). The averages were for DM (31.51 ± 5.67), CP (7.5 ± 1.05), NDF (67.67 ± 1.05) and ADF (38 ± 2.40). Furthermore, the season effect lacked to vary for all chemical determinations (P = 0.43 to 0.97). In contrast, the T×S interaction yielded statistical differences only for ash and organic matter (*P* = 0.008 to 0.010).

Table 2. Chemical composition of Brachiaria decumbens evaluated under silvopastoral systems.

Item	Treatment			Season[1]		SEM	*p*-Value		
	Control	SPs1	SPs2	HP	LP		T	S	T×S
DM at 103 ºC	32.23	33.76	28.54	34.47	28.55	5.67	0.81	0.43	0.92
Composition %									
Ash	11.64	10.93	12.38	11.62	11.69	0.95	0.117	0.970	0.008
Organic matter	79.53	80.19	78.85	79.54	79.50	0.87	0.105	0.979	0.010
Crude protein (N × 6.25)	7.64	7.15	7.87	7.16	7.95	1.05	0.883	0.520	0.751
Crude fiber	35.18	33.46	34.39	33.32	35.37	2.53	0.716	0.646	0.921
NDF	68.63	66.69	67.71	66.51	68.84	2.85	0.718	0.644	0.927
ADF	37.81	36.18	37.06	36.04	37.99	2.40	0.716	0.646	0.922
Eter extract	45.35	48.67	42.20	47.66	45.15	2.53	0.964	0.902	0.677

[1]Season; HP = rainy season; LP = dry season; SEM: standard error of the mean

Various studies observed greater CP content (10 to 14% of CP) when *Brachiaria decumbens* was cultivated in a silvopastoral system, but with similar NDF (68 vs. 68%) and ADF (35 vs. 37%) contents to those observed in our manuscript (Evitayani et al (2004); Lima et al., 2019a; Lima et al., 2019b). Whereas, elsewhere similar CP (6.4%) and NDF (74%) contents were reported compared to our research data (Mlay et al 2006). In our study, despite the fact that CP values were lower than optimal contents for ruminant nutrition (Van Amburgh et al 2009; Givens et al 2000; > 8% in DM basis), it is important to highlight that the benefits of using trees in the paddock could be reflected in the long term due to biological N_2 fixation and C sequestration, as reported recently (Costa et al., 2016). Such study also indicated a negative correlation of CP with NDF and ADF ($r = -0.64$; $P < 0.001$), but the low CP contents could affect the efficient use of the fibrous carbohydrates and this lower CP content could be the first limiting factor to intake for a lower microorganism activity (Garcez et al 2020). Different *Brachiaria* cultivars were studied in humid tropical conditions of Ecuador, reporting clear differences in the CP contents when compared to rainy and dry seasons (11 vs. 8%, DM basis) (Garay et al., 2017). Therefore, the forage quality could be conditioned for climatic factors such as precipitation and temperature (Garay et al 2017).

The nutritive values of *Brachiaria decumbens*, as detailed in Table 3, remained consistent across different treatments, seasons, and their interactions. Statistical analysis yielded no significant variations in energy values (P = 0.66 to 0.88) or protein content (P = 0.26 to 0.88) for any of the factors evaluated. This indicates that the nutritive quality of the forage was not influenced by the experimental conditions considered in this study.

Table 3. Nutritional values of Brachiaria decumbens assessment under silvopastoral systems.

Item	Treatment			Season[1]		SEM	p-Value		
	Control	SPs1	SPs2	HP	LP		T	S	T×S[1]
Energy, Kcal/kg DM									
GE	4.58	4.57	4.58	4.57	4.59	1.6	0.88	0.51	0.74
DE	1.09	1.03	1.07	1.03	1.1	0.84	0.66	0.62	0.90
ME	0.90	0.85	0.88	0.84	0.91	0.10	0.77	0.66	0.93
ENL	0.49	0.46	0.48	0.46	0.49	0.10	0.76	0.67	0.92
Protein, g/kg DM									
PDIA	0.42	0.39	0.42	0.39	0.44	0.04	0.85	0.40	0.69
PDI	73	73	73	73	73	0.05	0.72	0.26	0.59
RPB	−42	−44	−44	−44	−40	5	0.88	0.51	0.75

[1]Treatment × season interaction; SEM: standard error of the mean.

Worldwide, important progress has been made in improving the nutrition of dairy cows. The structural carbohydrate contents of the forages under grazing conditions supply energy values for ruminants (Guamán-Rivera et al., 2023a; Guamán-Rivera et al., 2023b). Except for GE, the other energy values had a positive correlation with NDF and ADF contents ($r = 0.99$; $P < 0.001$). This condition will indicate a strong influence of the cell walls of the forages on the energy contents (Melo and Soares de Olivera, 2022). Although it has been demonstrated that CP contents were positively correlated with GE, this study due to lower CP did not yield any correlation ($r = 0.04$; $P < 0.001$) (Guamán-Rivera et al., 2023a). Referential studies yielded a lower GE content than the present study (4.57 vs. 1.64 Mcal/kg DM) due to a lower CP content (6.4 vs. 7.5%) (Mlay et al., 2006). Similarly, lower values were reported by INRA (2018; 4.16 Mcal/kg DM). However, there were furher reports of a greater ME (1.47 to 1.69 Mcal/kg DM) as well as UFL (0.57 Mcal/kg DM) contents (Ogoukayode et al., 2021).

A recent study in Orellana province with *Panicum maximum* reported similar energy values, but with greater RPB than those obtained for *Brachiaria decumbes* (Guamán-Rivera et al. 2023). INRA (2018) informed lower PDIA (18 g/kg DM) and RPB (− 4 g/kg DM) contents than the current study, but with greater PDI contents (73 g/kg DM). Consequently, a positive correlation has been detected between CP and PDIA, as well as PDI and RPB ($r = 0.99$; $P < 0,001$). The RPB is a new concept that quantifies the difference between CP intake and non-ammonia CP flowing out at the duodenum (Sauvant and Nozière, 2016) which also indicates that OM digestibility decreases when the RPB determines values below zero (Guamán Rivera et al., 2023b).

Conclusions

The current study demonstrates that silvopastoral systems with low tree density significantly enhance the agronomic performance of *Brachiaria decumbens*, particularly in plant height and crude protein content, compared to higher tree density or monoculture systems.

Although chemical composition and nutritive values remained stable across treatments, the findings suggest that integrating trees into pastures offers long-term potential for improving soil quality and forage characteristics.

Further research is recommended to validate these benefits and optimize silvopastoral practices under similar environmental conditions.

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