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Evaluation of a long-established silvopastoral *Brachiaria decumbens* system: plant characteristics and feeding value for cattle

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Abstract. One of the main challenges of using a silvopastoral system (SPS) is maintaining pasture and animal productivity over time. Our objective was to compare the productive characteristics and nutritive value of signal grass (*Brachiaria decumbens* cv. Basilisk) and the liveweight gain of dairy heifers in a SPS and open pasture (OP, signal grass under full sunlight) during the rainy seasons of four experiments between 2003 and 2016, which characterised systems from their 6th to 19th years after establishment in south-eastern Brazil when analysed together. The experimental design was a randomised complete block in a 2 × 4 factorial scheme (two production systems (SPS and OP) and four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016)). From the 7th year onwards, the progressive reduction of photosynthetically active radiation negatively impacted the productive characteristics of the SPS pasture. Total forage mass was reduced by 19% in SPS compared with the OP in 2004–2007, 38% in 2011–2014 and 31% in 2014–2016. Crude protein content was 23% and 30% higher in the SPS than in the OP in 2011–2014 and 2014–2016, respectively. However, during the study period (until the 19th year), the liveweight gain of heifers was similar between systems since the higher crude protein content available in SPS contributed to improved forage nutritional value. From the 17th to the 19th year, weight gain per area was lower in the SPS compared with the OP (169 vs 199 kg ha^{-1}), although the difference between systems was small. Signal grass presents a high degree of phenotypic plasticity in response to changes in shade levels, which gives this species a high potential for use in SPS.

Additional keywords: dry matter production, integrated land management, nutritive value of pasture, shading, sward structure, tropical pastures.

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Introduction

Globally, much has been discussed regarding the impacts of agriculture on climate change. One production strategy for the sustainable intensification of land use with the potential of mitigating or compensating for environmental impacts is the integration of livestock and forestry activities (trees, pastures, and animals) in the same area within a silvopastoral system (SPS) (Nahed-Toral *et al*. 2013; de Moura Oliveira *et al*. 2018). The potential benefits of SPS include increased soil fertility, soil organic carbon and soil carbon stock (Murgueitio *et al*. 2011; Cárdenas *et al*. 2019; Aryal *et al*. 2019); decreased greenhouse gas emissions (Torres *et al*. 2017); increased crude protein (CP) and decreased fibre content in forage (Neel and Belesky 2017; Lima *et al*. 2019); greater animal welfare and thermal comfort (de Oliveira *et al*. 2018; Améndola *et al*. 2019; Pezzopane *et al*. 2019); and increased income diversification for farms (Broom *et al*. 2013).

However, in systems incorporating trees (e.g. SPS), management can represent a greater challenge due to the various interactions that occur among their components. In fact, one of the limitations of SPS related to the advancement of tree age (i.e. greater height and tree crown diameter), which causes a reduction in photosynthetic photon flux density and in the red to far-red (R : FR) ratio of photosynthetically active radiation (PAR) that reaches the understory. In general, changes in forage plant physiology and morphology compensate for low light quantity and quality by optimising for light interception (Cavagnaro and Trione 2007; do Nascimento *et al*. 2019), thus affecting forage production, its nutritive value, and the response of animals (Geremia *et al*. 2018; Santos *et al*. 2018).

For example, certain studies with C_4 tropical grasses have suggested that sward cultivated under lower sunlight incidence develop adaptations such as increased specific leaf area and shoot/root ratios as well as decreased tiller population density, forage bulk density, and morphological components of forage mass (Paciullo *et al*. 2010; Santos *et al*. 2016, 2018; Lima *et al*. 2019). These predominant changes may decrease the daily nutrient intake and, consequently, animal production (Geremia *et al*. 2018; da Silveira Pontes *et al*. 2018; Santos *et al*. 2018). Moreover, shade increases chlorophyll content (Martuscello *et al*. 2009) and CP content (Santos *et al*. 2016; Paciullo *et al*. 2017), whereas neutral detergent fibre (NDF) and *in vitro* dry matter digestibility (IVDMD) content have not shown a definite pattern of response to shading in SPS (Gobbi *et al*. 2009; Soares *et al*. 2009).

In this context, the intensity of the plant response depends on the ability of forage species to adapt to more intense light restriction. Signal grass (*Brachiaria decumbens* cv. Basilisk, syn. *Urochloa decumbens* Stapf R.D. Webster) is one of the most important tropical perennial grasses. Notably, it utilises the C_4 photosynthetic pathway, which is widely used in production systems of the Brazilian tropics and has been reported as being tolerant to moderate shading (Paciullo *et al*. 2007; Guenni *et al*. 2008). Additionally, it presents good productivity and nutritive value and represents a forage species that adapts to soils with low-input usage, as indicated by its use in the recovery of degraded areas.

In the present study, we investigated the hypothesis that the long-term increase of forage CP content under an SPS positively influences the individual performance of dairy heifers, and that increased shading limits forage production, thereby reducing stocking rate (SR) and animal production per area. Our objective was to compare the productive characteristics and nutritive value of signal grass (*B. decumbens* cv. Basilisk) as well as the liveweight gain of dairy heifers in a SPS and open pasture (OP, signal grass under full sunlight) system from 2003 to 2016, which characterised the systems from their 6th to 19th years after establishment in south-eastern Brazil.

Materials and methods

Study area

The study was conducted at Embrapa Dairy Cattle experimental station, located in the municipality of Coronel Pacheco, Minas Gerais state, Brazil (21°33′S, 43°15′W; 410 m above sea level; Fig. 1) during the rainy seasons (December to May each year) of four experiments: 2003–2004, 2004–2007, 2011–2014, and

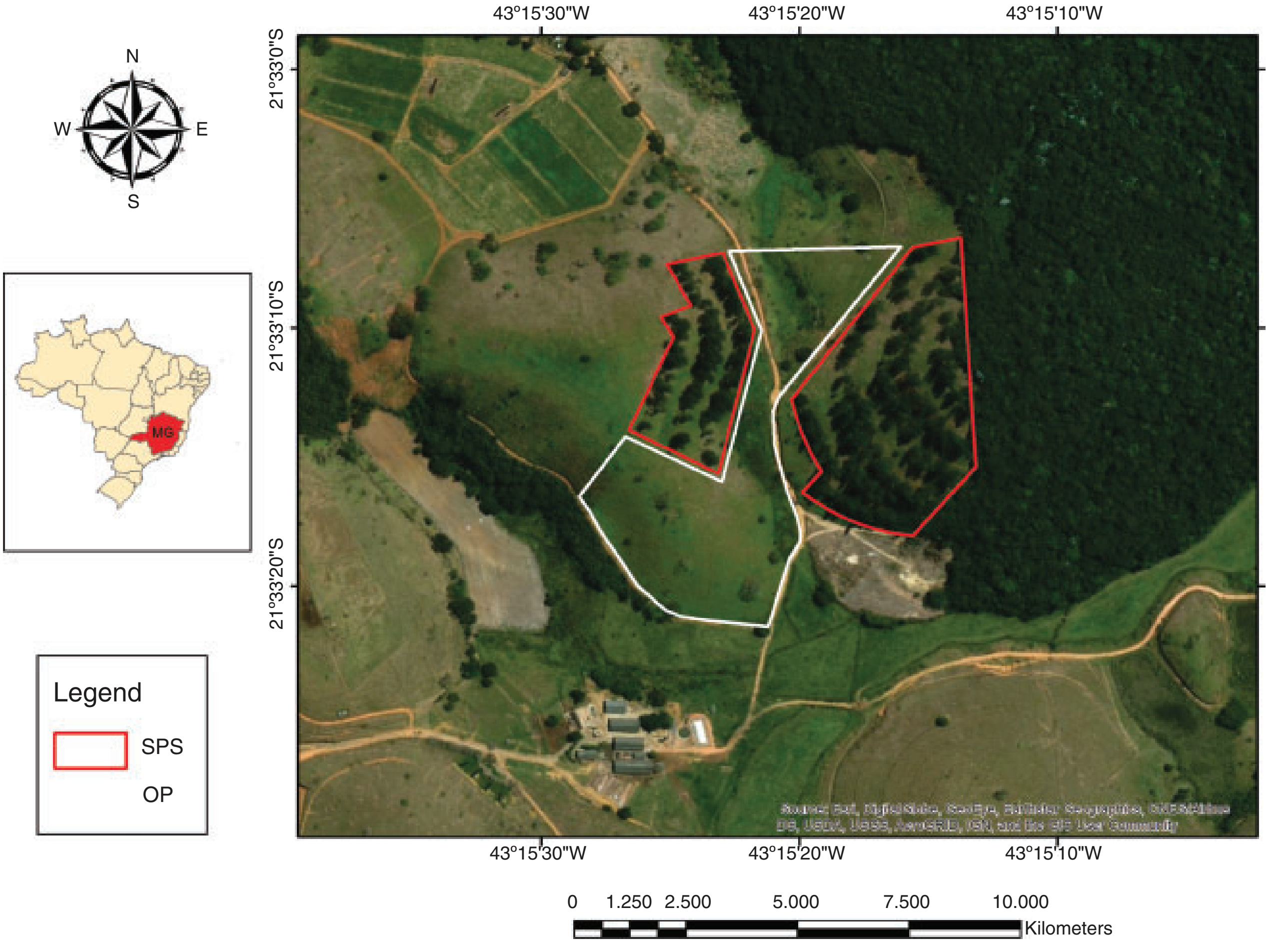

Fig. 1. Location map of the study area for the silvopastoral system (SPS) and open pasture (OP) at Embrapa Dairy Cattle, Minas Gerais (MG), Brazil.

2014–2016. According to the Köppen classification, the climate of the region is Cwa type (humid subtropical), with dry winters and rainy summers. Weather data for the four experiments were recorded at the Embrapa Dairy Cattle weather station located 500 m from the study site (Fig. 2). The experimental area was on a west-facing hillside with a slope of 30–40%. The soil is classified as dystrophic Red–Yellow Latosol with a medium clay texture and undulating relief (Embrapa 2013). Soil samples were collected at depths of 0–20 cm using a probe type for chemical characterisation (for details on soil, see Supplementary Material table S1 available at the journal's website). For the SPS, samples were collected from two positions: near a tree (0.5 m from the tree trunk) and far from trees (15 m from the tree trunk), providing a total of 20 samples for each replicate (paddock). For the OP, no sampling by position was performed, thus providing a total of 20 randomly collected samples for this system. After sampling, the soils were transported to a laboratory in plastic bags, air-dried, crushed, and then passed through 2-mm sieves, thereby obtaining air-dried fine earth for subsequent analysis.

The experimental area was established in November 1997. To establish the experiment, the area was tilled along the contour using a horse-drawn mouldboard plough. The forage component was composed of signal grass planted in an OP (full sunlight) and in an SPS. The SPS encompassed a pasture area 30 m wide, alternating with 10 m wide groves with the trees species *Eucalyptus grandis* and the tree legumes *Acacia mangium*, *Acacia angustissima*, *Mimosa artemisiana* and *Leucaena leucocephala*, which were planted perpendicular to the incline of the slope in a north–south direction to prevent soils from surface erosion. Trees were arranged in groves comprising four parallel rows with an intra-row spacing of 3.0 m and an inter-row spacing of 3.0 m, totalling 342 trees ha^{-1}. The tree species were planted alternately (mixed) in each of the four rows. The *L. leucocephala*, *A. angustissima* and *M. artemisiana* did not survive the term years (probably due to the acidic soil conditions, even after liming). A schematic representation of the experimental site and tree species present in the SPS is provided in Fig. 3. Tree legumes were used for the purpose of providing shade and biomass rich in nitrogen (N) and other nutrients, whereas the *Eucalyptus* were planted for the purpose of producing shade and wood. During the first year, the area remained without animals to allow pasture establishment and initial tree growth.

Prior to planting the trees, and according to the soil analysis, 1000 kg ha^{-1} of dolomitic limestone, 600 kg ha^{-1} of natural rock phosphate (200 kg ha^{-1} of P_2O_5), 250 kg ha^{-1} of single superphosphate (45 kg ha^{-1} of P_2O_5), 100 kg ha^{-1} of potassium chloride (60 kg ha^{-1} of K_2O), and 30 kg ha^{-1} of micronutrients FTE BR-16 (35, 15, 35, and 0.4 g kg^{-1} of Zn, B, Cu and Mo, respectively), were applied in the area where grass was planted. The planting hole for each legume tree seedling was fertilised with 50 g of dolomitic limestone, 80 g of natural rock phosphate, 100 g of P (P_2O_5), 25 g of K (KCL), and 10 g of FTE BR-16 and, for *E. grandis*, 75 g of N as ($(NH_4)_2SO_4$), 225 g of P (P_2O_5), and 15 g of K (KCL) was applied.

For the establishment of the OP, the protocol of soil preparation and application of correctives and fertilisers was similar to that adopted in the SPS since the areas were contiguous and presented the same slope and type of soil. Since planting, the pasture areas had not received any additional fertiliser or corrective applications until 2010. Between 2011 and 2014, the pastures received 64 kg N ha^{-1} urea, 16 kg P ha^{-1} (P_2O_5), and 64 kg K ha^{-1} (K_2O) annually, divided into two applications during the summer. From 2014 to 2016, there were no fertiliser applications. Weeds and leaf-cutting ants were controlled during the entire experiment duration in both systems. Leaf-cutting ants were controlled by the application of granulated baits (sulfluramid 0.3% active ingredient) at a dosage of 10 g per square meter of ant hill. Weeds were controlled by the herbicide application 2,4-dichlorophenoxyacetic acid at 1.0 L ha^{-1} (670 g active ingredient ha^{-1}). The application of the herbicide was done with a manual costal sprayer, with capacity for 20 L.

In 2003–2004 and 2004–2007, the experimental area consisted of 16 ha (8 ha for each system) with 32 paddocks of 0.5 ha each. For the experiments in 2011–2014 and 2014–2016, a total area of 8.4 ha (4.2 ha for each system) was used, with six paddocks of 1.4 ha each.

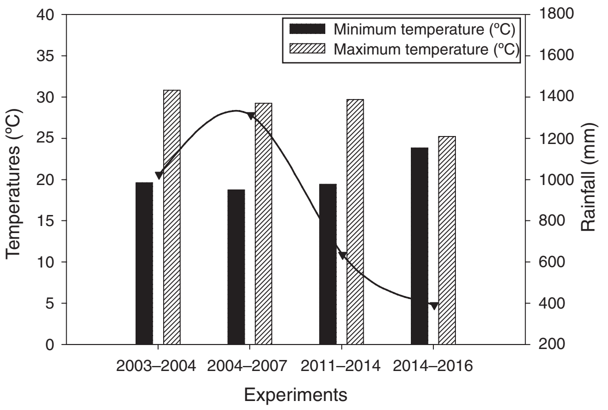

Fig. 2. Average temperatures and rainfall during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016).

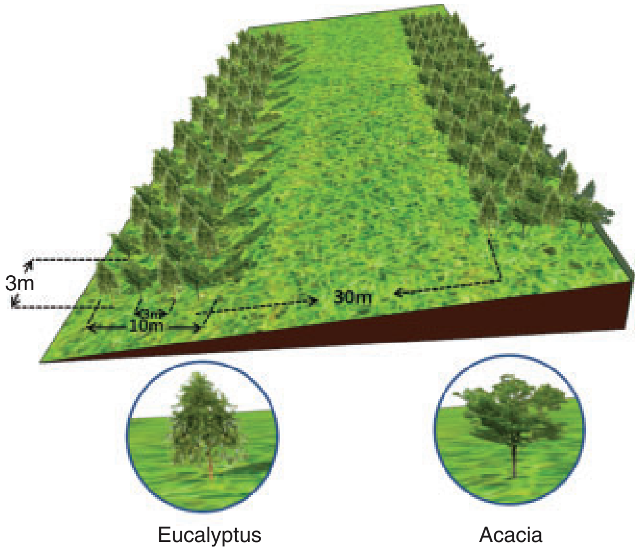

Fig. 3. Schematic representation of the distribution of trees in the silvopastoral system (SPS).

Experimental design and treatments

All experiments were performed under a randomised complete block design (due to the heterogeneity of the experimental area) in a 2 × 4 factorial scheme (two production systems – SPS [i.e. shaded] and OP [i.e. full sunlight]; four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016)). Two replicates (paddocks) were used for the experiment between 2003–2004, and three replicates were used in the experiments between 2004–2007, 2011–2014, and 2014–2016.

Tree measurements and shade percentage

Tree height, diameter at breast height (DBH), and shade percentage were measured during experiments (Table 1). Height measurements were estimated using the optical height meter (clinometer) and DBH was measured using a dendrometric tape where the circumference was measured at 1.30 m above the ground. Shade was measured using a LI-190SA ceptometer connected to a LI-COR portable model radiometer (model LI-189) in 2003–2004, and an AccuPAR LP-80 ceptometer (Decagon Devices) in 2004–2007, 2011–2014, and 2014–2016, by which the PAR that arrived in the understory was non-destructively evaluated. Percentage shade measurements were taken under clear skies during the rainy season at 09:00, 12:00 and 15:00 hours at 1 m above ground level nearby the trees (between 1 and 2 m from the tree trunk) in the middle of the tree grove (between the second and third tree rows).

Animals and grazing management

All animal care and handling procedures followed regulations and were approved by the Ethics Committee of the Embrapa Dairy Cattle. Between 1998 and 2000, the pastures remained free of animals in order to guarantee the initial growth of the trees. In 2001 and 2002, the pasture was grazed for non-lactating crossbred (Holstein × Gyr) cows, according to the Aroeira *et al*. (2005). During the four experiments, paddocks were grazed by crossbred (Holstein × Gyr) dairy heifers that were an average age of 12 months of age and with a bodyweight (BW) of 200 ± 50 kg. All animals had unrestricted (*ad libitum*) access to shade in the SPS, with water and mineral supplements being provided in both the SPS and OP.

For the experiments in 2003–2004 and 2004–2007, pastures were managed under rotational stocking with a defoliation interval of 35 days and 7 days of paddock occupation being established, which, at the time of the interruption of regrowth, coincided with pre- and post-grazing canopy heights of 40 and 20 cm respectively. In 2011–2014 and 2014–2016, pastures were continuously stocked by using a variable stocking rate to maintain a canopy height at around 30–35 cm. Each paddock received 'testers animals' (animals that remained throughout the experimental period). According to the need for an adjustment of the SR, additional 'grazers animals' were added to, or subtracted from, each paddock to maintain the desired heights according to put-and-take method (Mott and Lucas 1952).

Pasture measurements

Canopy height was measured weekly using a ruler graduated in centimetres. A total of 50 points were measured in each paddock (replicates) in 2003–2004 and 2004–2007, and 140 points were measured in 2011–2014 and 2014–2016. In the OP, these measurements were taken at random in each paddock. In the SPS, due to the influence of shade on the structural characteristics of the sward, 30% of the measurements were made within the tree groves (10 m), while the remainder were taken in the area situated between two groves (30 m) while avoiding areas around gates, watering points, and resting sites.

Forage mass was estimated by direct (destructive) sampling every 14 days in 2003–2004 (20 samples from each paddock), 35 days in 2004–2007 (20 samples from each paddock), 21 days in 2011–2014 (10 samples from each paddock), and 28 days in 2014–2016 (12 samples from each paddock). For forage mass estimation, samples were cut at 5 cm from ground level at sites representative of the mean canopy height using a 0.25 m^2 (0.5 m × 0.5 m) metal frame and a manual cutter. The samples were weighed and separated into two subsamples. One subsample (300 g) set was placed in paper bags and dried in a forced-air oven at 55°C for 72 h to estimate the dry matter (DM) content of the total sample. The other subsample (200 g) was manually separated into green and dead fractions. In the green fraction, the number of tillers was counted to estimate the tiller population density. Then, the green fraction was separated into leaves and stems to determine the morphological composition by separation

Table 1. Tree characteristics and shade in the silvopastoral system (SPS) during four experiments

DBH, diameter at breast height (= 1.3 m); n.m., not measured

Variable	Experiments			
	2003–2004[A]	2004–2007[B]	2011–2014[C]	2014–2016[D]
Years after establishment	6–7	7–10	14–17	17–19
Tree height (m) (*Eucalyptus grandis*)	n.m.	22	n.m.	29
DBH (cm) (*Eucalyptus grandis*)	n.m.	26	n.m.	45
Tree height (m) (*Acacia mangium*)	n.m.	14	n.m.	14
DBH (cm) (*Acacia mangium*)	n.m.	20	n.m.	32
Trees ha^{-1}	170	105	n.m.	81
Shade (%)	23	29	46	51

[A] Paciullo *et al*. (2009).
[B] Paciullo *et al*. (2011).
[C] Fernandes (2016).
[D] Lima *et al*. (2019).

of the following components of the plants: green leaf blades, considered to be those blades with less than 50% senescent tissue plus leaf blades in expansion; stem and sheath of the tiller that either had or did not have an inflorescence; and dead material, necrotic leaf tissue that adhered to the tiller and completely necrotic material that did not adhere to the tiller. The plant components were then placed in paper bags and dried in a forced-air oven at 55°C for 72 h, to determine their DM.

Based on this information, the total forage, leaf blade, stem, and dead material forage masses were estimated. The green forage mass consisted of the sum of the leaf and stem masses, while the total forage mass represented the sum of green forage mass and dead material. The total and green forage bulk densities were calculated from the total and green and forage mass divided by the mean height of the pasture.

Forage samples were cut using a hand-plucking technique proposed by Sollenberger and Cherney (1995), in which forage is collected manually after observing the grazing habits of the animals. At the end of the resting period (forage grass with 35 days of regrowth) from 2003–2004 and 2004–2007 and every 28 days from 2010 to 2016, the samples were cut at 15 sites within paddocks at points with average canopy height. The samples from each point were pooled and constituted a single sample per paddock. This was assessed in order to detect differences in the quality of the forage that animals were consuming. These samples were placed in paper bags and dried in a forced-air oven at 55°C for 72 h. After drying, ~300 g of sample was ground using a Wiley mill, then passed through a 1-mm sieve and sent for analysis of the nutritive value at the Animal Nutrition Laboratory of Embrapa Dairy Cattle. Forage samples were analysed for their DM content at 105°C. The CP, NDF and IVDMD contents were also analysed. N content was determined according to the Kjeldahl method (AOAC 1990). CP content was calculated as the total N content × 6.25. NDF was analysed according to the methodology proposed by Van Soest *et al.* (1991), whereas the IVDMD analysis was performed according to the technique described by Tilley and Terry (1963).

Weight gain of heifers

The animals were weighed every 35 days in 2003–2004 and 2004–2007 and every 28 days in 2011–2014 and 2014–2016, after fasting from solids and liquids for 12 h. The SR (based on an adult animal with 450 kg BW) was calculated based on the weights of the 'testers animals' plus the weights of the 'grazers animals' during the period that they remained in the paddock and the total area of each treatment. The average daily gain (ADG) of all animals (testers and grazers) was obtained by the difference between weights (final and initial weights) divided by the weighing interval. The gain per area (GPA) was obtained by multiplying the average daily gain of the animals (testers and grazers) by the SR per paddock and by the number of days that remained in the grazing period.

Statistical analysis

All statistical procedures were performed using the PROC MIXED of SAS software (SAS Institute). The experiments, systems and its respective interactions were assumed as fixed effects. In order to account for variation among experiments, the random effect of blocks within experiments was included as random subject in the mixed model. For all analyses, the used significance level was 0.05.

Results

Shading percentage

The decrease in PAR in the SPS compared with the OP was 23% in 2003–2004, 29% in 2004–2007, 46% in 2011–2014 and 51% in 2014–2016 (Table 1).

Sward structural characteristics, forage mass, forage bulk density and morphological composition

There was no effect between systems for the canopy height variable ($P > 0.05$; Fig. 4*a*). Tiller population density only varied with system in the 2011–2014 experiment, when lower tiller density was observed in the SPS relative to the OP (634 vs 760 tillers m^{-2}) ($P < 0.05$; Fig. 4*b*). Lower total and green forage mass as well as lower total and green forage bulk density were observed in the SPS compared with the OP from 2004 to 2016 ($P < 0.05$; Fig. 4*c–f*). Total forage mass was reduced by 19% in SPS compared with the OP in 2004–2007, 38% in 2011–2014 and 31% in 2014–2016 whereas total forage bulk density was decreased by 18% in SPS compared with the OP in 2004–2007, 34% in 2011–2014 and 30% in 2014–2016 respectively.

A significant difference between systems was observed for the variables leaf blade mass, stem, and dead material ($P < 0.05$; Fig. 5). A reduction in leaf blade mass was observed in the SPS compared with the OP in 2004–2007 (918 vs 1152 kg ha^{-1} respectively), 2011–2014 (713 vs 1047 kg ha^{-1} respectively) and 2014–2016 (716 vs 947 kg ha^{-1} respectively) (Fig. 5*a*). The stem mass was higher in the OP than in the SPS in 2011–2014 (1688 vs 1088 kg ha^{-1} respectively) and 2014–2016 (1331 vs 998 kg ha^{-1} respectively) ($P < 0.05$; Fig. 5*b*). Similar behaviour was observed for dead material mass, with higher values in the OP than in the SPS in 2011–2014 (739 vs 379 kg ha^{-1} respectively), and 2014–2016 (862 vs 494 kg ha^{-1} respectively) ($P < 0.05$; Fig. 5*c*).

Nutritive value

For CP content, there were significant differences between systems during the experiments ($P < 0.05$; Fig. 6*a*). CP content was 23 and 30% higher in the SPS than in the OP in 2011–2014 (139 vs 113 g kg^{-1} respectively) and 2014–2016 (118 vs 91 g kg^{-1} respectively), whereas no significant difference was observed between systems in 2003–2004 and 2004–2007. NDF content did not vary with system in any experiment ($P > 0.05$; Fig. 6*b*). IVDMD was only affected by system in 2011–2014 ($P < 0.05$; Fig. 6*c*). The IVDMD value for the OP was higher than that observed for the SPS (637 vs 597 g kg^{-1} respectively).

Weight gain of heifers

Due to N fertilisation in 2011–2014 and the greater availability of forage mass in the OP, SR (heifer ha^{-1}) was significantly higher in the OP than in the SPS (2.5 vs 2.3 respectively); however, there

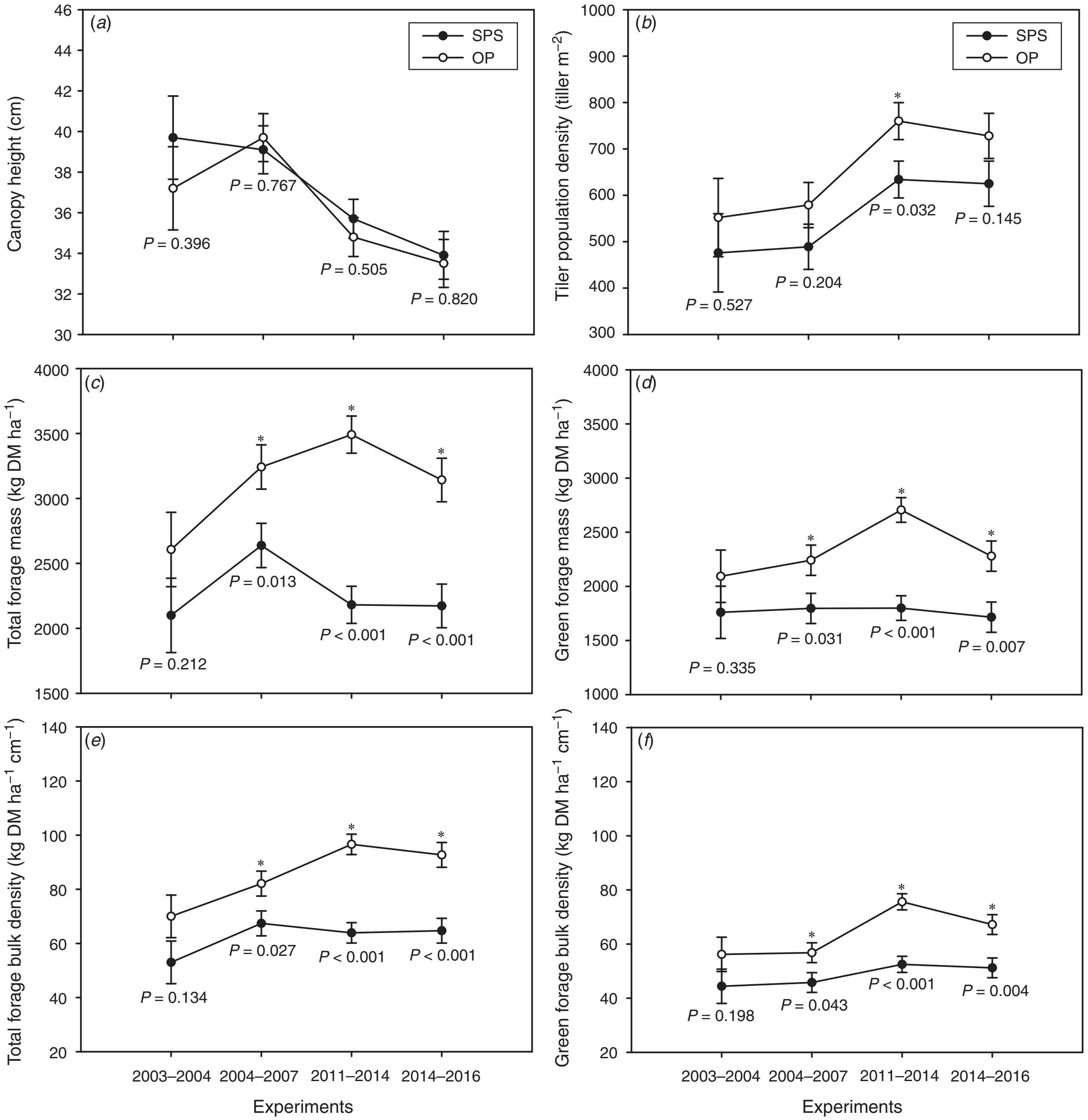

Fig. 4. Structural characteristics and forage production of signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

was no difference between systems in the other experiments ($P < 0.05$; Fig. 7*a*). For SR (animal unit/ha – AU ha^{-1}), no significant effect was observed ($P > 0.05$; Fig. 7*b*). Moreover, no significant differences were observed between systems for ADG during the experimental period ($P > 0.05$; Fig. 7*c*). GPA was only influenced by system in 2014–2016, when weight gain in the OP was higher than in the SPS (199 vs 169 kg ha^{-1} respectively) ($P < 0.05$; Fig. 7*d*).

Discussion

Sward structural characteristics, forage mass, forage bulk density, and morphological composition

The significant difference in tiller density between systems in 2011–2014 may be associated with the N fertilisation performed during this period, which had a greater positive effect on the OP than on the SPS, favouring a greater disparity between values

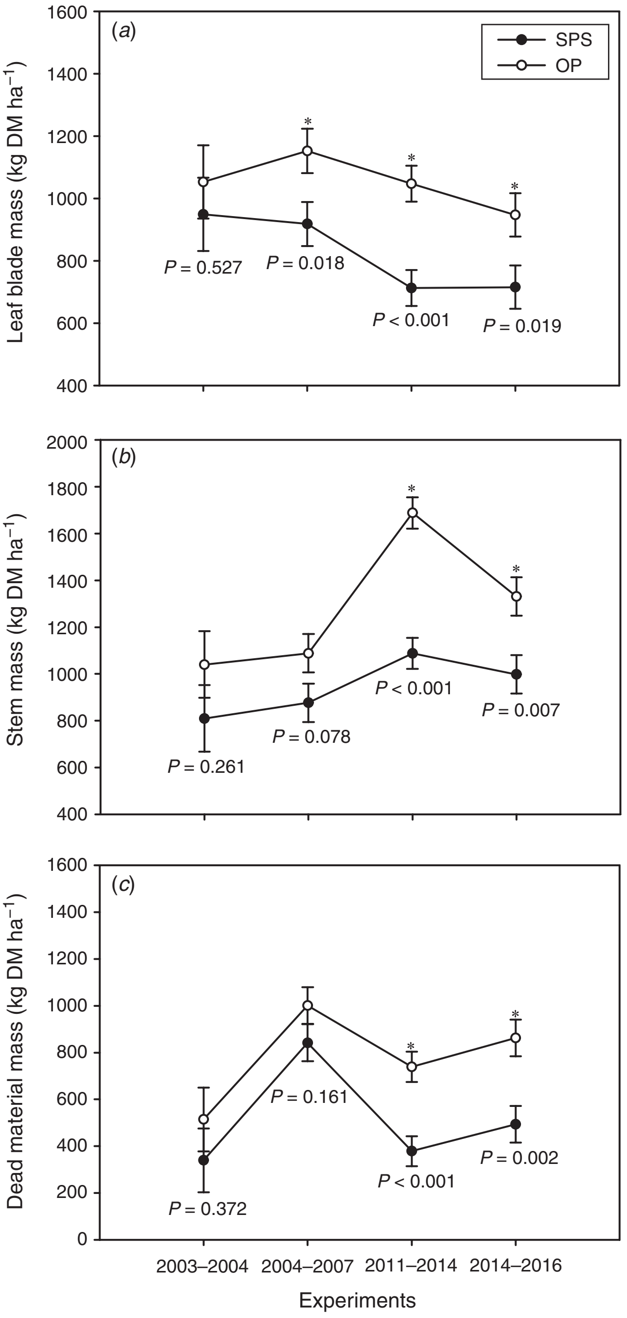

Fig. 5. Morphological composition of signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

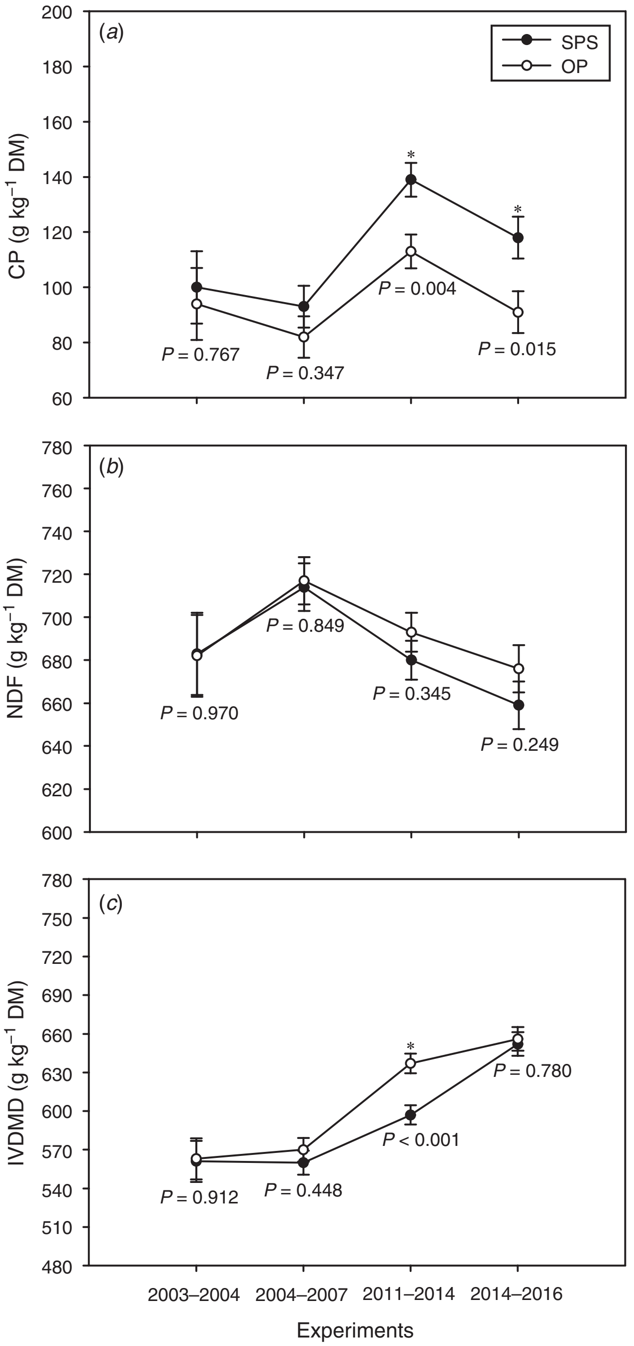

Fig. 6. Crude protein (CP), neutral detergent fibre (NDF), and *in vitro* dry matter digestibility (IVDMD) content of signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

(Fig. 4*b*). Lopes *et al*. (2017) found that fertilisation is more effective in increasing tillering under full sun conditions than under shade. N fertilisation increases the rate of leaf appearance and the number of basal buds that can produce new tillers, resulting in increased tiller density (De Bona and Monteiro 2010). Even with higher N availability in soil under the SPS, there was less response to N fertilisation due to the low carbon supply for plants via photosynthesis, which limits tillering. Faria *et al*. (2018) evaluated the productive and qualitative response of *B. decumbens* and *Brachiaria ruziziensis* to three levels of shade (0, 36 and 54%) and four N fertilisation doses (0, 50, 100 and

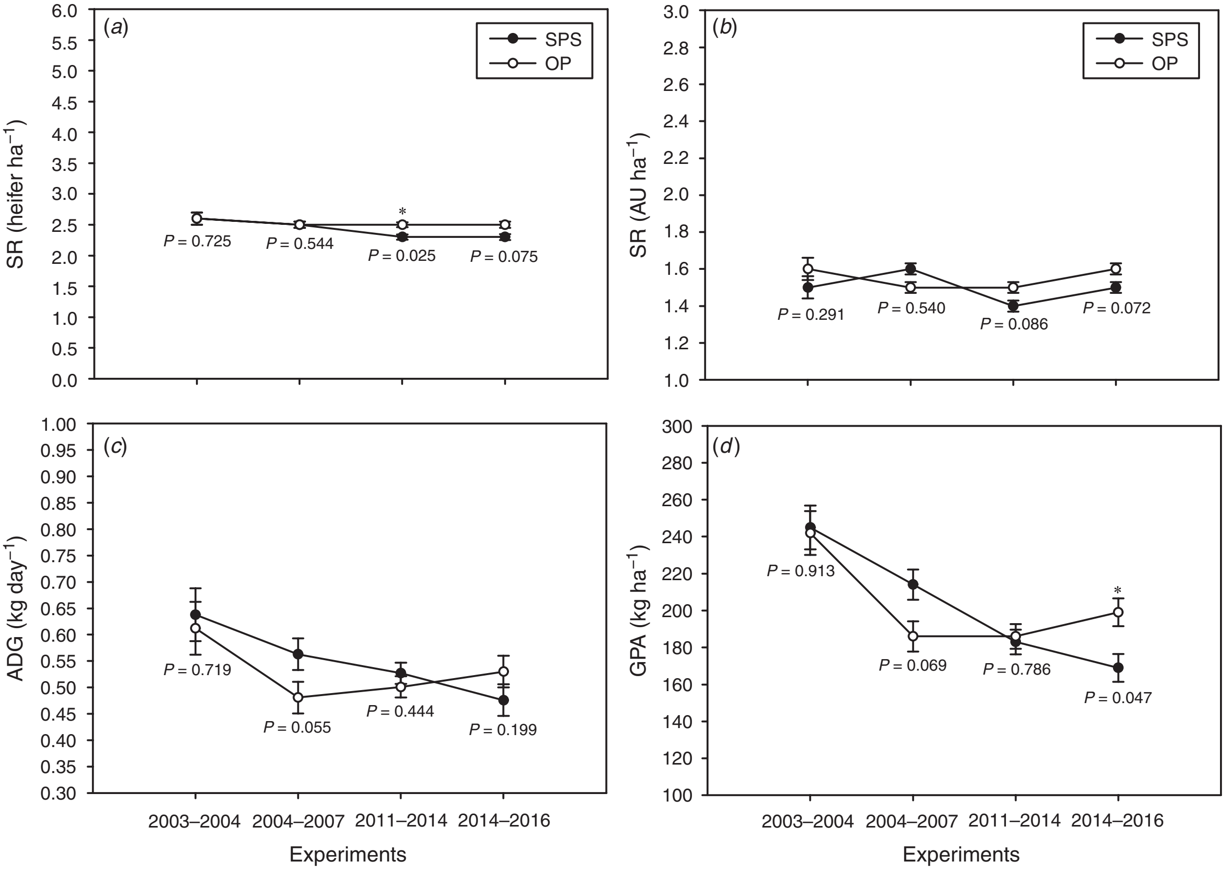

Fig. 7. Stocking rate (SR), average daily gain (ADG), and average gain per area (GPA) of dairy heifers (Holstein × Gyr) grazing on signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

150 mg dm^{-3} soil), and observed a reduction in tillering for both species with increased shade and N levels, whereas highlighting that forage under shade requires lower levels of N, unlike the response of forage grown in full sun. However, this result indicates the ability of signal grass to adapt and maintain tillering, even under conditions of increasingly intense light restriction. However, it was observed that the change in rotational grazing method for continuous stocking during the experiments during 2011–2014 and 2014–2016 provided an increase in tiller density across both systems.

The similarity in total and green forage mass between the SPS and the OP in 2003–2004 is related to the tolerance of signal grass to moderate shade (i.e. 23%) imposed by the tree component (Paciullo *et al*. 2007; Guenni *et al*. 2008; Fig. 4*c*, *d*). In the subsequent years, there was a progressive increase in shade levels in the SPS, which resulted in a reduced total and green forage mass in relation to the OP. Reduction in the productive capacity of pastures in SPS has mainly been related to lower light quantity (i.e. photon flux density) and quality (e.g. changes in the red to far-red (R : FR) ratio) of the light spectrum arriving at the understory with advancing tree age (Wilson and Ludlow 1991; Dodd *et al*. 2005; Beaudet *et al*. 2011). A decrease in the forage mass with increased shade level in SPS has been observed by other authors (Gómez *et al*. 2013; Bosi *et al*. 2014; de Oliveira *et al*. 2014; Santos *et al*. 2018). In 2011–2014 and 2014–2016, the average height/DBH of *E. grandis* and *A. mangium* trees were 21.7 m/25.5 cm and 14 m/20 cm, respectively, for 2011–2014 and 29 m/45 cm and 14.2 m/32 cm, respectively, for 2014–2016. The increased dendrometric characteristics associated with quadrupled tree rows and north–south direction planting was responsible for decreased forage mass in the SPS over time. Santos *et al*. (2016) observed that the planting of *Eucalyptus* trees in simple lines in an east–west orientation, with a space between groves of 22 m and tree management through pruning and thinning could favour forage production in a SPS.

The observed decrease in forage bulk density the SPS compared with the OP in 2004–2007 is associated with total and green forage mass being lower in the SPS, since canopy height was the same for both systems (Fig. 4*e*, *f*). Lopes *et al*. (2017) observed a reduction of 18 and 58% in the forage bulk density of the forage mass of signal grass grown with 20 and 70% sunlight respectively. The lower forage bulk densities observed in the SPS with increased shade could decrease the bite mass and forage intake of animals, which would result in compromised animal productivity. Santos *et al*. (2018) observed reductions of

40 and 60% in the forage density of an SPS with increased shade (21.9% for an SPS with 22 m between groves and 39.5% for an SPS with 12 m between groves) relative to full sunlight. According to Sollenberger and Burns (2001), the density of forage is one of the structural characteristics of a pasture that can determine the amount of time animals spend grazing, thereby affecting nutrient intake by interfering with the ingestive behaviour of the animals.

The SPS sward in 2004–2007, 2011–2014 and 2014–2016 presented lower leaf blades mass compared with the OP. The distribution of morphological components in the forage mass – such as vertical structure – influence animal grazing behaviour, thereby affecting forage intake (Carvalho *et al.* 2009). Stem mass and dead material was reduced in the SPS compared with the OP in 2011–2014 and 2014–2016. The lower values observed in the SPS were the result of lower total forage mass observed during this period. Moreover, pastures cultivated in the OP had higher photosynthetic rates than those in shaded conditions, providing accelerated development and tissue senescence. Notably, Neel *et al.* (2016) reported that plants grown in shaded areas tend to have a morphological maturity delay of 4–6 days compared with plants grown in OP. Thus, plants grown in SPS tend to be physiologically younger, which prolongs the vegetative phase and reduces tissue death (Lopes *et al.* 2017).

Nutritive value

The higher CP content observed in the SPS compared with the OP in 2011–2014 and 2014–2016 (Fig. 6*a*) can be attributed to the effect of more intense shade levels during this period (46 and 51% of shade respectively). The increase in CP content in forage in the SPS compared with the OP in 2011–2014 and 2014–2016 was 23 and 30% respectively. This increased CP content with increased shade level is consistent with results from the literature (Soares *et al.* 2009; Kyriazopoulos *et al.* 2013; Paciullo *et al.* 2017; Geremia *et al.* 2018; Santos *et al.* 2018). Such an increase in the CP content of forage in shaded environments may be related to both the direct effect of shade on photosynthesis and the effect of soil N dynamics (Wilson 1996; Peri *et al.* 2007). In addition, signal grass may have benefited from the N fixed by the tree legumes present in the study area, resulting in a higher CP content in the forage. The greater difference in CP over the last two experiments (2011–2014 and 2014–2016) could be the result of altered grazing management. Under continuous stocking, forage samples were cut each 28 days above a canopy height of 30 cm, and practically only leaves with higher CP content were present in this superior portion of pastures. Samples from the two initial experiments (2003–2004 and 2004–2007) when rotational stocking was adopted, were cut after a regrowth of 35 days, adopted a post-grazing stubble height of 20 cm. Therefore, the different managements and sampling strategies may have contributed to the elevated difference in CP content during the last two experimental periods.

The NDF content of forage in the SPS has not presented a well defined pattern, as studies have shown that it may increase, reduce, or even remain constant with increased shade level compared with OP (Lin *et al.* 2001; Paciullo *et al.* 2014; Neel *et al.* 2016; Santos *et al.* 2018). The results obtained were dependent on the forage species, percentage of shade, stage of maturity, and forage management (Neel *et al.* 2008). It is possible that the management grazing strategy during the experiments in both systems prevented the accumulation of fibrous fractions in the forage. The increased IVDMD of forage in the OP – relative to the SPS – in 2011–2014 is contradictory to the results observed by Paciullo *et al.* (2007), where they associated the highest IVDMD with the highest CP content in the forage. Several studies have demonstrated different patterns in the variation of IVDMD in forage grown in SPS; with reduction, similarity and increases in IVDMD among SPS in relation to OP (Sousa *et al.* 2010; Paciullo *et al.* 2011; Neel *et al.* 2016).

Weight gain of heifers

According to the hypothesis of the present study, a decrease in SR was expected with advancing system age, especially in the SPS, due to the progressive increase in competition for available PAR between the forage and tree components. The joint analysis, which characterised the temporal evolution of each system, only showed the tendency for a decrease in the number of heifers ha^{-1}, particularly in the SPS. These results demonstrate the ability of signal grass to adapt to conditions of reduced light intensity, especially in systems with low-input usage.

The higher SR (heifer ha^{-1}) observed in the OP compared with the SPS in 2011—2014 can be explained by the significant fertilisation effect during this period. Fertilisation, especially by N, directly reflects an increase in tiller population density, thereby resulting in a higher availability of forage mass and, consequently, an increase in the carrying capacity of the OP compared with the SPS (Fig. 7*a*).

It was expected that the ADG could be positively influenced by the elevated CP content in the SPS; however, during the four experiments, the ADG remained similar between the systems despite lower forage mass and forage bulk density being observed in the SPS from 2004 to 2016. In fact, the ingestion of forage is directly related to the structural and morphological characteristics of the pasture. Therefore, we can infer that the animals that grazed on the SPS were able to remain over a longer grazing bouts per day to ensure nutrient supply throughout the day, since the forage masses and forage bulk densities were lower in the SPS. Maintenance of the same forage canopy height in both systems during each experiment (but with different densities) may have favoured a greater opportunity for the selection and ingestion of forage in the OP than in the SPS. The higher CP content of forage in the SPS observed in this study, which was associated with microclimatic conditions that were more favourable to the thermal comfort of the animals (Sousa *et al.* 2010), may have compensated for the lower observed masses and forage bulk density in the SPS, thereby contributing to the similar ADG among systems.

Despite similarity in SR and ADG between systems during the experiments, there was a progressive decrease in GPA in the SPS over time, culminating in lower values being observed in 2014–2016. In the OP, a sharp decrease between 2003–2004 and 2004–2007 was observed, though the relative stabilisation of GPA over the period between the experiments (2004–2007 and 2014–2016) is noteworthy. The comparison of systems indicates that there a significant GPA difference in favour of the OP in the last experiment only.

The results of the present study confirmed the expectation of reduced animal productivity by area in the long term SPS. Despite this, the magnitude of differences can be considered small and attributed to forest thinning over time – either by death or the intentional removal of trees – preventing a greater increase in the level of shade in the SPS. It is also emphasised that the extensive management model may have reduced differences between the systems. Considering the results of this long-term SPS study on animal production, it should be expected that income from wood, and its benefits to the environment such as increased the carbon stock in the aerial biomass, will compensate for the lowest animal GPA values from the 17th to 19th years. In addition, the commercialisation of this wood over the long-term represents a method of adding value to the product.

Conclusions

The growth of trees in a SPS over time progressively reduces the PAR available for grass growth. In the present study, the progressive reduction of the PAR negatively impacted the productive characteristics of the pasture in the SPS from the 7th year onwards. However, the liveweight gain of heifers were similar between systems most of the time. To some extent, the higher protein content in the SPS nutritionally compensated for reduced forage mass, leaf mass, and forage bulk density over time. The weight gain per area was lower in the SPS from the 17th to 19th years; however, the difference between systems was relatively minor. Even under intense shade, signal grass presents a high degree of phenotypic plasticity which gives this species a high potential for use in SPS.

Conflicts of interest

The authors declare no conflicts of interest.

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