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Effect of Light on Yield, Nutritive Value of *Brachiaria decumbens* and Soil Properties in Silvopastoral Systems, Peruvian Amazon

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Abstract: This study evaluated the effect of light conditions on the yield and nutritional value of *Brachiaria decumbens* (Brachiaria) in different silvopastoral systems (SPS) in the Peruvian Amazon, aiming to contribute to developing sustainable livestock systems. A 3 × 2 factorial design with three replications was used to compare three SPS with *Inga edulis* (guaba), *Eucalyptus torrelliana* (eucalyptus), and *Cedrelinga cateniformis* (tornillo) under shaded and open-field conditions. The results showed no significant interactions between the SPS and light conditions for most variables evaluated. However, forage availability per cut was higher in the guaba system under shade (1406 kg DM ha^{-1}). Protein content was significantly higher in the tornillo system (10.64%) and under shade (9.55%). eucalyptus increased neutral detergent fiber (69.72%), while metabolizable energy reached its highest in the guava system (8.09 MJ kg^{-1} DM). Principal component analysis revealed that guaba improves soil moisture and cation exchange capacity; tornillo increases forage protein and soil phosphorus; and eucalyptus influences fiber and soil bulk density. Integrating Brachiaria into SPS with guaba under shade enhances forage production and soil structure, highlighting the potential of SPS for sustainable livestock in tropical regions.

Keywords: Silvopastoral; sustainable livestock production; forage yield; shade

1. Introduction

Silvopastoral systems, which integrate trees, forage plants, and livestock within the same space, are widely recognized as an innovative strategy to enhance the sustainability of livestock systems [1,2]. These systems are valued for offering various agroecological benefits, including improvements in animal welfare, biodiversity conservation [3,4], and carbon sequestration capacity [5]. Research over the years has highlighted that the implementation of silvopastoral systems varies according to local conditions and available tree species, providing outcomes tailored to the specific needs of each region.

In Central and South America, tree species such as *Leucaena leucocephala*, *Gliricidia sepium*, and *Erythrina* spp. are widely used in these systems, as they not only provide shade but also fix nitrogen and can serve as supplemental forage [6]. In the Peruvian Amazon, silvopastoral systems are being promoted as a sustainable alternative to traditional grazing [7]. This region hosts high biodiversity

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and a variety of native tree species, such as *Inga edulis* (guaba), *Guazuma ulmifolia* (bolaina negra), and *Cedrelinga cateneiformis* (tornillo), which offer significant ecological and economic benefits [8].

Tree species contribute not only to environmental sustainability but also impact microclimatic conditions, soil quality, and forage production [9]. For instance, the shade generated by trees can moderate temperature, improve soil moisture, and facilitate nutrient cycling, promoting more efficient growth of forage grasses such as *Brachiaria decumbens* [10]. Various studies have shown that moderate levels of shade can increase crude protein content and improve forage digestibility by reducing lignification of plant cells [11–13]. However, excessive shade can limit light availability and consequently reduce biomass yield [14,15].

A particular case is that of eucalyptus, which in tropical regions can exert allelopathic effects on the soil and nearby grasses [16], altering their competition for nutrients and negatively affecting microbial biodiversity [17]. Despite these limitations, systems that integrate trees generally show significant improvements in the physical and chemical properties of the soil [18,19]. Tree roots increase soil porosity, improve water infiltration, and promote nutrient retention through the accumulation of organic matter [20,21] and microbial activity [22].

Given the socioeconomic importance of livestock farming in the Peruvian Amazon and the fragility of its ecosystems, it is essential to develop practices that not only enhance agricultural productivity but also contribute to environmental conservation. Therefore, the present study aimed to evaluate the effect of light conditions on the yield and nutritional quality of *Brachiaria decumbens* in silvopastoral systems of the Peruvian Amazon. This analysis seeks to generate useful knowledge to guide producers towards more sustainable and resilient livestock practices that meet both productive and environmental conservation demands.

2. Materials and Methods

2.1. Site Description

The study was conducted on livestock farms with silvopastoral systems (SPS) located in the district of Soritor, province of Moyobamba, San Martín region, Peru. Soritor is classified as a premontane tropical moist forest zone according to the Holdridge life zone system. The urban area of the district is situated at 860 meters above sea level (m.a.s.l.), with mountainous elevations reaching up to 3,000 m.a.s.l. Geographically, the study area is positioned between the coordinates 6°8'21.2" south latitude and 77°6'7.8" west longitude. The average annual precipitation is 52.7 mm, and the mean annual temperature is 26°C (Figure 1). The district covers an area of 3,772.31 km² and has an approximate population of 25,810 inhabitants.

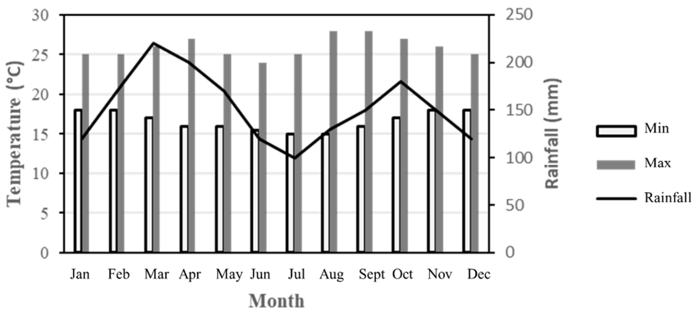

Figure 1. Average precipitation, maximum and minimum long-term temperatures (1991-2021). Min: minimum temperature, Max: maximum temperature [23].

2.2. Experimental Design

The experimental design employed was a completely randomized design with a 3 × 2 factorial arrangement and three repetitions. The factors investigated were three silvopastoral systems (SPS) and two light conditions. The systems evaluated included dispersed trees of guaba, live fences of eucalyptus, and dispersed trees of tornillo. The light conditions considered were under shade (tree canopy) and open field (no shade).

2.3. Treatments and Sampling

Brachiaria decumbens was selected as the main grass in all the silvopastoral systems (SPS). For comparative analysis, adjacent open field areas without shade, managed by the same producers, were used to ensure homogeneity in soil, grass, and topography. The forage evaluations were conducted during the warn season, between May and September 2017. Forage samples were collected 45 days after grazing using a 50 × 50 cm wooden quadrant placed randomly in a zigzag pattern within the pastures. Samples were taken both under shade and in the open field, with seven repetitions per treatment. Fresh forage was weighed, and composite samples of 2 kg were collected for laboratory analysis. The forage quality analysis followed the AOAC protocol [24], using method 950.46 to determine dry matter (DM) and method 2001.11 to determine crude protein (CP). For neutral detergent fiber (NDF) determination, the ANKOM protocol was applied using method No. 6, and method No. 3 was used for in vitro dry matter digestibility (IVDMD). To evaluate forage availability over time, plots of 3 × 6 m² were established both under shade and in the open field (18 plots in total). Forage was harvested at 30, 45, 60, and 75 days (seven samples per light condition in each system), with fresh weights recorded and 200 g subsamples taken to determine dry matter (DM). Metabolizable energy (ME) was estimated using the equation suggested by Indah et al. [25].

$$EM(MJ\ kg^{-1}\ DM) = 46.93 - 0.52\ \times NDF \qquad (1)$$

Where ME is metabolizable energy, NDF is neutral detergent neutral.

Soil samples were taken at a depth of 0-15 cm in each silvopastoral system (SPS) and analyzed for the following variables: soil moisture, bulk density [26], porosity [27], pH, organic matter (OM) [28], phosphorus (P), cation exchange capacity (CEC) [29], and macronutrients (Ca, Mg, Na, K, Al). The analyses were conducted in the soil analysis laboratory of the National Agrarian University La Molina. Table 1 shows the physical and chemical characteristics of the three silvopastoral systems evaluated in the San Martin region.

Table 1. Physical and chemical properties of three silvopastoral systems in the San Martin region.

System	BD g cm^{-3}	pH --	OM %	P Ppm	CEC	Ca $^{2+}$	Mg $^{2+}$ Meq/100 g	k $^{+}$	Al $^{3+}$
Tornillo	1,33±0,18	4,24±0,50	3,12±0,18	3,43±0,21	9,07±0,56	0,36±0,18	0,25±0,03	0,14±0,02	0,83±0,40
Eucalyptus	1,38±0,04	4,85±0,10	3,76±0,26	3,20±0,95	9,01±5,05	7,61±4,01	1,81±0,97	0,35±0,35	0,00±0,00
Guaba	1,22±0,10	4,99±0,13	2,88±0,85	0,93±0,25	25,49±3,05	4,67±2,18	1,77±0,62	0,64±0,54	6,87±3,87

±Standard error, BD= Bulk density, OM= Organic matter, CEC= Cation Exchange capacity. The soil fertility profile results are derived from a previous study conducted in the same location as the present study, providing a consistent baseline for comparison [30].

2.4. Statistical Analysis

The statistical analysis of the variables was performed using SAS software version 9.4. To determine the relationship between the studied variables and the factors Light Conditions × Silvopastoral System, a principal component analysis (PCA) was conducted using R software. Variables related to the chemical and physical characteristics of the soil were included in the PCA to determine their relationships with the forage quality variables.

3. Results

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No significant interactions (P > 0.05) were found between silvopastoral systems (SSP) and light conditions for forage availability (FA), protein (P), neutral detergent fiber (NDF), in vitro dry matter digestibility (IVDMD), metabolizable energy (ME), or productive efficiency, except for forage availability by cut (FAC) (P < 0.05) (Table 2).

Table 2. Forage mass and quality in silvopastoral systems under different light conditions.

Var	System			Light		System × Light						EE	*P* value		
						SSPI		SSPII		SSPIII					
	SSPI	SSPII	SSPIII	S	WS	S	WS	S	WS	S	WS		System	Light	System × Light
FM (kg DM ha^{-1})	1051	1051	1280	1164	1090	1103	999	1001	1100	1388	1171	318.29	0.5975	0.7284	0.8233
FMH (kg MS ha^{-1})	1210	1085	1161	1256	1047	1406^{a}	1014BC	983C	1187ABC	1380AB	942C	131.87	0.6384	0.0585	0.0328*
Protein (%)	8.57b	7.17b	10.63^{a}	9.55^{a}	8.03b	9.20	7.94	7.81	6.53	11.63	9.53	0.81	0.0045*	0.0431*	0.8764
NDF (%)	65.39 b	69.72 a	68.16 ab	67.46	68.04	64.92	65.86	69.35	70.08	68.12	68.20	1.31	0.0215*	0.5981	0.9439
IVDMD (%)	41.96	37.62	40.72	40.68	39.53	43.14	40.79	38.25	37.00	40.64	40.81	1.73	0.2017	0.5574	0.8637
ME (MJ kg^{-1} de DM)	8.08 a	7.69 b	7.77^{a}	7.85	7.78	8.14	8.03	7.76	7.62	7.64	7.69	0.15	0.0214*	0.5974	0.9437

SSPI: Silvopastoral System with Guaba, SSPII: Silvopastoral System with Eucalyptus, SSPIII: Silvopastoral System with Tornillo, CS: With shade, SS: Without shade, FM: Forage Mass, FMH: Forage Mass by harvest, NDF: Neutral detergent fiber, IVDMD: In vitro dry matter digestibility, ME: Metabolizable energy, DM: Dry matter. *Indicates significant differences and interactions at a 5% significance level. Averages followed by different lowercase letters between the system and light factors are significantly different at the 5% probability level. Averages followed by different uppercase letters between the factor x light interactions are significantly different at the 5% probability level.

3.1. Forage Availability and Nutritional Quality

3.1.1. Forage mass

Forage mass by harvest was higher in the system with guaba under shaded conditions (1406 kg DM ha^{-1}), compared to the system with eucalyptus under shade (983 kg DM ha^{-1}) and the system with tornillo without shade (942 kg DM ha^{-1}). The most significant values were observed in cutting intervals of 75 days (Figure 2).

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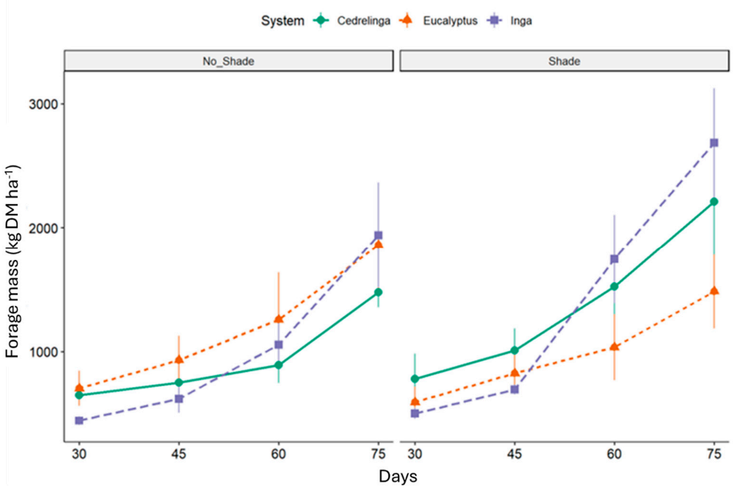

Figure 2. Forage mass of *Brachiaria decumbens*, kg DM ha^{-1}, at different cutting frequencies, by SSP, under shaded and open field conditions. Cedrelinga=Tornillo, Inga=Guaba.

3.1.2. Nutritional Quality

Protein content was higher in the system with tornillo, reaching 10.63%, compared to the systems with eucalyptus and guaba ($P < 0.05$). Shaded conditions significantly increased protein content (9.55%) compared to direct light conditions ($P < 0.05$). As for neutral detergent fiber (NDF), it was highest in the system with eucalyptus (69.72%) and lowest in the system with guaba ($P < 0.05$), while light conditions had no significant effect on this parameter. Metabolizable energy (ME) was higher in the systems with guaba (8.08 MJ kg^{-1} DM) and tornillo (7.77 MJ kg^{-1} DM), and lower in the system with eucalyptus (Table 1).

3.1.3. Soil and Forage Correlations

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3.2.1. Principal Component Analysis (PCA)

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The figure 3 presents a principal component analysis (PCA) that visualizes how different variables are correlated with three tree species: Inga (guaba), Eucalyptus, and Cedrelinga (tornillo). The guaba system, represented by the yellow point and ellipse, shows a strong positive correlation with various variables such as neutral detergent fiber (NDF), sodium (Na), and many soil physicochemical properties, including cation exchange capacity (CEC), porosity, moisture, organic matter (OM), pH, magnesium (Mg), and calcium (Ca) and forage quality as dry matter (DM), in vitro digestibility (IVDDM), eucalyptus shows positive correlations with NDF and Na. Tornillo is notably correlated with forage protein and phosphorus (P).The first principal component (PC1) explained 28.1% of the variability, while the second principal component (PC2) explained 21.8%, totaling 49.9%.

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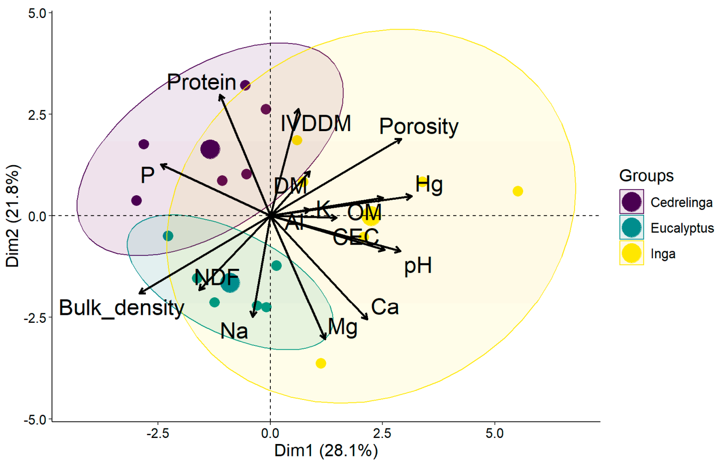

Figure 3. Principal component analysis (PCA) of the forage quality of *Brachiaria decumbens* and soil characteristics in different silvopastoral systems (SSP) and under different light conditions.

Forage parameters; Protein: protein, IVDDM: in vitro digestibility of dry matter, DM: dry matter, NDF: neutral detergent fiber; Soil parameters, Hg: soil moisture, OM: organic matter, Mg: magnesium, Ca: calcium, CEC: cation exchange capacity, Na: sodium, P: phosphorus, K: potassium. Cedrelinga: tornillo, Inga: Guaba.

4. Discussion

This study demonstrates that *Brachiaria decumbens* in silvopastoral systems (SSP) with tornillo and guaba under shade tends to produce a higher amount of forage. This behavior can be attributed to factors such as the grass's ability to fix nitrogen, improved microclimatic conditions due to moderate shading, and the contribution of organic matter to the soil, which together enhance its structure and fertility [31].

However, the findings also reflect the variable influence of trees on forage yields. For example, a previous study by Freitas et al. [32] in southern Minas Gerais, Brazil, found significantly lower yields of 324 kg DM ha^{-1} in SSP with guaba, compared to the 1406 kg DM ha^{-1} reported in this study. This discrepancy may be related to differences in management, climatic and soil conditions, or tree age. Additionally, previous research highlights that shading above 40% can inhibit *Brachiaria* growth due to reduced light availability [17].

Among the evaluated species, guaba showed the most significant effect on improving soil moisture, cation exchange capacity (CEC), and pH, likely due to its dense canopy that favors leaf litter accumulation and its subsequent decomposition, favored by its low relation C/N, that improves the release of bases like calcium, magnesium, and potassium [33]. This aligns with previous reports stating that organic matter decomposition can neutralize soil acidity and improve CEC [31].

In addition, the high correlation of guaba with the studied parameters can be attributed to its unique ecological functions and contributions to soil health. This species is well-known for its nitrogen-fixing capabilities [32], which enhance soil fertility by increasing the organic matter content [34] and improving the cation exchange capacity (CEC) [32]. The root system of guaba contributes to better soil structure by increasing porosity and moisture retention, creating favorable conditions for plant growth [35].

The improved water balance and nutrient retention under guaba can explain the higher concentrations of Na, magnesium (Mg), and calcium (Ca) in the soil, which are essential for plant nutrition [32]. The stabilization of soil pH and the enhancement in in vitro digestibility of grass

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(IVDDM) under guaba reflect the optimal growing conditions that this system provides, promoting higher forage quality.

In contrast, systems with eucalyptus significantly increased the neutral detergent fiber (NDF) content. This increase can be attributed to factors such as competition-induced stress, allelopathic effects, and alterations in soil microbiota [36]. Elevated NDF levels are important for forage management as they influence the digestibility and intake of the forage by ruminants. Higher NDF content typically results in lower digestibility and slower passage through the digestive system, which can reduce feed intake and overall animal performance [37]. Understanding and managing NDF levels is crucial for optimizing forage quality and ensuring that the nutritional needs of livestock are met, particularly in systems where eucalyptus may impact the growth dynamics and structural composition of the grass.

Leguminous species, such as tornillo and guaba, had a positive impact on forage protein content, likely due to their ability to fix nitrogen in symbiosis with *Rhizobium* bacteria. However, the greater influence of tornillo could be attributed to its older age (40 years compared to 5 years for guaba), which favored a more stable and efficient symbiosis [38,39]. This could also explain the increase in metabolizable energy [40].

Principal component analysis (PCA) allowed for the identification of interactions between forage quality variables and soil characteristics. The first two dimensions explained 49.9% of the total variability (28.1% for PC1 and 21.8% for PC2), providing an initial view of the observed patterns. While a significant portion of the variability is captured in these dimensions, the remaining components still contribute valuable information, suggesting that further detailed analyses could further enhance the understanding of these interactions [41].

The results of this study highlight the importance of properly selecting tree species in SSP to maximize the benefits in forage yield and soil quality. Future studies should focus on evaluating the specific contribution of each species to nitrogen fixation, organic matter dynamics, and the effect of shading management in different agroecological contexts. Additionally, it is recommended to investigate the long-term relationship between the age of legumes and their ability to influence forage quality and soil properties.

5. Conclusions

The study demonstrates that the integration of *Brachiaria decumbens* into SSP with guaba under shade can be beneficial for forage production by improving the microclimate and soil structure through nitrogen fixation and organic matter deposition. However, the effects of shade and the presence of trees, such as eucalyptus, can have a complex influence, improving soil conditions but also increasing fiber content and reducing pasture quality. Leguminous species, such as tornillo, stand out for their ability to fix nitrogen and enhance the nutritional quality of forage, especially in terms of protein and metabolizable energy. These results highlight the importance of selecting suitable tree species to optimize both forage production and quality in SSP.

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Data Availability Statement: Data can be requested by email: maryondiaz@hotmail.com

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