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***Research Paper***

# Influence of shade on productivity and nutritional value of *Urochloa decumbens* in silvopastoral systems using different spatial arrangements of eucalyptus cultivars

## *Influencia de la sombra sobre la productividad y el valor nutricional de* Urochloa decumbens *en sistemas silvopastoriles utilizando diferentes arreglos espaciales de cultivares de eucalipto*

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**Abstract**

This study evaluated pasture productivity and nutritional characteristics of *Urochloa decumbens* in silvopastoral systems (SPS) with different eucalyptus cultivars and spatial arrangements providing differing levels of shade. SPS were arranged to provide 46 % shade (eucalyptus trees arranged in 2 double rows 2 m apart, with trees every 3 m in each row, and 20 m between double rows), 60 % shade (eucalyptus trees arranged in 2 double rows 2 m apart, with trees every 2 m in each row in double rows and 9 m between double rows) and 57 % shade (eucalyptus trees arranged in a single row, with trees every 2 m in the row and 9 m between rows) using eucalyptus cultivars 'GG100', 'I144' or 'VM58'. Two full sun pastures treated as managed (soil pH correction and N, P and K fertilizer application) or non-managed (no correction or fertilizer application) were evaluated in addition to the 3 SPS arrangements. Photosynthetically active radiation (PAR) was 1,439 µmol/m$^2$/s in full sun compared with a mean of 715 µmol/m$^2$/s under different SPS arrangements. Leaf area index of *U. decumbens* was 28 % higher in 46 % shade and lower in all shade arrangements compared with full sun managed pasture. The dry matter yield was 58 % lower in 46 % shade and 86 % lower in 60 % shade compared with full sun managed pasture. The crude protein content in SPS pastures was higher than in the full sun pastures, with higher values in 57 % and 60 % shade. SPS significantly reduced the PAR and forage yield. These results indicate that in systems where the main objective is animal production, spacing between tree rows greater than 20 m should be used to provide sufficient high-quality grass.

**Keywords:** Chemical composition, integrated systems, integration of livestock-forest plantations, tropical grasslands.

**Resumen**

Este estudio evaluó la producción y las características nutricionales del pasto *Urochloa decumbens* en sistemas silvopastoriles (SSP) con diferentes variedades de eucalipto y diferentes arreglos espaciales que brindan diferentes niveles de sombra. Los SSP evaluados fueron establecidos para dar sombra más leve (eucaliptos dispuestos en hileras dobles separadas por 2 m, con árboles a cada 3 m en cada hilera y 20 m entre hileras dobles – 46 % sombreado),

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sombra más densa (eucaliptos dispuestos en hileras dobles separadas por 2 m, con árboles a cada 2 m en cada hilera y 9 m entre hileras dobles - 60 % sombreado) y sombra intermedia (eucaliptos dispuestos en una sola hilera, con árboles cada 2 m por hilera y 9 m entre hileras - 57 % sombreado) usando cultivares de eucalipto 'GG100', 'I144' o 'VM58'. Además de los 3 arreglos SSP, se evaluaron dos pastizales a pleno sol, um tratado con manejo (corrección del pH del suelo y aplicación de fertilizantes como N, P y K) y otro no manejado (sin corrección ni aplicación de fertilizantes). La radiación fotosintéticamente activa (PAR) fue de 1,439 $\mu$mol/m$^2$/s a pleno sol en comparación con una media de 715 $\mu$mol/m$^2$/s bajo los SSP. El índice de área foliar de *U. decumbens* fue 28 % más alto en sombra leve que en sombra densa y más bajo en todos los tipos de sombra en comparación con los pastos manejados a pleno sol. El rendimiento de materia seca fue 58 % más bajo en 46 % de sombra y 86 % más bajo en 60 % de sombra en comparación con los pastos manejados a pleno sol. El contenido de proteína cruda en los pastos en SSP fue mayor que en pastos a pleno sol, con los valores más altos para 57 y 60 % de sombra. Los SSP redujeron significativamente la PAR y el rendimiento de forraje. Por lo tanto, en sistemas donde el objetivo principal es la producción animal, se debe utilizar un espacio entre hileras de árboles mayor a 20 m para proporcionar suficiente pasto de alta calidad.

**Palabras clave:** Composición química, integración ganadería-plantaciones forestales, pastos tropicales, sistemas integrados.

## Introduction

The large area of degraded pastures in Brazil is one of the main factors reducing national agriculture sustainability, with an estimated 70 % of pastures showing some degree of degradation (Dias-Filho 2014). This is mainly due to unsuitable stocking rates without maintenance of soil fertility. Silvopastoral systems (SPS) provide a viable option for recovery of degraded pastures to increase production system profitability (Torres et al. 2017).

Spatial arrangement of trees in SPS can reduce photosynthetically active radiation (PAR) reaching the pasture canopy, generating changes in agronomic and nutritional attributes (Santos et al. 2016; 2018). Forages growing under moderate shading have compensatory adaptive mechanisms, such as greater height, specific leaf area and photosynthetic efficiency, which allow the plant to maintain performance (Gómez et al. 2012; Gomes et al. 2020). However, in very dense shade, forage productivity is reduced and can compromise livestock production (Santos et al. 2018). Grasses grown under lower PAR show changes in nutritional value, mainly crude protein (CP) increase and fibrous fractions reduction (Santos et al. 2016; Lima et al. 2019).

Eucalyptus (*Eucalyptus species*) is one of the main tree species used in SPS in Brazilian tropical climates (Tonucci et al. 2011), mainly intercropped with *Urochloa* grasses. Trees canopy characteristics and spatial arrangement are the main factors that determine PAR and pasture performance. The objective of this study was to evaluate the productivity and nutritional value of *U. decumbens* in SPS using different eucalyptus cultivars and spatial arrangements to provide different levels of shading to the pasture to determine the best combinations of grass and eucalyptus trees.

## Materials and Methods

### *Experimental area*

The experiment was carried out in the Cerrado biome at the Minas Gerais Agricultural Research Corporation (Epamig), Prudente de Morais, Minas Gerais, Brazil (19°27'15'' S, 44°09'11'' W; 732 masl). The area has a monsoon-influenced humid subtropical climate with hot and rainy summers and dry winters (Alvares et al. 2013). The climatological data during the experiment and the last 30 years are shown in Figure 1. The soil is classified as red ferralsols (WRB 2006). The experimental area soil chemical characteristics at 0–20 and 20–40 cm depths are shown in Table 1.

### *Experimental area history and treatments*

A 10 ha pasture of *U. decumbens* planted in 1993 was converted into an integrated crop-livestock-forest system (ICLFS) in 2008. At conversion, ants were controlled and the entire vegetation cover was removed using 4 L of glycophosphate/ha [N-(phosphonomethyl) glycine]. Dolomitic limestone was applied at 2,000 kg limestone/ha to increase soil pH. The entire area was plowed and harrowed and subsoiling carried out in the eucalyptus planting rows. Reactive natural phosphate was applied at 400 kg P/ha in the entire area.

The experimental area had a slope with different soil fertilities. Therefore, the area was divided into 3 blocks along the slope with similar fertility and similar altitude. One replicate per treatment was randomly allocated to each block. Eucalyptus cultivars 'GG100', 'I144' (*E. grandis* × *E. urophylla*) and 'VM 58' (*E. grandis* × *E. camaldulensis*)

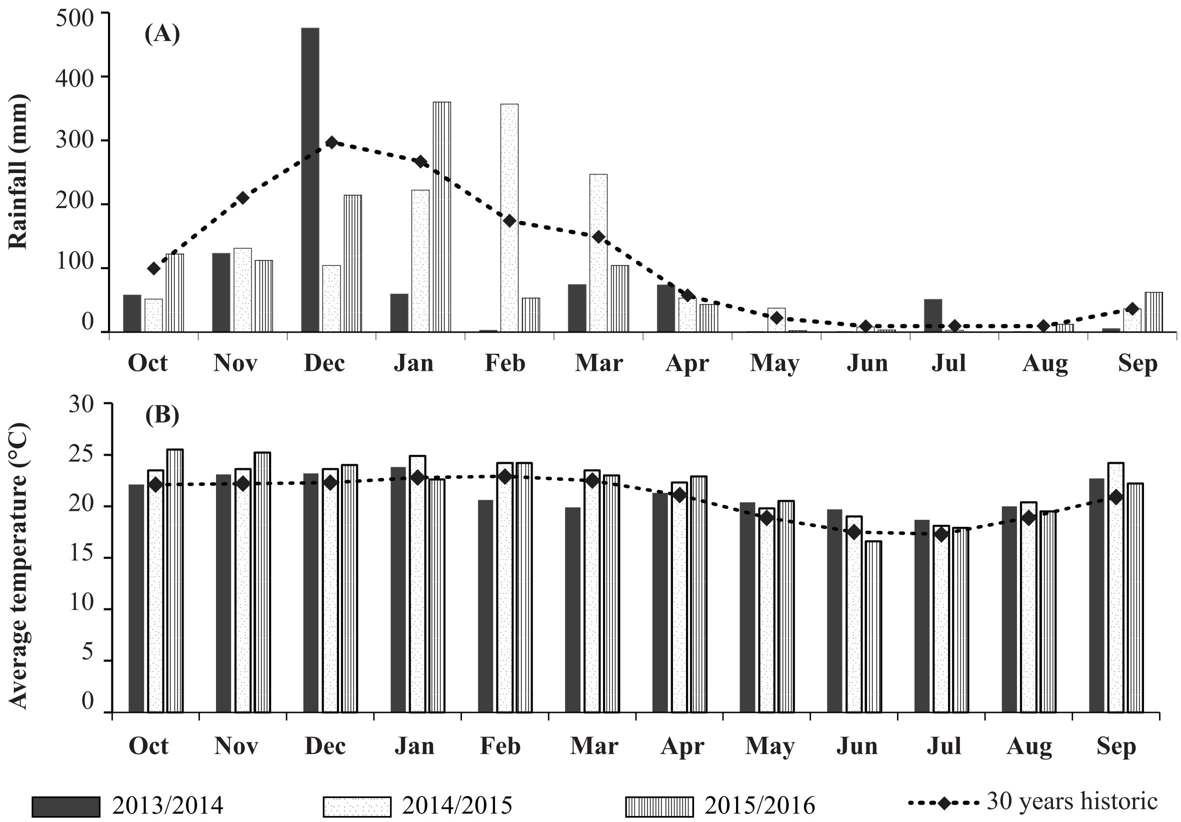


**Figure 1**. Monthly rainfall (A) and average temperature (B) during the experimental period and last 30 years climatological data in the experimental area. Source: National Institute of Meteorology (INMET).

were randomly allocated in each spatial arrangement to each block. Eucalyptus trees were planted in an east-west direction in 2008 when the ICLFS was established in 3 spatial arrangements to provide (A) 46 % shade with 434 trees/ha (2 double rows 2 m apart, with within row spacing between trees of 3 m and 20 m between double rows), (B) 60 % shade with 909 trees/ha (trees in a double row with trees every 2 m in each row and 9 m between double rows) and (C) 57 % shade of 556 trees/ha (single row of eucalyptus trees every 2 m in a row and 9 m between rows) (Figure 2).

**Table 1.** Experimental area soil chemical characteristics at 0–20 and 20–40 cm depth.

| Soil depth (cm) | pH | H+Al | Al | Ca | K | P | OM |
|---|---|---|---|---|---|---|---|
| | | Cmolc/dm³ | | | Mg/dm³ | | dag/kg |
| 0–20 | 5.4 | 7.5 | 0.2 | 3.2 | 70.3 | 3.7 | 4.3 |
| 20–40 | 5.3 | 7.6 | 0.6 | 2.5 | 56.7 | 3.7 | 4.3 |

pH=pH in water suspension at rate of 1:2.5; H+Al=sum of hydrogen and aluminum obtained by extraction with Ca $(OAc)_2$ 0.5 mol pH 7.0; Al=aluminum concentration obtained by extraction with KCl 1 mol/L; Ca=calcium concentration obtained by extraction with KCl 1 mol/L; K=potassium concentration obtained by Mehlich extraction technique; P=phosphorus concentration obtained by Mehlich extraction technique; OM=organic matter obtained by Walkley and Black method.

In the first 3 agricultural cycles (2009/2010, 2010/2011 and 2011/2012) maize (*Zea mays*) was grown intercropped with *U. decumbens* cultivar 'Basilisk' between eucalyptus tree rows. In the fourth agricultural cycle (2012/2013), only *U. decumbens* cultivar 'Basilisk' pasture was intercropped and the system was converted into SPS.

Two pastures of 1 ha each of *U. decumbens* planted in 1993 adjacent to the SPS were used as full sun controls. One pasture received the same management from the start of the experiment as the pasture used in SPS (soil pH correction and N, P and K fertilizer application) and the other did not receive any management (no soil pH correction nor fertilizer application). Both pastures were divided into 3 replicates. The total experimental area was 12 ha, with 10 ha of SPS (3.33 ha for each spatial arrangement with 1.11 ha for each replicate) and 2 ha of pasture in full sun (0.33 ha for each replicate).

All managed and SPS pastures were fertilized with 100 kg N/ha and 83 kg K/ha in the 2014/2015 agricultural cycle and 100 kg N/ha, 33 kg K/ha and 21.8 kg P/ha in the 2015/2016 agricultural cycle. All fertilizers were applied in December, except for N, which was divided into 2 applications, with the second dose applied in March 2015 and 2016.

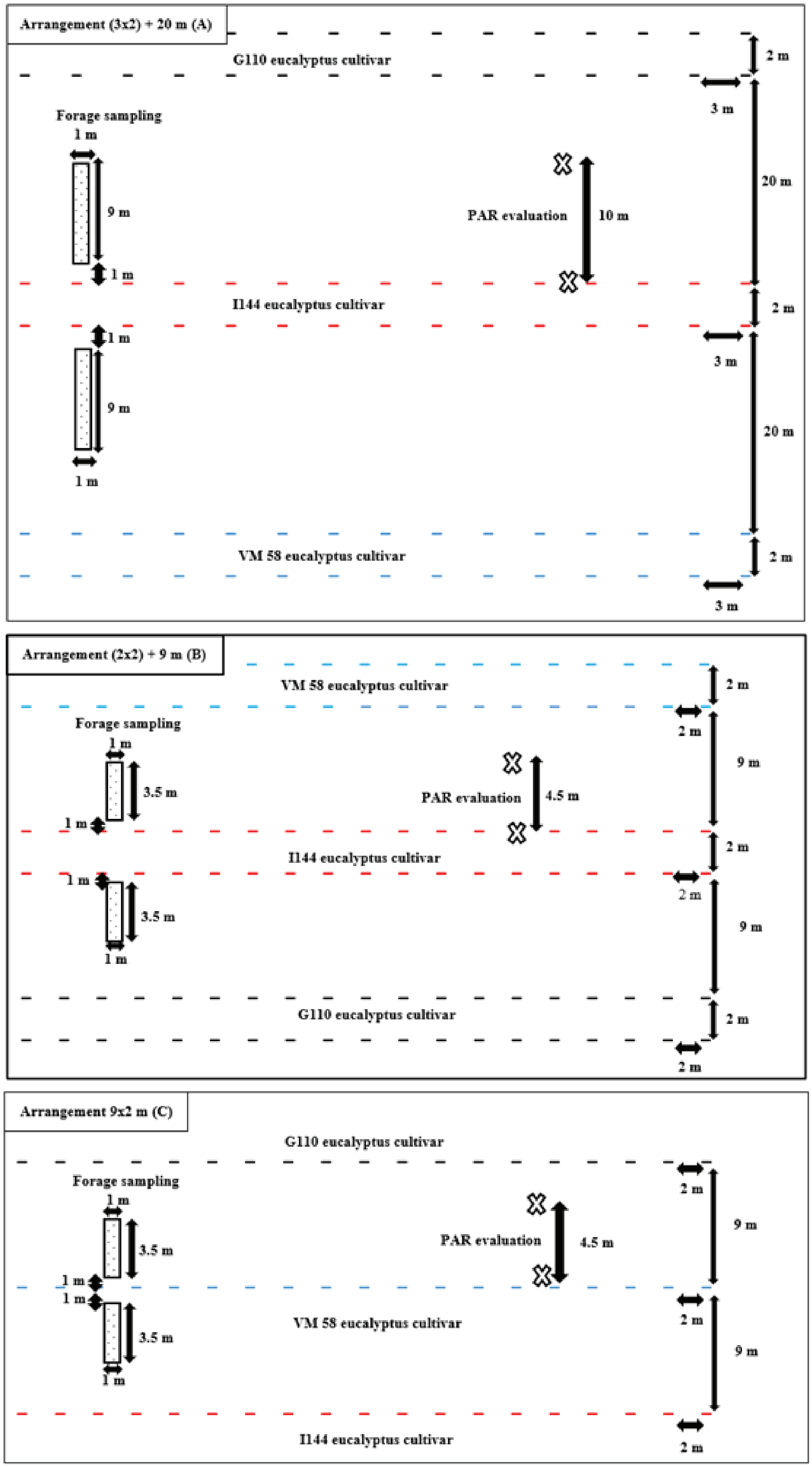


**Figure 2**. Spacing schematic representation providing light shade (A); denser shade (B) and moderate shade (C) formed by eucalyptus cultivars 'GG100', 'I144' and 'VM 58' in each of 3 blocks indicating areas used for forage sampling and photosynthetically active radiation measurement.

*Photosynthetically active radiation*

Incident photosynthetically active radiation (PAR) was measured (μmol/m$^2$/s) using the indirect method with the SunScan Canopy Analysis System Probe type SS1 (Delta-T Devices Inc). The apparatus was positioned approximately 1 m above the forage canopy parallel to the ground and PAR measurements made on 25 May 2016 (autumn), 2 August 2016 (winter), 25 November 2016 (spring) and 21 February 2017 (summer) with cloud absence certified. Measurements were made at 08:00, 11:00, 13:00 and 16:00 h and the average value was considered as 1 replicate.

In open pastures, measurements were made above the canopy at 3 random points in a homogeneous pasture area and the average was considered the replicate. In SPS, measurements were conducted above the forage under the tree canopy and between the tree rows for each eucalyptus cultivar in each replicate. Measurements between rows were taken midway between the tree rows at 4.5 m from the trees in 57 % and 60 % shade treatments and at 10 m from the trees in the 46 % shade treatment. Measurements were made at 3 points within the plot at the selected distance from the trees and the average was considered as a replicate.

*Forage sampling*

Leaf area index (LAI) was measured by the indirect method with the SunScan Canopy Analysis System Probe type SS1 (Delta-T Devices Inc) at 12:00 h on an uncloudy day. LAI measurements were conducted at 2 positions within SPS, under the eucalyptus tree canopy and in the central area of the pasture between tree rows following the procedure used for PAR. LAI was not evaluated in winter due to low forage productivity during this period. Pasture height in SPS and full sun plots was measured weekly at 6 points within the sampling area for each treatment and the average was considered the replicate.

Forage sampling was carried out in each replicate in 2013/2014 (cycle 1), 2014/2015 (cycle 2) and 2015/2016 (cycle 3), with 4 cuts in each cycle. Cuts were made on 25 November 2013, 13 January 2014, 24 February 2014, 8 April 2014 (cycle 1); 18 December 2014, 23 January 2015, 13 April 2015, 10 June 2015 (cycle 2); 1 December 2015, 25 January 2016, 21 March 2016 and 24 May 2016 (cycle 3). Sampling in SPS arrangements with 9 m between double rows was carried out in a rectangular area of 1 × 3.5 m, starting 1 m away from the tree trunk in the inner row and ending 4.5 m away. In the arrangement with 20 m between double rows of trees, the rectangular sampling area was 1 × 9 m starting 1 m away from the tree trunk in the inner row and ending 10 m away. Sampling was performed on both sides of the tree double rows (Figure 2) and the average was considered for data analysis.

In full sun pastures, sampling was performed using a 1 m$^2$ metal quadrat, randomly placed at 4 points. Pastures were cut at 15 cm from the ground in all treatments on the same dates when pasture reached between 30 and 40 cm height in SPS. Pasture from each treatment was harvested and weighed to determine green forage yield/ha. Replicates from each treatment were homogenized and a subsample collected and dried in a forced air circulation oven at 55 °C, ground to 1 mm (Willey type Mill) and used to determine the DM content at 105 °C (AOAC 1995). The average green forage yield (kg/m) and DM were used to calculate total DM yield (kg/ha) in SPS and full sun.

Subsamples of forage collected during the main growing season on 13 January 2014 (cycle 1), 23 January 2015 (cycle 2) and 25 January 2016 (cycle 3) were separated into leaf (lamina and sheath), stem, inflorescence and dead material fractions. These fractions were weighed and DM content determined separately for each as described above (AOAC 1995).

After measurements were taken from random points, the SPS and full sun pastures were grazed by crossbred cattle at a stocking rate of 2 livestock units/ha until the average residual height reached 15 cm. For the first cycle (2013/2014), productivity was not measured due to lack of forage yield at the first cut and only plant fractions percentage (leaf, stem, dead material and inflorescence) were measured.

*Pasture nutritional characteristics*

Dried whole plant, leaf and stem samples collected for plant fraction analysis were used to determine DM, organic matter (OM), ash, CP and ether extract (EE) content according to AOAC (1995). Neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) were determined according to Van Soest et al. (1991) in the Ankom fiber analyzer (Ankom Technology, Macedon, NY).

*Statistical analysis*

All data were submitted to the Lilliefors and Bartlett tests to verify distribution of normality and homoscedasticity, respectively. Data were analyzed in random blocks with split-split-plot arrangement with 3 replicates per treatment. For PAR and LAI, spatial arrangement was considered as plot, sampling site within arrangement or eucalyptus cultivar as subplot and season as sub-subplot. For analysis of plant height, dry matter yield (DMY) and plant fractions, spatial arrangements were considered as main plot, eucalyptus clones as subplots and agricultural cycle as sub-subplot (2013/2014, 2014/2015 and 2015/2016 for plant fractions, and 2014/2015 and 2015/2016 for pasture productivity and height, respectively). Subplots (eucalyptus cultivar) were averaged within the respective plot (spatial arrangement) to evaluate season effects. The value obtained was considered as representative of the spatial arrangement. This procedure was used due to a priori statistical analysis indicating absence of significant effects of eucalyptus cultivars on canopy height and dry matter yield of *U. decumbens*. DMY and canopy height data were also analyzed with spatial arrangement as plot, agricultural cycle as subplot and cut as sub-subplot.

For nutritional value variables, spatial arrangement was considered as plot, eucalyptus cultivar as subplot and agricultural cycle (averaged over seasonal cuts) as sub-subplot. To determine cutting season effect, data were analyzed with arrangement as plot, agricultural cycle as subplot and cut as sub-subplot. Analysis of variance was performed and the Student-Newman-Keuls test (SNK) at 5 % probability of error was used to compare treatment means in SPS. Orthogonal contrasts analysis was performed between SPS spatial arrangements and full sun managed and non-managed pastures (Table 2) with weighting according to Satherthwaite using Fisher's test ($P<0.05$). All analyzes were performed using the R Core Team (2019) software.

## Results

### *Photosynthetically active radiation*

Season × SPS interaction significantly ($P<0.001$) affected PAR. The greatest reduction was observed in summer, with a 62 % lower PAR in SPS (Figure 3). In all treatments, PAR was higher in spring and lower in autumn (1,830 vs. 1,084 μmol/m$^2$/s in full sun and 1,053 vs. 481 μmol/m$^2$/s in the SPS), with reductions of 41 % and 54 %.

Within SPS, the interaction season × spatial arrangement had significant effect ($P<0.003$) on PAR (Table 3). PAR was 26 % higher in the spring (1,264 vs. 931 μmol/m$^2$/s) and 36 % higher in the summer (830 vs. 534 μmol/m$^2$/s) in lighter shade compared with denser shade. In all spatial arrangements the highest PAR was observed in the spring.

PAR had significant interaction effects between the location in SPS and spatial arrangement ($P=0.01$) (Table 3). In the arrangement providing denser shade, PAR was 33 % higher between the rows compared with under the tree canopy (1,003 vs. 676 μmol/m$^2$/s). PAR showed no significant difference under the tree canopy in all treatments. PAR was 24 % higher ($P<0.002$) using cultivars 'GG100' (769 μmol/m$^2$/s) and 'VM58' (764 μmol/m$^2$/s) compared with cultivar 'I144' (618 μmol/m$^2$/s).

**Table 2.** Orthogonal contrasts for comparison between the SPS level of shade and full sun managed and non-managed pastures.

| Level of shade | Eucalyptus Cultivar | Contrast coefficients | | | | | |
|---|---|---|---|---|---|---|---|
| | | C1 | C2 | C3 | C4 | C5 | C6 |
| 46 % shaded | GG100 | -1 | 0 | 0 | -1 | 0 | 0 |
| | I144 | -1 | 0 | 0 | -1 | 0 | 0 |
| | VM58 | -1 | 0 | 0 | -1 | 0 | 0 |
| 60 % shaded | GG100 | 0 | -1 | 0 | 0 | -1 | 0 |
| | I144 | 0 | -1 | 0 | 0 | -1 | 0 |
| | VM58 | 0 | -1 | 0 | 0 | -1 | 0 |
| 57 % shaded | GG100 | 0 | 0 | -1 | 0 | 0 | -1 |
| | I144 | 0 | 0 | -1 | 0 | 0 | -1 |
| | VM58 | 0 | 0 | -1 | 0 | 0 | -1 |
| Full sun managed pasture | | 3 | 3 | 3 | 0 | 0 | 0 |
| Full sun non-managed pasture | | 0 | 0 | 0 | 3 | 3 | 3 |

C1=comparison between systems with 46 % shade and full sun managed pasture; C2=comparison between systems with 60 % shade and full sun managed pasture; C3=comparison between systems with 57 % shade and full sun managed pasture; C4=comparison between systems with 46 % shade and full sun non-managed pasture; C5=comparison between systems with 60 % shade and full sun non-managed pasture; C6=comparison between systems with 57 % shade and full sun non-managed pasture.

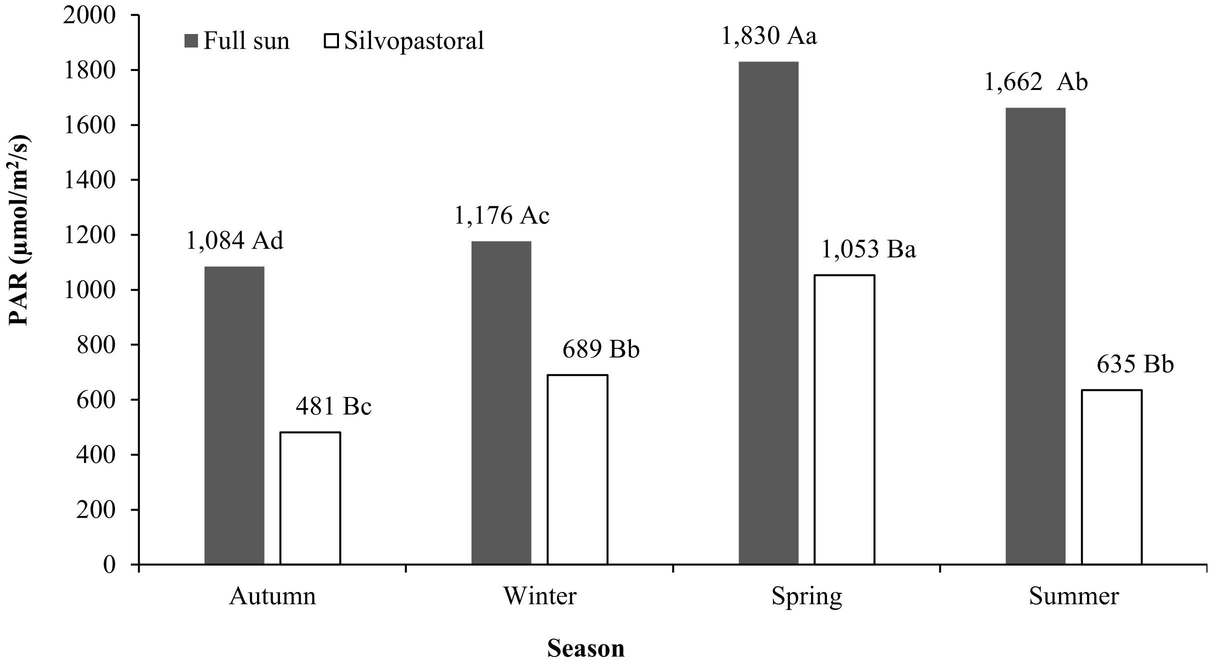


**Figure 3.** Incident photosynthetically active radiation (µmol/m²/s) in *Urochloa* decumbens forage canopy in full sun and silvopastoral system (averaged over cultivars and level of shade). Means followed by different letters, lowercase for season effect within the system and uppercase for system effect within the season, differ by the SNK test. SEM=0.015; P-value<0.001.

**Table 3.** Photosynthetically active radiation in *Urochloa decumbens* forage canopy in SPS with different *Eucalyptus* cultivars and level of shade according to the season and sampling location.

| | Level of shade | | | SEM | P-value |
|---|---|---|---|---|---|
| | 46 % shade | 60 % shade | 57 % shade | | |
| Photosynthetically active radiation with season (µmol/m²/s) | | | | | |
| Autumn | 533aC | 479aB | 462aB | 41.2 | 0.003 |
| Winter | 736aB | 666aB | 666aB | | |
| Spring | 1,264aA | 931bA | 964bA | | |
| Summer | 830aB | 534bB | 540bB | | |
| Photosynthetically active radiation with location in the system (µmol/m²/s) | | | | | |
| Under tree canopy | 676aB | 617aA | 634aA | 19.5 | 0.010 |
| Between tree rows | 1,003aA | 688bA | 682bA | | |

Means followed by different letters, lowercase in row and uppercase in column, differ by the SNK test.

*Forage sampling*

Spatial arrangement, season and cultivar as single effects had significant influence on LAI (P<0.05) (Table 4). *U. decumbens* LAI was 58 % higher (0.83 vs. 0.35) in the summer compared with autumn and spring. *U. decumbens* LAI in SPS with cultivar ‘I144’ (0.40) was 29 % lower compared with other eucalyptus cultivars (0.56). LAI was 28 % higher in the spatial arrangement providing lighter shade compared with that causing denser shade.

In open pastures, LAI was 0.86 on managed pasture and 0.61 on non-managed pasture. LAI was lower in all SPS arrangements, mainly in the denser shade (50 % reduction). In contrast to the non-managed pasture, LAI was lower (P=0.03) only in the denser shade spatial arrangement (30 % reduction) (Figure 4).

Average pasture canopy height in SPS was higher (P<0.05) in 2015/2016 (39.8 cm) compared with 2014/2015 (35.8 cm) and higher in SPS arrangements compared with full sun. The average pasture canopy height in SPS did not vary with arrangement (P=0.254) and eucalyptus cultivar (P=0.358). There was no interaction effect between cut and shade (P=0.72) for canopy height, although there was interaction between agricultural cycle and cut for pasture canopy height in SPS (P=0.017). In both periods, lower averages were observed in the last 2 cuts (Table 5).

**Table 4.** Leaf area index of *Urochloa decumbens* in silvopastoral system with *Eucalyptus* cultivars in different levels of shade according to season or location within SPS.

| | Level of shade | | | SEM | P-value | Average |
|---|---|---|---|---|---|---|
| | 46 % shade | 60 % shade | 57 % shade | | | |
| Season | | | | | | |
| Autumn (2016) | 0.38 | 0.22 | 0.32 | | | 0.31B |
| Spring (2016) | 0.51 | 0.25 | 0.39 | 0.07 | 0.73 | 0.38B |
| Summer (2017) | 0.86 | 0.79 | 0.82 | | | 0.83A |
| Location in the SPS System | | | | | | |
| Under tree canopy | 0.57 | 0.43 | 0.52 | | | 0.51A |
| Between tree rows | 0.60 | 0.41 | 0.50 | 0.04 | 0.11 | 0.50A |
| Average | 0.58a | 0.42b | 0.51ab | | | |

Means followed by different letters, lowercase in row and uppercase in column, differ by the SNK test.

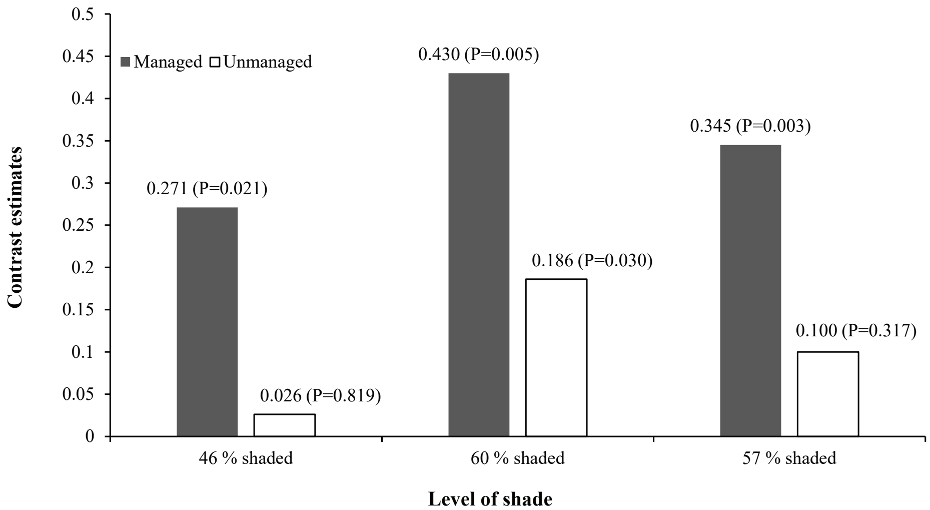


**Figure 4.** Contrasts estimate between full sun managed or non-managed pastures and level of shade for *Urochloa decumbens* leaf area index in silvopastoral system. The bar values indicate the difference between the means of full sun and SPS pastures and the P value is from Fisher's test.

**Table 5.** Canopy pasture height (cm) of *Urochloa decumbens* in silvopastoral system under *Eucalyptus* cultivars in the 2014/2015 and 2015/2016 agricultural cycles.

| Agricultural cycles | Cuts | | | | SEM | P-value |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | |
| 2014/2015 | 35.5abA | 36.5aB | 39.6aA | 31.5bA | 1.21 | 0.017 |
| 2015/2016 | 39.1bA | 45.4aA | 41.5bA | 33.2cA | | |

Means followed by different letters, lowercase on the line and uppercase on the column, differ by the SNK test.

The plant leaf percentage showed significant interaction between spatial arrangement and agricultural cycle (P<0.05). Leaf percentage was 24 % (34 vs. 45 %) lower in lighter shade in the 2015/2016 agricultural cycle compared with the moderate shade arrangement (Table 6). In all systems, highest leaf percentage was observed in the 2014/2015 agricultural cycle. Stem and inflorescence percentage did not differ between spatial arrangements. Plant dead material percentage was 52 % higher (P<0.05) in lighter shade compared with that under spatial arrangements with 9 meters between rows (12 vs. 8 %) (Table 7).

Leaf percentage in managed and non-managed open pasture was 44 % and 39 % of total grass biomass, respectively. Contrast analysis showed that non-managed pasture had 15 % lower leaf percentage than pastures in SPS with 9 meters between tree rows (39 vs. 46 %). Dead material percentage was 1.12 times lower in SPS with 9 meters between tree rows (16 vs. 8 %) compared with full sun managed pasture and 1.68 times lower in SPS pastures (24 vs. 9 %) compared with full sun non-managed pasture (Table 8). Stem percentage was 40 % in full sun managed pasture and 36 % of total grass biomass in full sun non-managed pasture. Full sun pasture stem percentage was 16 % lower in managed pastures compared with those in SPS (38 vs. 44 %) and 24 % lower in non-managed pastures (36 vs. 44.0 %).

**Table 6.** Leaf percentage in *Urochloa decumbens* in silvopastoral system with different levels of shade in the agricultural cycles of 2013/2014, 2014/2015 and 2015/2016.

| Agricultural cycles | Level of shade | | | SEM | P-value |
|---|---|---|---|---|---|
| | 46 % shade | 60 % shade | 57 % shade | | |
| 2013/2014 | 40.9aB | 40.7aB | 42.7aB | | |
| 2014/2015 | 49.3aA | 50.1aA | 50.0aA | 1.38 | 0.021 |
| 2015/2016 | 34.1bC | 44.8aAB | 44.6aAB | | |

Means followed by different letters, lowercase in row and uppercase in column, differ by the SNK test.

**Table 7.** Stem, dead material and inflorescence percentage (DM basis) of *Urochloa decumbens* in silvopastoral system under *Eucalyptus* and varying levels of shade.

| Parameter | Level of shade | | | SEM | P-value |
|---|---|---|---|---|---|
| | 46 % shade | 60 % shade | 57 % shade | | |
| % of stem | 44.1 | 43.8 | 44.1 | 1.08 | 0.973 |
| % os dead material | 11.7a | 8.23b | 7.21b | 0.20 | 0.021 |
| % of inflorescence | 3.03 | 2.53 | 2.84 | 0.09 | 0.918 |

Means followed by different letters differ by the SNK test (P<0.05).

**Table 8.** Leaf and dead material percentages (DM basis) of *Urochloa decumbens* grown in silvopastoral systems with differing eucalyptus level of shade and full sun managed and non-managed pastures.

| Parameter | Level of shade | Managed pasture | | Non-managed pasture | |
|---|---|---|---|---|---|
| | | Estimate | P-value | Estimate | P-value |
| % of leaf | 46 % shade | 2.28 | 0.249 | -2.71 | 0.174 |
| | 60 % shade | -1.43 | 0.466 | -6.52 | 0.003 |
| | 57 % shade | -2.02 | 0.305 | -7.01 | 0.001 |
| % of dead material | 46 % shade | 4.73 | 0.202 | 12.6 | 0.001 |
| | 60 % shade | 8.20 | 0.009 | 16.0 | <0.001 |
| | 57 % shade | 9.22 | 0.004 | 17.1 | <0.001 |

The estimate values indicate the difference between the means of full sun and SPS pastures.

*U. decumbens* annual DMY under SPS was 1.87 and 1.11 times higher in the lighter shade compared with moderate and denser shade (Figure 5B). DMY was 77 % higher in the 2015/2016 cycle compared with the 2014/2015 cycle. There was no interaction effect between cuts and agricultural cycles (P=0.28) on DMY. DMY was 62 % higher in the last 2 cuts compared with the first 2 cuts (Figure 5C).

DMY in managed full sun pasture was 10,248 kg DM/ha and in non-managed full sun pasture was 8,476 kg DM/ha. DMY reduced 59 % in SPS under lighter shade, 86 % in SPS under denser shade and 81 % in SPS under moderate shade compared with the full sun managed pasture. In full sun non-managed pasture, the reduction was 50 % in SPS with lighter shade, 83 % in SPS with denser shade and 76 % in SPS with moderate shade (Table 9).

*Pasture nutritional characteristics*

Whole plant DM, OM, ash, EE and ADL contents of the grass did not differ among the spatial arrangements (P>0.05) (Table 10). CP content was 11 % lower (P<0.05) in the arrangement with lighter shade (105 g CP/kg) compared with the other arrangements (118 g CP/kg). NDF was 2 % higher and ADF was 3 % higher in lighter shade compared with other SPS arrangements.

DM content was similar only between full sun managed pasture and SPS with 20 m between rows (P>0.05). In all other shade arrangements, lower (P<0.05) DM content was observed in SPS pasture compared with full sun pastures, with greater reductions in denser shade in SPS (Table 11). CP content was 21 % higher (P<0.05) in SPS with 20 m between rows (105 vs. 87.3 g CP/kg) and 36 % higher in SPS with 9 m between rows (118 vs. 87.3 g CP/kg) compared with full sun managed pasture. Compared with non-managed pasture, CP content was 56 % higher (P<0.05) in the SPS with 20 m between rows (105 vs. 67.8 g CP/kg) and 75 % higher in SPS with 9 m between rows (118 vs. 67.8 g CP/kg).

NDF content was 4 % higher (P<0.05) in the full sun managed pasture compared with SPS with 9 m between rows (Table 11). NDF content was 4 % lower in the 20 m between rows arrangement and 6 % lower in the 9 m between rows arrangement compared with full sun non-managed pasture.

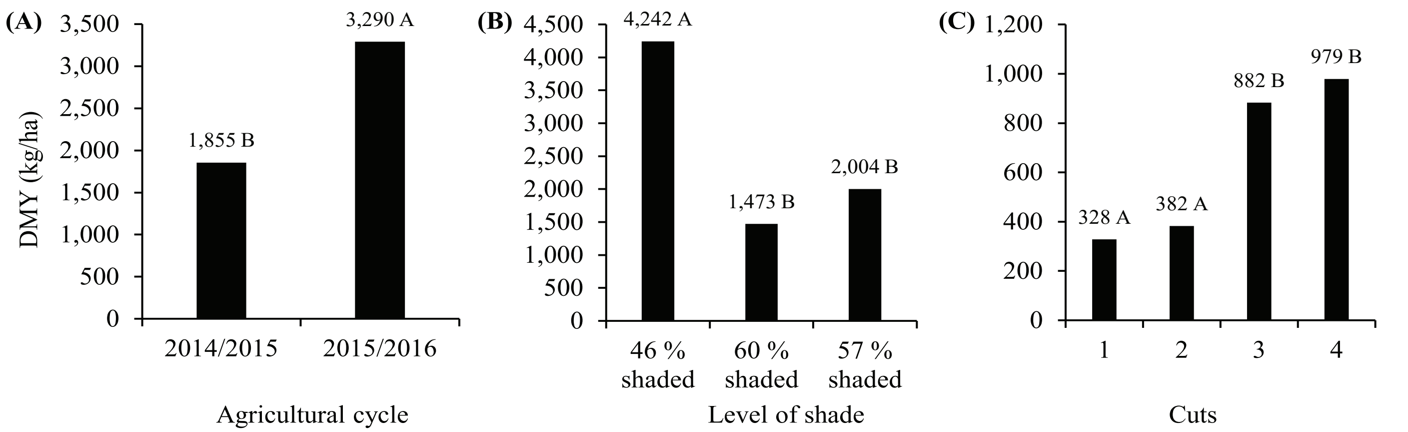


**Figure 5.** *Urochloa decumbens* annual dry matter yield (kg/ha) in SPS according to the agricultural cycle (A) (SEM=53.4), spatial arrangement (B) (SEM=65.4) and cut (C) (SEM=75.5). Means followed by different letters differ by the SNK test (P<0.05).

**Table 9.** Contrasts estimate between dry matter yield and canopy height in full sun managed and non-managed pasture and silvopastoral systems with different eucalyptus levels of shade.

| Parameter | Level of shade | Managed pasture | | Non-managed pasture | |
|---|---|---|---|---|---|
| | | Estimate | P-value | Estimate | P-value |
| Dry matter yield (kg DM/ha) | 46 % shade | 6,007 | <0.001 | 4,235 | <0.001 |
| | 60 % shade | 8,776 | <0.001 | 7,004 | <0.001 |
| | 57 % shade | 8,244 | <0.001 | 6,472 | <0.001 |
| Canopy height (cm) | 46 % shade | -2.40 | 0.020 | -4.20 | 0.050 |
| | 60 % shade | -4.60 | 0.050 | -3.50 | 0.011 |
| | 57 % shade | -2.10 | 0.033 | -1.00 | 0.045 |

The estimate values indicate the difference between the means of full sun and SPS pastures.

**Table 10.** Whole plant nutritional values (DM basis) of *Urochloa decumbens* in silvopastoral system with different tree levels of shade and agricultural cycles.

| Parameter | Level of shade | | | SEM | P-value |
|---|---|---|---|---|---|
| | 46 % shade | 60 % shade | 57 % shade | | |
| Dry matter (g/kg) | 259 | 245 | 242 | 3.90 | 0.111 |
| Organic matter (g/kg) | 920 | 916 | 914 | 1.30 | 0.054 |
| Ash (g/kg) | 79.0 | 84.0 | 85.4 | 1.30 | 0.054 |
| Ether extract (g/kg) | 15.3 | 17.4 | 16.5 | 0.60 | 0.245 |
| Crude protein (g/kg) | 105b | 118a | 118a | 0.40 | <0.001 |
| NDF (g/kg) | 698a | 683b | 683b | 2.60 | 0.025 |
| ADF (g/kg) | 369a | 359b | 360b | 2.70 | 0.011 |
| ADL (g/kg) | 44.5 | 41.5 | 43.6 | 0.60 | 0.065 |
| | Agricultural cycle | | | | |
| | 2013/2014 | 2014/2015 | 2015/2016 | | |
| Dry matter (g/kg) | 275a | 214c | 257b | 2.70 | <0.001 |
| Organic matter (g/kg) | 920a | 910b | 92.0a | 0.80 | <0.001 |
| Ash (g/kg) | 79.3b | 89.2a | 80.0b | 0.80 | <0.001 |
| Ether extract (g/kg) | 15.1b | 16.6ab | 17.5a | 1.60 | <0.001 |
| Crude protein (g/kg) | 109b | 125a | 108b | 1.60 | <0.001 |
| NDF (g/kg) | 688b | 671c | 704a | 2.80 | <0.001 |
| ADF (g/kg) | 362b | 348c | 378a | 2.30 | <0.001 |
| ADL (g/kg) | 35.2c | 41.9b | 52.5a | 0.80 | <0.001 |

NDF=neutral detergent fiber; ADF=acid detergent fiber; ADL=acid detergent lignin. Means followed by different letters in the same row differ according to the SNK test.

**Table 11.** Contrast estimates for whole plant nutritive value between full sun pastures (managed and non-managed) and the different SPS level of shade.

| Level of shade | DM | Ash | EE | CP | NDF | ADF | ADL |
|---|---|---|---|---|---|---|---|
| Managed pasture for whole plant nutritive value | | | | | | | |
| 46 % shade | 0.23ns | -0.34ns | 0.17ns | -1.77** | 1.60ns | 0.86ns | 0.28ns |
| 60 % shade | 1.61** | -0.84** | -0.04ns | -3.16*** | 3.09*** | 1.87** | 0.58** |
| 57 % shade | 1.98** | -0.98** | 0.05ns | -3.15*** | 3.02*** | 1.76** | 0.37ns |
| Non-managed pasture for whole plant nutritive value | | | | | | | |
| 46 % shade | 4.62** | -0.58** | -0.08ns | -3.76** | 2.85** | 1.32ns | 0.11ns |
| 60 % shade | 6.00** | -1.08** | -0.29** | -5.11*** | 4.34*** | 2.33** | 0.41ns |
| 57 % shade | 6.37** | -1.22** | -0.2ns | -5.10*** | 4.27*** | 2.22** | 0.20ns |

DM=dry matter; EE=ether extract; CP=crude protein; NDF=neutral detergent fiber; ADF=acid detergent fiber; ADL=acid detergent lignin; ns=not significant; *=significant at 10 % level; **=significant at 5 % level; ***=significant at 1 % level by Fisher's test. The estimate values indicate the difference between the means of full sun and SPS pastures.

## Discussion

PAR reduction of 50 % in all SPS compared with open pastures was expected as reported by Pontes et al. (2018) in SPS with 238 trees/ha and by Geremia et al. (2018) in SPS with 714 trees/ha, both with trees planted in an east-west direction. However, more intense reductions were found by Santos et al. (2016) in SPS with trees planted in a north-south direction. Although tree planting in SPS is best in an east-west direction to reduce shading, in sloping regions planting must be perpendicular to the slope to avoid soil losses due to erosion.

PAR reductions in SPS significantly reduced forage productivity in this study and was also observed by Paula et al. (2013) and Oliveira et al. (2015), but effects on pasture characteristics were not substantial. Pasture yield reduction is the main disadvantage of SPS with high tree density (Santos et al. 2018). In SPS with lower tree densities, reduction in DMY can be compensated by forage nutritional value improvement (Oliveira et al. 2022). Shade provides additional benefits for animal welfare (Giro et al. 2019) and trees also generate income, which can compensate for the reduction in pasture productivity in SPS (Müller et al. 2011). Pezzopane et al. (2019) observed higher PAR at 8.5 m from the tree compared with under the tree canopy and increased PAR 20 m away from the trees can increase photosynthetic rate (Gómez et al. 2012; Paciullo et al. 2016) and pasture yield, indicating that more widely spaced arrangements help to prevent productivity losses in SPS.

LAI is an indirect indicator of pasture productive capacity and pastures planted under shade have more tillers and leaves (Paciullo et al. 2016). Results from this study showed that pastures grown in SPS had significant LAI reductions compared with full sun managed pastures. *U. decumbens* is a semi-erect plant and LAI may be overestimated due to light interception by tillers. Pastures of *Brachiaria brizantha* cultivar 'Piatã' under the clone H13 (*Eucalyptus urophilla* × *Eucalyptus grandis*) in SPS developed more stem than in full-sun with a 7.2 % reduction in leaves and increase of 6.5 % in the stems (Geremia et al. 2018). Plants growing under shade tend to etiolate, therefore, there may have been less influence of stems on LAI in SPS. Increasing plant height in grass can compensate for reduction in radiation caused by trees (Paciullo et al. 2016). Reduction in LAI under shade in SPS pastures was also observed by Santos et al. (2016), Gómez et al. (2012) and Oliveira et al. (2022). These results are explained by the lower photosynthetic rate in plants growing under shade (Gómez et al. 2012), with consequent lower plant growth. Reductions in plant population in SPS (Paciullo et al. 2016; Gomes et al. 2020) could also explain LAI reduction in denser shade. However, in the study of Gomes et al. (2020), who used distance between groves of 30 m, there was no decrease in leaf productivity between pastures in full sun and under shade, indicating that the spacing used in the present study was too dense and wider spacing should be used to reduce effects of reductions in LAI.

Plants growing under shade may develop compensatory mechanisms to maintain their photosynthetic level, including increasing leaf area (Santos et al. 2016; Gomes et al. 2020), changing shoot/root ratio, increasing chlorophyll b concentrations in leaves and establishing a low light compensation point (Gómez et al. 2012; Guenni et al. 2018). In addition, plants with C4 metabolism, such as *U. decumbens*, have high photosynthetic rates due to lower photorespiration rates even at low light conditions, which results in lower light compensation points. Plants also store carbon in cells in the malic and aspartic acid form, which improve the maintenance of cellular metabolism even when facing light restriction periods (Bjorkman and Berry 1973).

In some tropical regions, pasture-based animal production is maximized in summer by higher light, temperature and water availability. With the increase in water availability, eucalyptus leaf area and light interception increases (Stape et al. 2010), intensifying understory shading in denser SPS, reducing photosynthesis and resulting in reduced biomass production. Eucalyptus cultivars differ in canopy morphology and structure affecting PAR, indicating that the choice of cultivar can be an efficient strategy to reduce shading in SPS. PAR intensities in the pastures differed under different tree cultivars but were not sufficient to affect pasture yields, probably because of similar dendrological characteristics among the tree cultivars. LAI of *U. decumbens* under eucalyptus cultivar 'I144' was lower than for other cultivars. Tree aerial structure was not evaluated in the present study, but it suggests that this cultivar had a larger canopy density or diameter, which reduced PAR and LAI. Oliveira et al. (2015) reported variation of LAI in *U. brizantha* pasture with 5 eucalyptus cultivars. This result suggests it is better to choose cultivars with less robust aerial parts to reduce the impact of shade on pasture development.

Plants in SPS remain in younger ontogenic stages compared with full sun pasture (Paciullo et al. 2016), which explains the greater dead material percentage in full sun pasture. Since plants were harvested when pastures in SPS reached between 30 and 40 cm, full sun pastures, which were growing faster, had already reached a more advanced development stage with a greater proportion of dead material. These changes in pasture structural composition have direct impact on grazing dynamics. Geremia et al. (2018) showed that pasture in SPS has higher stem and lower leaf fraction in higher strata, resulting in a reduction in bite size and increase in bite rate, which can affect animal performance (Mezzalira et al. 2014; Oliveira et al. 2022).

Reduction in DMY in SPS compared with full sun pastures was also observed by Gómez et al. (2012) in *U. decumbens* and by Santos et al. (2016) and Geremia et al. (2018) in *U. brizantha* cultivar 'Piatã'. This reduction can be attributed to lower PAR resulting in lower plant photosynthesis rate (Gómez et al. 2012) under higher tree density in SPS and could also have a negative effect on profitability of livestock enterprises. Non-managed pasture yield was higher than SPS pasture yield, indicating low fertilizer use efficiency by forage plants under shade. Although *U. decumbens* in SPS showed lower forage yields, CP content was higher than in open pastures as previously reported by Paciullo et al. (2016), Santos et al. (2018) and Gomes et al. (2020). These increases in CP contents in shaded pastures are linked to increase in soil N content due to litter (Chatterjee et al. 2018) and lower nitrogen use efficiency. In addition, delay in the ontogenic development in shaded areas keeps the plants younger physiologically, which maintains the high cell metabolic rate and lower fiber accumulation (Paciullo et al. 2016). This may suggest that grass continues to accumulate N in tissues, rather than increasing yield, and indicates the need for further studies on fertilizer management in SPS with the aim of increasing nutrient use efficiency.

CP increase is a positive aspect and may improve individual animal performance in SPS. However, due to high DMY reduction, CP yields are also reduced, which can reduce pasture stocking rate and SPS productivity and profitability. NDF and ADF contents were lower in SPS pasture. Paciullo et al. (2016) also observed a reduction in NDF in a tropical forage from 652 g/kg in full sun to 642 g/kg with 58 % shade. These lower fiber contents are important because they allow higher intake (Van Soest 1994), which may improve individual animal performance. The difference in fibrous fractions was not found in other studies (Santos et al. 2018). Plants growing in SPS have higher stem percentage, which increases fibrous fractions. Delayed ontogenic development and reduction in cell wall thickness can also reduce fiber contents (Deinum et al. 1996). Gómez et al. (2012) reported that leaves growing under low light incidence have less supporting tissue and fewer mesophilic cells per unit area, which can result in thinner leaves with lower fiber content.

## Conclusions

SPS with 9 and 20 m between tree rows significantly reduces *U. decumbens* performance. All eucalyptus cultivars used affected PAR, however, there was no effect of eucalyptus cultivar on pasture productivity. In systems that prioritize animal production, spacings between rows greater than 20 m should be used to avoid pasture yield reduction. In experiments that aim to evaluate the effect of trees on SPS, it is necessary to previously evaluate potential variation in transmitted PAR among tree genotypes.

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