

**University of São Paulo
“Luiz de Queiroz” College of Agriculture**

**APSIM - Tropical Pasture parameterization for biomass
production, light and water competition in a
silvopastoral system with *B. brizantha* cv. Piatã and *E.
urograndis***

Lucas Filletaz Balcão

Thesis presented to obtain the degree of
Doctor in Science. Area: Animal Science and
Pastures

**Piracicaba
2021**

Lucas Filletaz Balcão
Animal Scientist

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:

Dr. **PATRÍCIA MENEZES SANTOS**

Co-advisor:

Dr. **JOSÉ RICARDO MACEDO PEZZOPANE**

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To my beloved family Pilar and Aline for all the love and patience.

To my parents Elaine and Amândio, for all the love and support since the beginning of this long journey

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"Red sky at night, shepherd's delight.

Red sky in the morning, shepherd's warning"

- Ancient saying

"Névoa na baixa, sol que racha,

névoa na serra, chuva que berra"

- Dito popular

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RESUMO

APSIM – Tropical Pasture, parametrização para produção de biomassa, competição por água e luz em um sistema silvipastoril com *B. brizantha* cv. Piatã e *E. urograndis*

Os SSP se caracterizam por associar árvores com forrageiras herbáceas numa mesma área com a presença de animais. Em geral, o prognóstico sobre a produtividade possui correlação com variáveis meteorológicas, como temperatura do ar e precipitação. Para estimar a capacidade produtiva dos sistemas agrícolas, pode ser utilizada a modelagem matemática. O presente trabalho teve como objetivo parametrizar o modelo APSIM (Agricultural Production Systems sIMulator) para estimar a produção de biomassa forrageira em SSP, bem como a competição por luz e água. Na primeira etapa foi realizado um experimento à campo em um sistema silvipastoril, onde foram coletados dados microclimáticos, produção de forragem e umidade do solo. O desenho experimental foi completamente casualizado com medidas repetidas no tempo. As variáveis relacionadas à produção de forragem foram tratadas como respostas às variáveis microclimáticas. Uma análise de fatores múltiplos (AFM) foi realizada para verificar quais variáveis micrometeorológicas tem maior participação na variabilidade dos resultados. Com base nessas informações foi realizada a parametrização do modelo APSIM - Tropical Pasture com relação ao crescimento das plantas forrageiras. Para avaliar a eficiência do modelo foram utilizadas análises de regressão linear múltipla e coeficiente de determinação (R^2), Nash-Sutclif Efficiency (NSE), erro médio (EM) e erro médio absoluto (EMA). Após a calibração do modelo as simulações se mostraram satisfatórias, indicando que o modelo teve boa performance em simular o crescimento da pastagem e seus componentes morfológicos sob sistema silvipastoril. O modelo APSIM-Slurp simulou bem a interceptação de luz ($R^2 = 0,64$ NSE = 0,60). O modelo APSIM-Tropical Pasture apresentou um bom desempenho para simular a biomassa da pastagem ($R^2 = 0,90$ NSE = 0,72), folha ($R^2 = 0,82$ NSE = 0,44), colmo ($R^2 = 0,82$ NSE = 0,75) e um desempenho aceitável para índice de área foliar da pastagem ($R^2 = 0,76$ NSE = 0,58).

Palavras-chave: Sistema agroflorestal, Integração pecuária-floresta, Modelagem de processos

ABSTRACT**APSIM – Tropical Pasture parameterization for biomass production, light and water competition in a silvopastoral system with *B. brizantha* cv. Piatã and *E. urograndis***

The SSP are characterised by associating trees with herbaceous forages in the same area with the presence of animals. In general, the prognosis about productivity is correlated with meteorological variables, such as air temperature and precipitation. To estimate the productive capacity of agricultural systems, mathematical modelling can be used. The present work aims to parameterise the APSIM model (Agricultural Production Systems sIMulator) to estimate the production of forage biomass in a SSP, as well as the competition for light and water. In the first stage, a field experiment was carried out in a silvopastoral system, where microclimate data were collected, of forage production and soil moisture. The experimental design was completely randomised with repeated measures over time. Forage production was analysed in relation to microclimate variables. A multiple factor analysis (AFM) was performed to verify which micro-meteorological variables have a greater participation in the variability of the results. Based on this information, the APSIM model was parameterized in relation to the growth of forage plants. To evaluate the efficiency of the model, multiple linear regression analyses and coefficient of determination (R^2), Nash-Sutclif Efficiency (NSE), mean error (EM) and mean absolute error (EAM) were used. The APSIM-Slurp model simulated well the light interception ($R^2 = 0.64$ NSE = 0.60). APSIM-Tropical Pasture model showed a good performance to simulate pasture biomass ($R^2 = 0.90$ NSE = 0.72), leaf ($R^2 = 0.82$ NSE = 0.44), stem ($R^2 = 0.82$ NSE = 0.75) and an acceptable performance for pasture leaf area index ($R^2 = 0.76$ NSE = 0.58).

Keywords: Agroforestry system, Livestock-forest integration, Process modelling

1. INTRODUCTION

Climate change has drawn attention to livestock production because its impact in greenhouse gases (GHG) emissions. Despite methane emission from bovine enteric fermentation, it is advocated that grasslands could represent an important carbon stock. Depending on the grazing management, the balance of carbon emission could be negative. Silvopastoral systems are pointed as one of such management that can contribute to keep the livestock production carbon free. However, the presence of tree in pasture may have some consequences in relation to the grass production.

The competition for resources, such as water and radiation, seems to be a prevalent concern among scientists dedicated to silvopastoral studies (Rao et al., 1998; Dulorme et al., 2004; Bosi et al., 2020). However, it is expected in natural ecosystems with high variability of species (Asner et al., 2004). The competition for water depends on the depth of the arboreal root systems in relation to the herbaceous roots. Even in places characterized by a drought period during the year, trees and pastures or crops don't compete for water due to differences in the depth where each species uptake the water (Gyenge et al., 2002). In some situations complementary interactions between grass and tree roots distribution may also occur through the soil layer, thus decreasing water and nutrients competition (Fernandez et al., 2008).

The ecosystems generally reach a dynamic equilibrium. The ecosystem resilience capacity allows the system to reorganise and keep its function and structure when some disturbance occurs (Holling, 1973). Therefore, the observation of competition and facilitation within silvopastoral ecosystems may consider the space and time dimensions. Thus, the implementation of agroecosystems that rely in a synergic relationship among its components is necessary to achieve the productivity goals without depleting the natural resources such as soil and water.

Farmers and scientists are engaged in seeking optimum silvopastoral system organisation and management that can promote satisfactory outcomes. Still, there are some doubts concerning light and water behaviour within a silvopastoral system. In this way, the mathematical modelling has been shown as an important tool to explore the variations around tree and grass management. Agricultural Production Systems Simulator (APSIM) is a platform that can combine models which account for interactions between different components of a silvopastoral system, such as soil, grass, tree, management, rainfall and solar radiation.

Our hypothesis is we can combine different biophysical models APSIM-Slurp representing tree and APSIM-Tropical Pasture the grass to promote interactions between the silvopastoral system components taking into account resources sharing.

1.1. Objectives

This thesis aims to better understand how the competition for light and water affect the pasture biomass production within a silvopastoral system composed by *Eucalyptus urograndis* and *Brachiaria brizantha* cv. Piatã.

1.1.1. Specific objectives

- Evaluate the pasture biomass production under the silvopastoral system and the pasture monoculture.
- Calibrate and validate APSIM models Tropical Pasture and Slurp to simulate pasture growth under a silvopastoral system.
- Simulate different management scenarios in a silvopastoral system seeking the optimum for pasture production regarding light and water competition.

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2. LITERATURE REVIEW

2.1. Climate change as a challenge for agriculture

Global warming has concerned governments, scientific community, and general public. Extreme weather conditions such as drought, floods and frost, have been more frequent in the last years (IPCC, 2014). Climatic changes could be seen as a threat to agriculture and food production (Lin et al., 2008). Long term climatic projections indicate that air temperature, rainfall, atmospheric CO₂ concentration, and solar radiation are the climatic variables that will change (Trenberth et al., 2007). The alteration in the patterns of rainfall and temperature challenges agriculture, especially in tropical regions (IPCC, 2014).

Weather simulations indicate that Brazilian Midwest region will probably be the most affected region in South America, where an increase in the average temperature will occur in all seasons of the year. Rainfall projections show a drier future in most regions of Brazil, particularly in Midwest and Southeast regions (Chou et al., 2016).

Forecasted scenarios generated by ETA-CPTEC and Precis models indicate positive consequences to annual forage production in grasslands mainly formed by *Megathyrus maximus* and *Urochloa brizantha* in Northern, Midwestern and Southeastern regions of Brazil (Santos et al., 2014).

With that, pasture management can be considered one of the most important factors associated to the environmental impact of cattle production, because it will determine the balance between emission and sequestration of carbon (Leahy et al., 2004).

2.2. Silvopastoral systems

Agroforestry systems are recognised as a more resilient agroecosystems against climatic extremes when compared to monocultures (Amézquita et al., 2004; Matocha et al., 2012). Silvopastoral systems, a kind of agroforestry, combines grass, trees, and animals in the same area at the same time. The synergism between those components may promote positive consequences for forage production, tree development and animal performance. Silvopastoral systems compared with pasture monoculture have better capacity to thrive facing water stress (Natarajan; Willey, 1986). The superficial runoff could be reduced by the presence of trees in the grassland, enhancing water infiltration through the soil profiles (Sanchez et al., 1997). The increase in the litter deposition by trees also contribute for soil surface protection (Wallace, 2000). The presence of trees in pasture directly affects micro-climate conditions, which affects

the sward structure (Dupont; Patton, 2012). These alterations could occur as a result of differences in the soil and air temperature under the tree canopy compared with pastures without trees. Thus, the preservation or the introduction of trees affect the micro-climate, litter dynamics and soil nutrients, contributing to the increase of nutrient cycling in these systems (Menezes et al., 2002). When the trees are arranged in rows, the wind speed, and the photosynthetic active radiation (PAR) are reduced and the combination of both factors promotes changes in the air temperature and humidity under the tree canopy (Pezzopane et al., 2015). The microclimate under tree canopies and the organic material added by trees reduce evapotranspiration rates, preserving water in soils layers (Siriri et al., 2013). However, change in microclimate only promote gain in plant biomass production if there is enough PAR for suitable plant growth and if there is enough water in the soil to attend the plant community demand (Nicodemo, 2011).

2.3. Crop and pasture modelling

Crop modelling has evolved fast in the last decades, mainly stimulated by the demand for accurate predictions of crop production concerning climate change scenarios and due to exponential growth in information technology and data science (Dourado-Neto et al., 1998; Fourcad et al., 2008; Holzworth et al., 2014; Keating 2020).

In general forage productivity can be estimated by mechanistic or empirical models. Empirical models may provide a practical tool for the farmer or farm adviser and generally needs few input variables (Thornley; Johnson, 1990). Tropical grass growth could be accurately simulated using empirical models (Cruz et al., 2011; Pezzopane et al., 2012; Pezzopane et al., 2018). In general these models require input variables such as air temperature, solar radiation, rainfall and latitude, which are broadly available from weather stations in most tropical regions (Andrade et al., 2015).

However, empirical models are limited to the context where they were created. Thus, there is a need for models capable to explain the mechanisms involved in the response dynamics of tropical grasses (Thornley; Johnson, 1990). An interdisciplinary approach, which integrates mathematical, biological and computer science is necessary to advance research in plant growth modelling and simulation (Fourcad et al., 2008). For model development and forage biomass simulation, two main platforms have excelled, the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003) and Agricultural Production Systems sIMulator (APSIM)-NextGeneration (Holzworth et al., 2014). Both platforms comprise more than 30 plant

models including grasses, crops and trees. Also, they have models to represent soil physical and chemical properties, soil water dynamics, weather and farm management.

CROPGRO Perennial Forage is a model part of DSSAT that is capable to accurately simulate forage production based on physiological plant processes, soil characteristics, climate and management (Boote et al., 1998). Despite been a mechanistic model for temperate forages in the USA and Australia, it has been calibrated for tropical forages in Brazil with satisfactory performance (Andrade et al., 2015). Some examples of tropical grasses which were satisfactorily simulated by CROPGRO are *B. brizantha* cv. Xaraés (Pedreira et al., 2011), *P. maximum* cv. Tanzania (Lara et al., 2012), *B. brizantha* cv. Marandu (Pequeno et al., 2014), *B. brizantha* cv. Piatã (Bosi et al., 2020a).

APSIM Classic has models to simulate pasture growth, such as AgPasture model (Li et al., 2010), which simulates mixed pastures of C3 and C4 grasses and legumes; Lucerne (Robertson et al., 2002), which simulates lucerne (*Medicago sativa*) and recently was adapted by Ojeda et al. (2017) to simulate switch grass; and APSIM-Growth that was originally parametrized to simulate Bambatsi coloured guineagrass (*P. coloratum* L.) in Australia and was parameterised for Brazilian conditions (*P. maximum* cv. Mombaça) by Araujo et al. (2013).

APSIM-Growth is capable to simulate the fraction of biomass removed, biomass partitioning between plant organs, and senescence (Bosi et al., 2020b). The main variables involved in this process are radiation use efficiency, radiation interception, air temperature, water and nitrogen deficit, and vapour pressure deficit. However, APSIM-Growth has no phenology model, which is a limiting factor to simulate tropical pastures. Thus, the simulations do not have changes in partitioning and senescence in relation to phenological phases, the specific leaf area is fixed and is not affected by environmental factors, it does not have any remobilisation of reserves, and does not simulate grazing effects on pastures (Bosi et al., 2020b).

As APSIM Classic is less used and outdated and APSIM-Growth does not provide functions necessary to simulate tropical pastures, the APSIM-Tropical Pasture model (Bosi et al., 2020b) was developed within APSIM Next Generation, based on the Plant Modelling Framework (PMF) (Brown et al., 2014).

2.4. Silvopastoral modelling

Since silvopastoral systems are more complex than pasture monoculture, modelling such systems to simulate pasture production is challenging. This is because, the simulation of

such dynamic systems must describe changes caused by the interactions among trees and grasses (Huth et al., 2002).

Several models have been developed to simulate tree-crop interactions with different objectives and levels of detail (Luedeling et al., 2016). McMurtrie, R., & Wolf, L. (1983) developed a model consisting in a pair of differential equations to simulate the competition between trees and grass for radiation, water, and nutrients. ALWAYS is an object-oriented model linking five components of the silvopastoral system (climate, tree, sward, soil and animal), which interact through biophysical functions at a plot and daily scales (Bergez et al. 1999). The HyPAR model attempts to provide a useful tool to explore opportunities for complementarity of light and water use by trees and sorghum in a range of climates (Mobbs et al., 1998). The WaNuLCAS model was developed to deal with a wide range of agroforestry systems: hedgerow intercropping on flat or sloping land, fallow-crop mosaics, or isolated trees in parklands, with minimum parameter adjustments (Van Noordwijk and Lusiana, 1998). The Yield-SAFE model was designed to predict growth, resource sharing and productivity in agroforestry systems acting as a tool to forecasts yield, economic optimisation of farming enterprises and exploration of policy options for land use in Europe (van der Werf et al., 2007).

These models have some limitations regarding the adaptation and application in other contexts different from where they were developed. Thus, the need to obtain reliable predictions of tree and crop performance in a wide range of agroforestry practices, across distinct environmental conditions, must be achieved by a modular and flexible modelling approach (Luedeling et al., 2016). APSIM offers an agroforestry functionality for crops (Huth et al., 2002) that is already available and widely used.

The APSIM agroforestry tree-proxy model can accurately simulate maize productivity in agroforestry systems (Smethurst et al., 2017; Dilla et al., 2018). The same model also was used to simulate the response of maize yield to N fertilizer applications and tree pruning practices through virtual experiments (Dilla et al., 2020).

B. brizantha cv. Piatã was simulated using APSIM-Tropical Pasture and APSIM-Slurp models, the latter used to simulate the Eucalyptus tree presence in the system, intercepting solar radiation and uptaking water from soil layers through tree's root extension (Bosi, 2017). The CROPGRO-Perennial Forage also was used to simulate Piatã palisade grass under a silvopastoral system condition. However, the simulations considered only the competition for solar radiation using measured data of incoming solar radiation understory at different distances from the tree's canopy (Bosi et al., 2020a). APSIM-Tropical Pasture also has been satisfactory adapted to simulate Marandu palisade grass in a silvopastoral system located at amazon biome, Brazil (Gomes et al., 2020).

Despite the remarkable advances in silvopastoral modelling concerning tropical grasses production, still, there is a long journey to achieve an ideal modelling framework. In the face of that undeniable truth, the best to be done is to dig deeper to construct and adapt models within a framework capable of simulating the silvopastoral system in a broad range of possibilities.

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3. RESOURCE COMPETITION AND PRODUCTIVITY OF *Brachiaria brizantha* CV. BRS PIATÃ IN A SILVOPASTORAL AND AN OPEN PASTURE SYSTEM

ABSTRACT

Trees and grasses coexist in natural environments such as savannas. Although, pasture production in silvopastoral systems is affected by a combination of different aspects related to soil, plant community, microclimate and grazing management. The dynamics of resource competition between trees and grasses is a puzzling question that does not have a simple answer. To investigate the effect of the trees on pasture regarding soil water and solar radiation competition, we conducted an experiment analysing different zones within a grassland. The zones are described as a pasture without trees (full sun (FS)) and different distances (SP1= 0.0m; SP2 = 3.75m; SP3 = 7.5m; SP4 = 11.25m) from the northern tree row in a silvopastoral system composed by Piatã palisade grass and *Eucalyptus urograndis* planted in 4x15m with near East-West orientation. We performed an exploratory analysis using the Multiple Factor Analysis (MFA) considering microclimate variables, soil water content and the pasture biomass and morphological components. The soil water content, pasture productivity and solar radiation levels had distinct values among the observed zones. However, due to the remarkable seasonal variability, during the winter the differences between silvopastoral environments and the full sun was milder when compared to the summer. Soil water content close to the trees (SP1) was lower than in the full sun (FS) and in the centre zone between the tree rows (SP3) most of the observed time. Besides that, we observed a greater presence of tree roots in zone SP1 than in the SP3, which denotes some influence of the trees in the hydrological dynamic within the silvopastoral system. There was a relation between the observed zones and the levels of radiation, the lower observed values were in silvopastoral zones compared to FS. The pasture biomass was most influenced by the trees during the summer.

Keywords: livestock-forest integration, radiation transmission, root water uptake

3.1 Introduction

Brazil is globally recognised as an important cattle producer. Around 215 million bovine heads (IBGE, 2020) are raised in grasslands that occupy 150 million hectares (IBGE, 2017). Despite the grasslands being the principal forage resource for the Brazilian herd, estimations point that pasture degradation occurs in 50 to 70% of all the pasture area (Dias Filho, 2011). Another issue associated with livestock production in Brazil is GHG emissions. Within the emission from the agricultural sector in 2016, 64.8% were accounted to bovine enteric fermentation (Azevedo et al., 2018; Seeg, 2018). Considering this context, a silvopastoral system could represent an opportunity to mitigate livestock environmental impact regarding the GHG emissions (Torres et al., 2017) as it is a more biodiverse and resilient agroecosystem than pasture monoculture. According to EMBRAPA (2016), 11.5 million hectares of pastureland in Brazil are integrated into other crops and/or silviculture, which represent a still low adoption of this type of livestock production when considering the growing body of evidence regarding the silvopastoral system benefits.

The presence of trees in the pasture has positive consequences compared to a treeless pasture. Silvopastoral systems compared with pasture mono-culture, have a better capacity to thrive facing water stress (Natarajan; Willey, 1986). That hydrological advantage may happen due to the superficial reduced runoff, enhancing water infiltration through the soil profile (Sanchez et al., 1997; Wallace, 2000). The microclimate under the tree canopy and the litter deposition from the trees reduce evapotranspiration rates (Tournebize, 1994; Pezzopane et al., 2015; Bosi et al., 2020), preserving water (Siriri et al., 2013) and increasing nutrient cycling (Menezes et al., 2002) in soil layers. The lower evapotranspiration rate under the tree canopy was the main factor responsible for the increased biomass of the grass growing under the trees rather than the same grass in open grasslands (Belsky et al., 1993).

Despite the ecological benefits that a silvopastoral system could promote, there is some evidence that the competition between trees and pasture for soil water during drought periods may impair pasture production (Dulormne et al., 2004). The competition for water depends on the depth of the arboreous root system concerning the herbaceous roots; even under drought, trees and pastures or crops may not compete for water due to difference in depth where each species uptake water (Gyenge et al., 2002). In some situations there may be a complementary roots distribution along with the soil layers, thus pasture and trees may explore different depths of the soil profile, hence reducing the chance of competition for water and nutrients (Fernandez

et al., 2008). Therefore, the risk of soil water competition within a silvopastoral system may take into account space and time dimensions.

Thus, our study aims to evaluate the Piatã palisade grass production and morphological characteristics under a silvopastoral system and an open pasture considering the microclimate and soil water content as multiple interacting factors. Also, we investigate the influence of tree roots on soil water dynamics.

3.2 Material and Methods

3.2.1 Study site

The experiment was carried out in São Carlos, São Paulo state, Brazil (latitude 22°01' S, longitude 47°53' W, alt 860 m), from April 2018 to May 2019. São Carlos climate is Cwa (Köppen) with a cool and dry season from April to September (average air temperature of 19.9°C and total rainfall of 250 mm), and a warm and wet season from October to March (average air temperature of 23.0°C and total rainfall of 1100 mm) (Alvares et al. 2013). The soil in the experimental area is an Oxisol with sandy loam texture and available water capacity between 100 and 110 mm at 1m depth. A full sun (FS) pasture and a silvopastoral (SP) area were used as experimental sites, with 3 ha for each system. The FS system was composed by *Urochloa* (syn. *Brachiaria*) *brizantha* (Hochst ex A. Rich.) Stapf cv. BRS Piatã, whereas the silvopastoral system was an adjacent area with the same forage grass cultivar, and rows of *Eucalyptus urograndis* (*Eucalyptus grandis* x *Eucalyptus urophylla*) of the GG100 clonal. A total of 333 trees ha⁻¹ were planted in April 2011 over the already established pasture, and arranged in simple rows in a near East-West orientation, with 15 m between rows and 2 m between trees in the row. In July 2016 half of the trees were thinned, leaving 116 trees ha⁻¹ with 15 m between rows and 4 m between trees. The experimental site was used before for other studies in different stages of the silvopastoral system development, before thinning (Pezzopane et al., 2020a; Bosi et al., 2020) and after thinning (Pezzopane et al., 2020b). To investigate the effect of the tree's presence in the pasture, we conducted an experiment analysing different zones within the observed paddocks. The FS was considered a pasture zone without the effect of trees. Different distances (SP1= 0.0m; SP2 = 3.75m; SP3 = 7.5m; SP4 = 11.25m) from the northern row of *Eucalyptus* trees in the silvopastoral system were considered zones under the trees' influence (Figure 1).

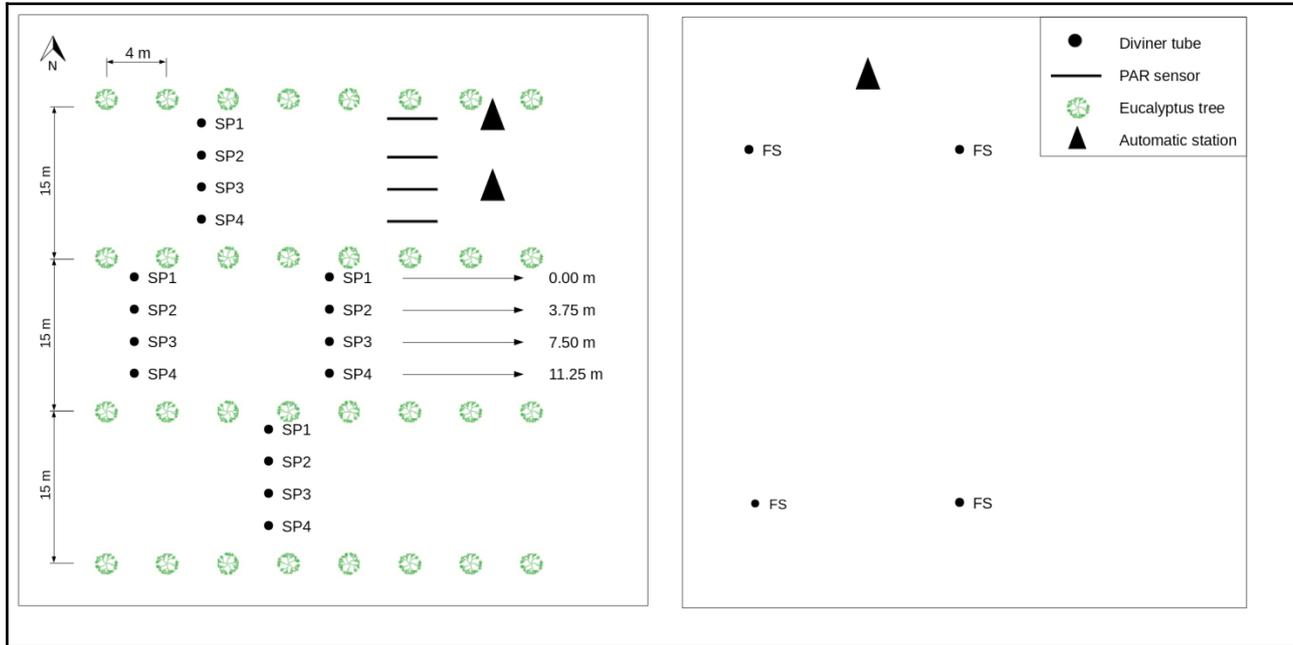


Figure 1. Schematic representation of the experimental site after thinning in 2016. On the left is the silvopastoral system with the four observed zones (SP1 = 0.00 m; SP2 = 3.75 m; SP3 = 7.50 m and SP4 = 11.25 m). On the right is the full sun (FS) pasture zone. In both figures, the diviner access tubes, the PAR sensors and the weather stations (P1 = 0.00 m; SP3 = 7.50 m and FS) are represented.

3.2.2 Weather measurements

Three weather stations were installed, one in the FS and two others in the silvopastoral system at positions SP1 and SP3. These weather stations measured wind speed, relative air humidity and air temperature continuously during the experiment period. The photosynthetically active radiation (PAR) was measured in all treatments using a linear quantum sensor (Apogee, Logan, UT, USA) in the silvopastoral zones and a single sensor in the FS. The sensors used to measure these variables were: ultrasonic anemometer (Windsonic, Gill, Lymington, Hampshire, UK), thermo-hygrometer (HC2-S3, Rotronic, Bassersdorf, Swiss). These sensors were connected to a datalogger (CR3000, Campbell Scientific, Logan, UT, USA), configured to log the data every 5 seconds and to record averages every 15 and 60 minutes. Daily averages, maximum and minimum air and soil temperatures and relative air humidity, average and maximum wind speed and total values of PAR, net radiation and soil heat flux were also recorded. The sensors were installed at 1.7 m height, except for the linear quantum sensors, which were installed at 0.6 m above the ground. Three rain gauges (TB4, Hydrological Services

Pty Ltd, Warwick Farm, NSW, Australia) were installed at 1.5 m height, being one in the open pasture and two in the silvopastoral system. The measurements have been taken at FS, SP1, and SP3, logging (CR3000, Campbell Scientific, Logan, UT, USA) total rainfall every 15 minutes, hourly and daily.

3.2.3 Soil moisture measurements

Soil moisture was measured with a portable capacitance probe (Diviner 2000, SENTEK Pty Ltd., Stepney, SA, Australia). There were 16 access tubes distributed in the field with four tubes for each zone (Figure 1). The soil water content was measured at least once a week at every 0.1 m until 1.0 m depth. The Diviner 2000 probe was calibrated with a soil type similar to the soil of the field experiment (da Cruz et al., 2020).

3.2.4 Pasture aboveground biomass

The rotational grazing was done with Canchim and Nelore beef cattle at a 30 days interval with a grazing period of six days. Between April 2018 and May 2019, we evaluated the pasture in 12 cycles (C1 to C12) in all five zones (FS, SP1, SP2, SP3, SP4) before grazing.

The pasture samples were taken with a 0.25 m² (0.5 x 0.5 m) quadrat at ground level. Every zone was sampled with four replicants. The pasture samples were weighed to obtain the fresh pasture weight. A subsample was taken and weighed after oven-dry at 60°C for 72 hours to calculate the dry mass (DM) percentage. Another subsample was used for morphological separation (leaf, stem and dead material). The leaf amount separated was scanned by the leaf area meter Li-Cor 3100 (Li-Cor, Lincoln, NE, USA) to determine the leaf area index (LAI) and specific leaf area (SLA).

3.2.5 Root system biomass and carbon isotopic analysis

Soil cores were collected with a cylindrical probe of 8.95 cm diameter to evaluate the root mass distribution among the treatments. The soil cores were taken from every 0.2 m until 1.0 m depth. The soil samples were washed over a sieve with a 1 mm mesh size to separate roots from the soil. Then roots were dried at 60°C for 72 hours and weighed. The roots were evaluated in July 2018 and in March 2019.

A mass spectrophotometer was used to determine the carbon isotopes ratio ($^{13}\text{C}/^{12}\text{C}$) in the root samples, and this ratio was used as a parameter to estimate the proportion of Eucalyptus and Brachiaria root mass through the soil layers. This sort of analysis follows an international pattern and the result is expressed by the difference of $\delta^{13}\text{C}$ to the pattern. For the carbon isotopes, the pattern used is a calcareous rock called Pee Dee Belemnite (PDB). The isotopic composition of plants compared to the PDB is determined by equation (1) (Smith; Epstein, 1971).

$$\delta^{13}\text{C}_{\text{pdb}}(\text{‰}) = \left(\frac{R_{\text{amostra}} - R_{\text{pdb}}}{R_{\text{pdb}}} \right) \times 1,000 \quad (1)$$

The carbon isotopic composition between species with different cycles, C3 and C4 are different (Farquhar et al., 1989). The Rubisco enzyme shows more affinity to CO_2 and in general, avoids the heavier carbon isotope ^{13}C to the ^{12}C . Thus, plants with C3 cycle accumulate less ^{13}C than C4 plants (Smith; Epstein, 1971). To calculate the proportion of C3 and C4 roots in each sample we used the same equations described by Moreira et al., 2000, and considered $\delta^{13}\text{C}$ values of -12.01 (PDB) for Piatã palisade grass and -27.42 (PDB) for the Eucalyptus.

3.2.6 Statistical analysis

The experimental design was completely randomised with repeated measures through time, considering each measure as a pseudoreplication. A Multiple Factor Analysis (MFA) investigated the characteristics of pasture growth and morphology, soil water dynamics and microclimate variables within the silvopastoral system and the full sun. The MFA was designed to separate the variables into four groups. Group 1 = qualitative (descriptive variables), Group 2 = pasture biomass and morphology, Group 3 = soil water content and Group 4 = microclimate variables (Table 1). The objective of this analysis was to find the most important relations between the variables. The analyses were performed in R version 3.6.3 (R Core Team, 2020) using the package FactoMineR (Lê et al., 2008) to run the MFA.

Table 1. Groups of variables distributed into groups used for the MFA.

Group name	Variable name	Quantitative measuring units	Qualitative descriptive categories
Identity	Cycle		C1 to C12
	Zone		FS, SP1, SP2, SP3, SP4
	Season		summer, autumn, winter, spring
Pasture	total mass	kg ha ⁻¹	
	live mass	kg ha ⁻¹	
	leaf	kg ha ⁻¹	
	stem	kg ha ⁻¹	
	dead mass	kg ha ⁻¹	
	LAI	m ² m ⁻²	
	SLA	cm ² g ⁻¹	
	height	cm	
Soil Water	leaf:stem	%	
	0 to 30 cm		
	30 to 60 cm	mm mm ⁻¹	
Weather	60 to 100 cm		
	PAR	MJ m ⁻² cycle ⁻¹	
	T mean	°C (cycle average)	
	rain	mm cycle ⁻¹	
	wind speed	m s ⁻¹ (cycle average)	
	relative air humidity	% (cycle average)	

3.3 Results

The MFA showed that soil water variables were correlated to relative air humidity (%) and accumulated rainfall in each pasture growth cycle. The mean air temperature and accumulated PAR were correlated with pasture height, leaf mass and LAI. Dead material had a negative correlation with leaf:stem ratio and SLA. Live biomass and stem are closely correlated. The first two dimensions (Dim1 and Dim2) explained 67% of data variability (Figure 2).

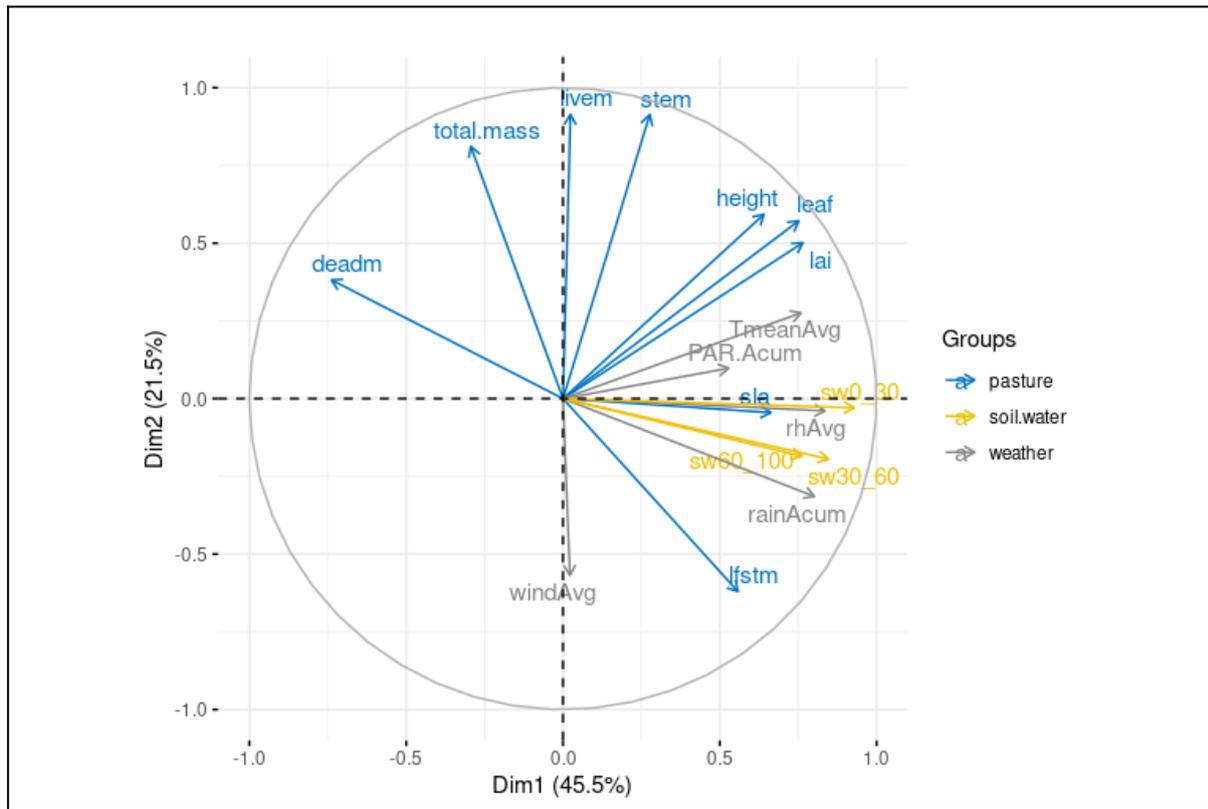


Figure 2. MFA biplot. The colour of arrows separate the variables into groups; arrows with small angles within are highly correlated, arrows with large angles have a negative correlation and arrows with angles close to 90° are non-correlated. The arrow's length represents the influence of each variable on data variability; longer lengths represent greater influence.

The MFA factor map, when organised according to the season distribution, showed distinct ellipses formation, which denotes the season influence over the data variability. The winter had the smallest ellipsis and its centre is close to dimension one axis. The autumn had its ellipsis close to the winter one and its centre is positive for dimension two and negative for dimension one. The summer ellipsis had its centre positive for both dimensions. The spring ellipsis had its centre negative for dimension two and positive for dimension one (Figure 3).

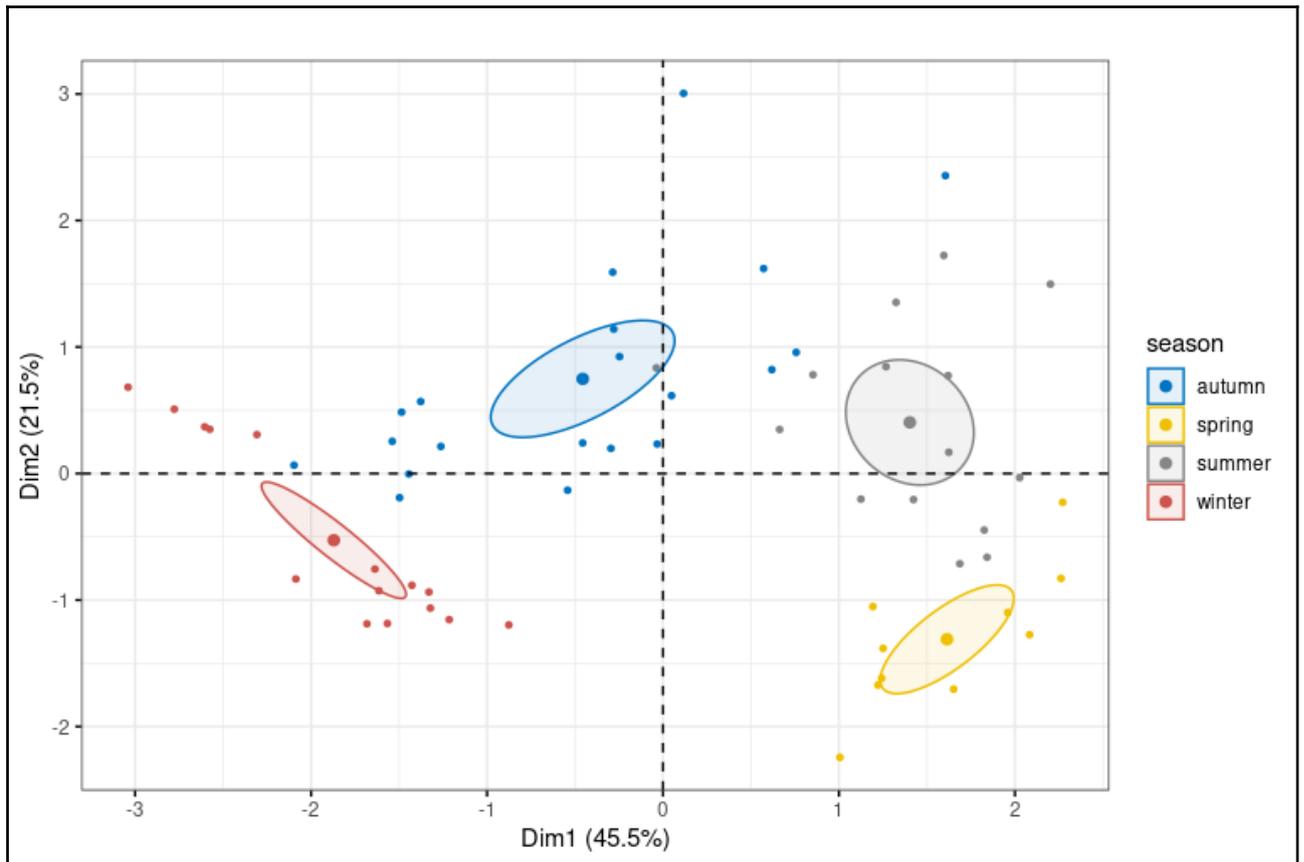


Figure 3. Ellipses according to the season, distributed across dimensions 1 and 2. Each colour represents one season. Blue for autumn, yellow for spring, grey for summer and red for winter. These ellipses were generated from the MFA considering all observed zones (FS, SP1, SP2, SP3, SP4).

The factor map also could be organised according to the observed zones. The most distinct group of observed variables was the FS with its centre located at the positive side for Dim1 and Dim2, whereas the SP1 had its ellipses centre at the opposite quadrant, negative for the first two evaluated dimensions. The other observed zones had their ellipses centre close to each other, which represent a closer relationship among those zones (Figure 4).

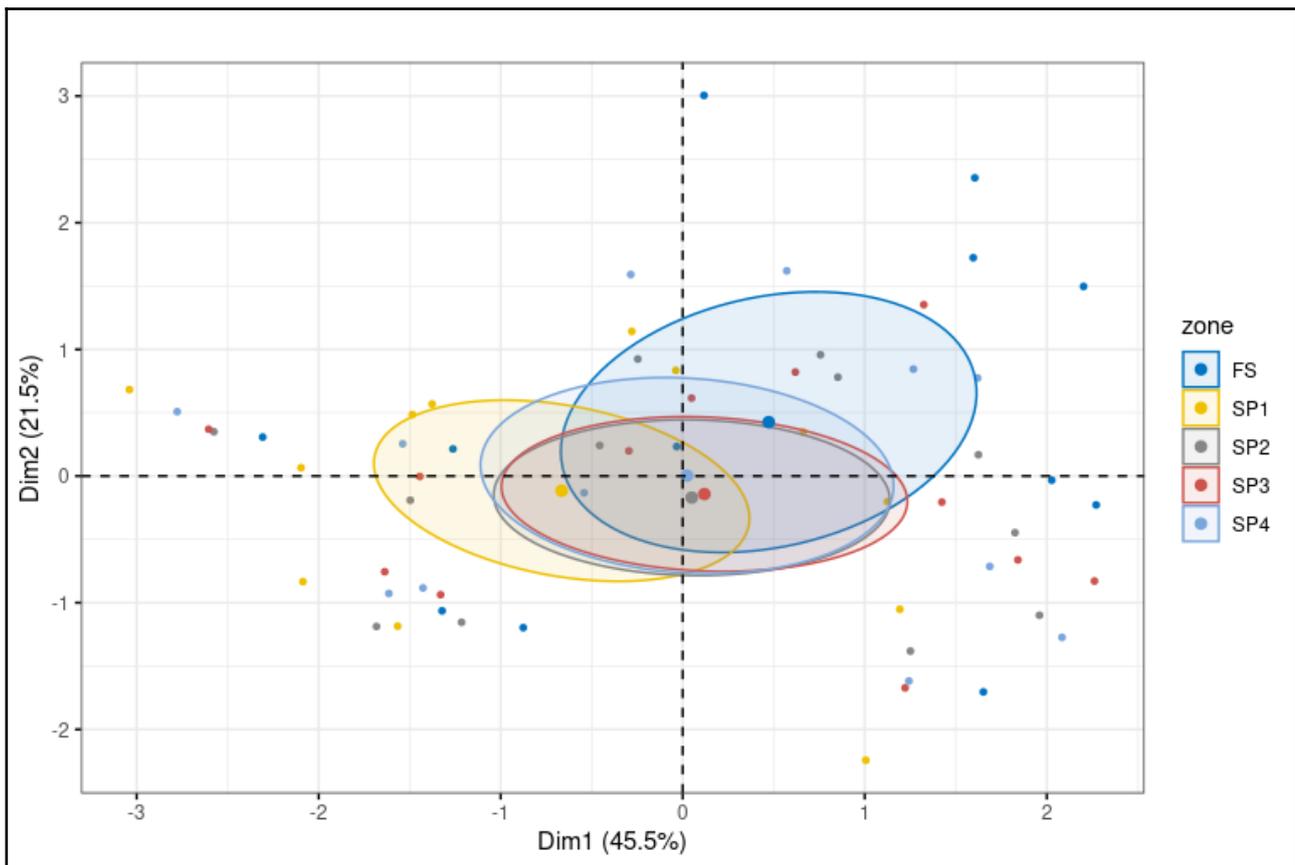


Figure 4. Ellipses according to the observed zone, distributed across dimensions 1 and 2. Each colour represents one zone. Dark blue for FS, yellow for SP1, grey for SP2, red for SP3 and light blue for SP4. These ellipses were generated from the MFA considering all observed zones (FS, SP1, SP2, SP3, SP4).

There is also a relation between the PAR and the observed zones. Under the zones far from the trees (SP2 and SP3) PAR was higher when compared to the other silvopastoral zones during the summer. During the other seasons of the year, the percentage of PAR reduction regarding the FS measurements wasn't different enough to be noted (Figure 5).

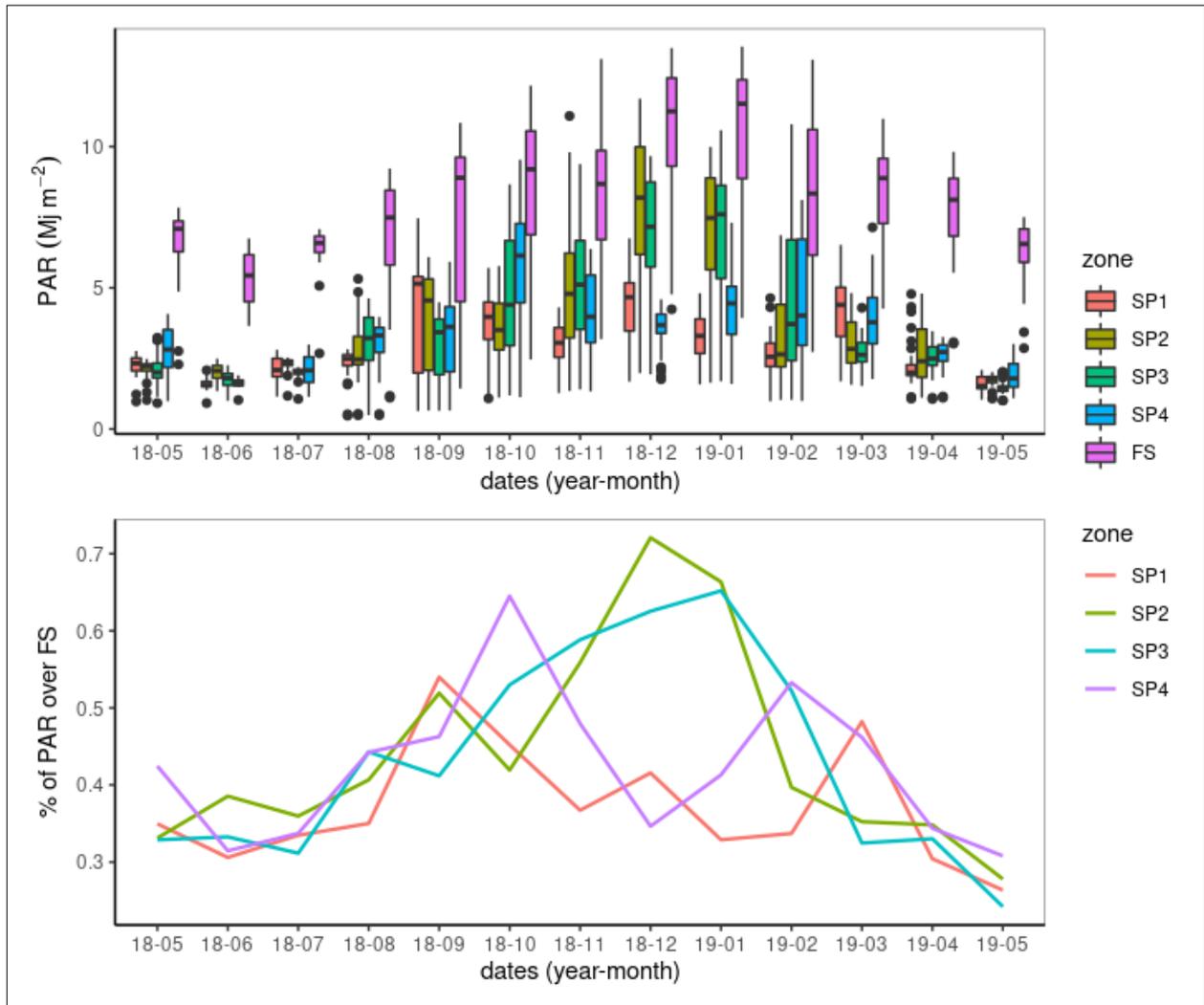


Figure 5. The top graph is a boxplot regarding the PAR (Mj m⁻²) according to the cycle and observed zones. At the bottom, there is a timeline graph representing the percentage of PAR regarding the silvopastoral zones to FS.

The SP1 zone was the driest one when compared with the other zones, especially at deeper layers (60 to 100 cm) and after September 2018 (Figure 6). Tree canopies must have intercepted part of the rain, thus representing a reduction in the effective rainfall collected by the rain gauges in the silvopastoral zones compared to the FS zone (Figure 6). However, it's important to report that during the rainfall recording we noticed some issues in the rain gauges. From November 4th to 26th of 2018 the rain gauge located at SP1 did not register the rain, which distorted the measurements in the cycle C7. From March 20th to April 4th of 2019 the rain gauge located at SP3 zone did not register the rain, which distorted the measurements in the cycle C11.

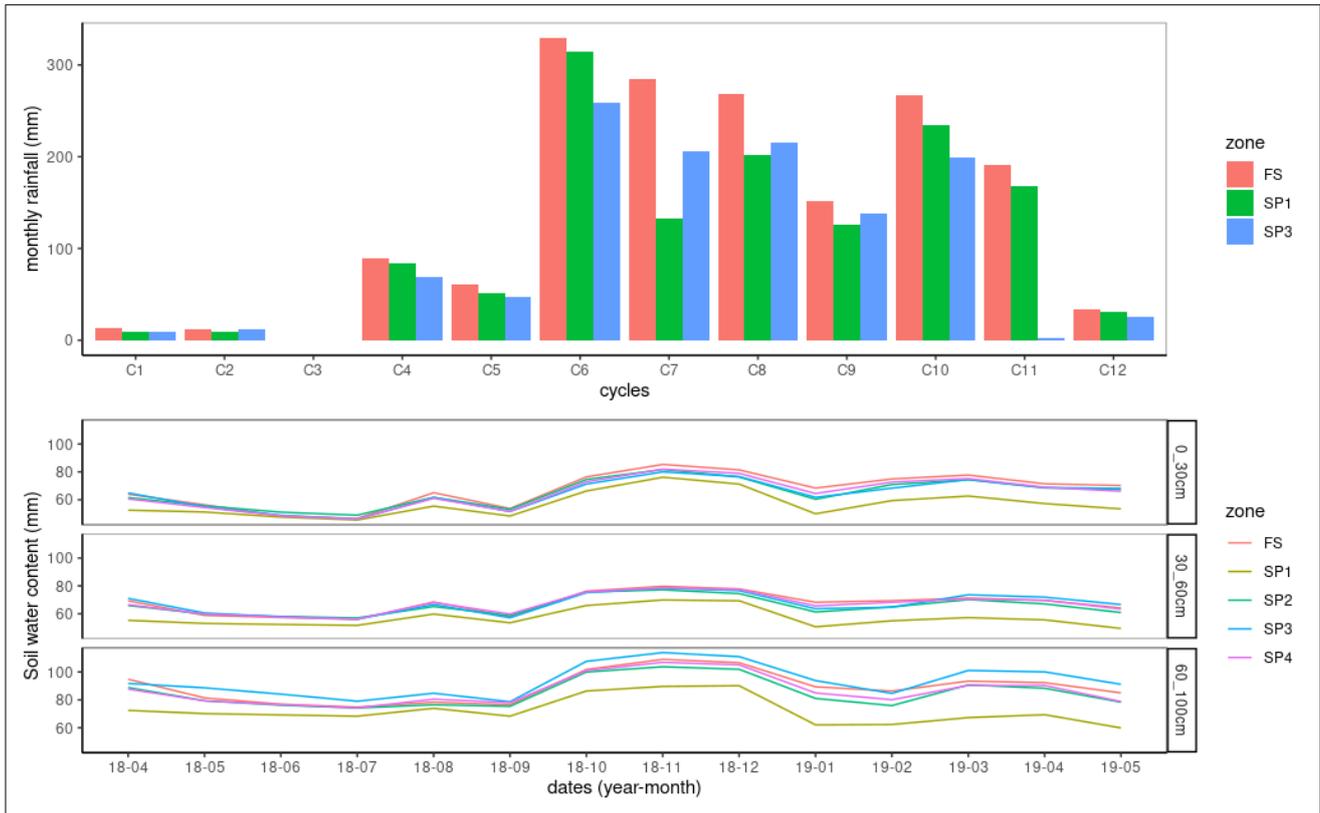


Figure 6. The top graph is the monthly accumulated rainfall (mm) according to each observed zone (FS, SP1, SP3), represented by bars with different colours. The bottom graph is the soil water content (mm) according to the observed zones (lines with different colours) distributed into the soil profile from 0 to 30 cm, 30 to 60 cm and 60 to 100 cm. The soil water content is the monthly average for the determined zone.

The pasture live biomass was affected mainly by the season. The main differences observed among the zones occurred during the summer and latter autumn, also during these seasons there is greater variability in the data compared with the previous seasons (Figure 7).

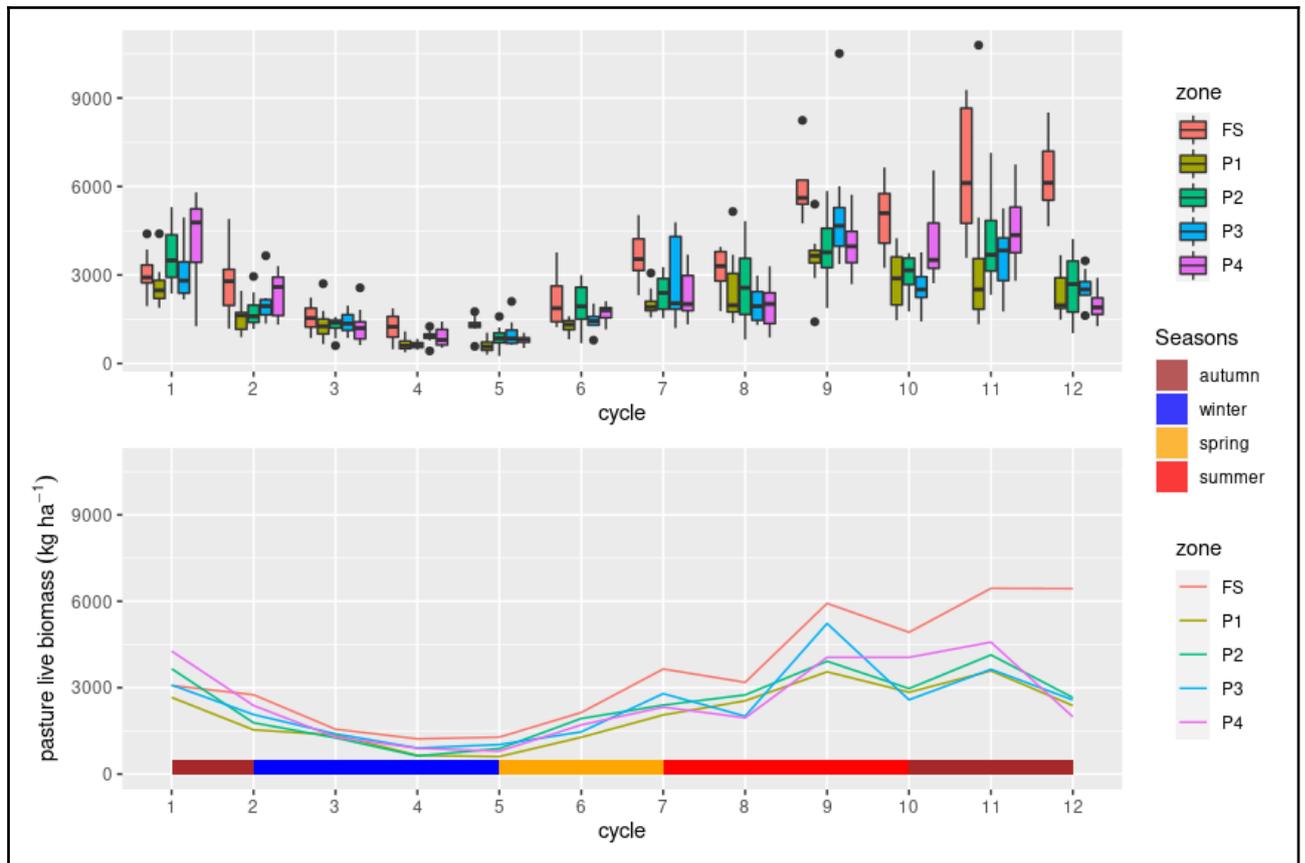


Figure 7. The top graph is a boxplot regarding the pasture biomass (kg ha^{-1}) according to the cycle and observed zone. At the bottom, there is a timeline graph of the pasture biomass (kg ha^{-1}) according to the cycles with season highlights.

The percentage of tree roots in the SP1 zone is approximately double when compared to the other zones during the summer. Even during the winter, the SP1 zone showed a greater proportion of tree roots concerning the SP3 and SP2 and had similar values compared to the SP4 (Figure 8).

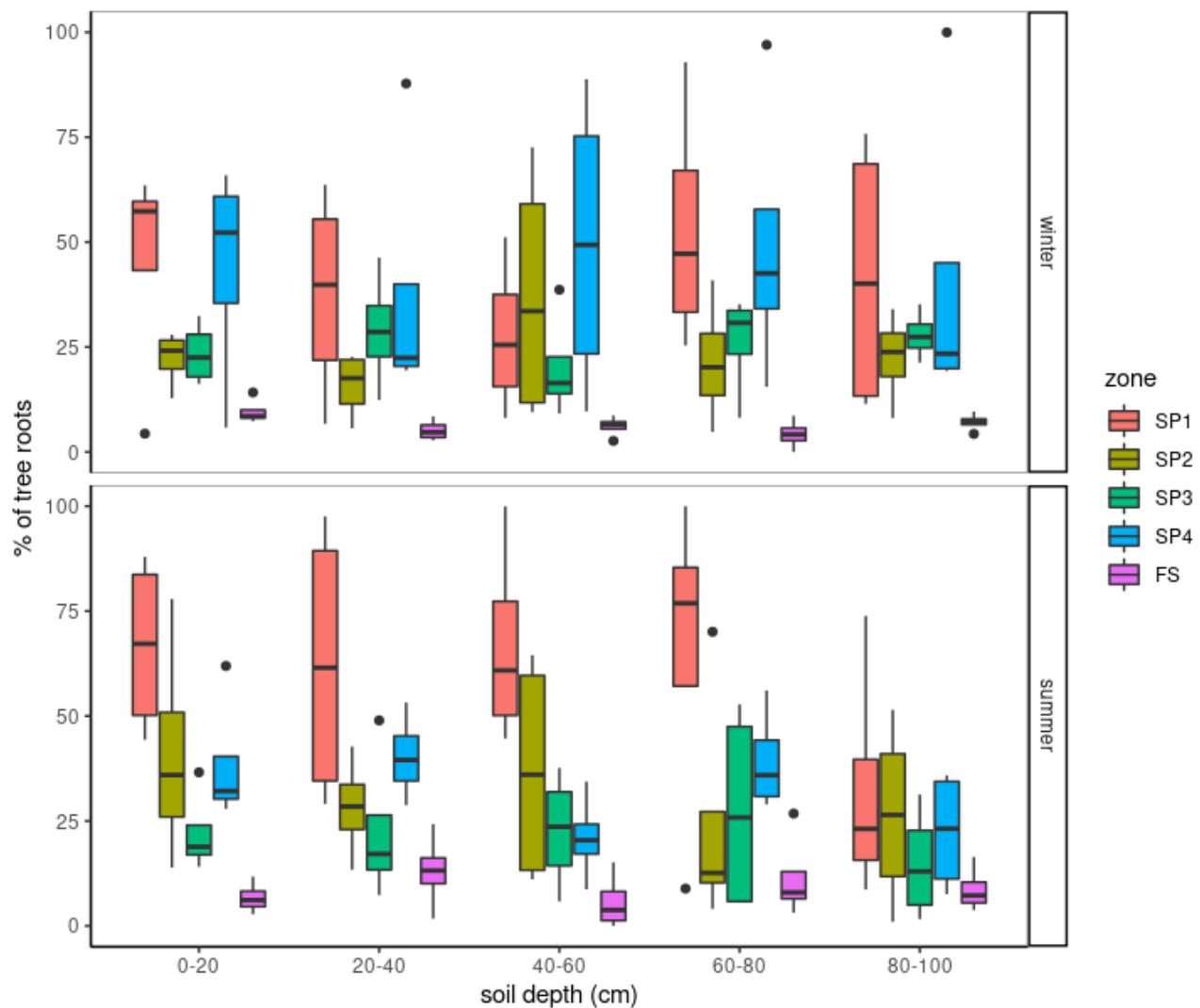


Figure 8. The Eucalyptus root percentage to the total root mass (grass + trees). Each coloured box represents one of the observed zones (SP1, SP2, SP3, SP4, FS). The percentage of tree roots are distributed along with the soil profile by 20 cm layers until 100 cm. This data was collected in two periods, winter and summer.

3.4 Discussion

3.4.1 Multiple Factor Analysis

The exploratory analysis performed by the MFA showed important relations between the group of variables. PAR and temperature were closely correlated with pasture LAI and leaf mass. Soil water was less correlated to pasture variables, which demonstrates the stronger influence of PAR over pasture production. The soil water was also related to the rainfall.

The size and the shape of the confidence ellipsis regarding the season and the observed zones highlighted the dataset overdispersion, which is commonly found in ecological studies (Harrison, 2014). The segregation of the season ellipsis (Figure 3) and the zone ellipsis overlapping (Figure 4) is evidence that the season had more influence on the data variability than the observed zones. Although winter and spring showed less variability than summer and autumn (Figure 3), that must be explained by the slower pasture growth (Figure 7) and hydrological dynamics (Figure 6) during winter and spring compared to summer and autumn.

3.4.2 PAR transmission

The most relevant differences in PAR transmission occurred during the summer where the PAR transmission for zones SP2 and SP3 were approximately double than the observed in SP1 and SP4 (Figure 5). While the SP2 and SP3 had their highest values of PAR transmission during the summer, SP1 and SP4 had theirs during spring and autumn. It could be explained by row orientation (east-west) and solar declination throughout the year.

In the same area where the present study was conducted, other experiments happened before. One of them was conducted between the years 2013/2014 and 2014/2015. Despite the differences in tree population, previous study had double the trees, some relationships between the season and pasture production were the same as in the present study. For example during winter, because of drought stress, differences between the full sun and shaded areas were minimal (Pezzopane et al., 2020a). We observed the same situation in our study (Figure 7).

Before thinning the trees, PAR transmissions between the years 2013 and 2014 presented the maximum value of 70 % in January and a minimum of 30 % in May and June; between the years 2014 and 2015 was observed a reduction in PAR transmission by 10% in both maximum and minimum values (Pezzopane et al., 2020a). The authors attributed these PAR transmission reductions to tree height, which increased 6.9 m from October 2013 to April 2015. Also, they observed the same fluctuations throughout the year caused by the East-West orientation of tree rows.

After thinning the trees, PAR transmission varied from 55.6% to 73.1% among the four observed zones with lower values in autumn and winter (February 2017 to February 2018); the eucalyptus trees were about 28.6 m high during these PAR evaluations (Pezzopane et al., 2020b). That modification in PAR along the years shows the dynamism of the system and the necessity of management of trees to regulate the amount of shade projected on the grass. Thus, pruning (Devkota et al., 2009) or thinning (Pezzopane et al., 2021) should be a strategy to avoid the pasture production losses caused by the excess of shade.

Thinning and pruning management must be done considering PAR transmission and not the tree population or the tree height, as PAR transmission must be different depending on the system arrangement and latitude. Comparing our study with other similar silvopastoral studies, we noticed some differences regarding PAR transmission, which must be explained by the differences in tree arrangement and latitude where the silvopastoral system is placed.

Nascimento et al. (2019) studying a silvopastoral system with *Eucalyptus urograndis* planted in East-West orientation, arranged in groves with three rows each, 30 m between groves, and 3 m of intra-row spacing, reported reductions of PAR transmission in relation to full sun of

~ 7, 23, and 38 % at 15, 7.5, and 4 m distances from the grove, respectively. When this system was evaluated the trees were around four years old and 18 m tall. Thus, tree arrangement is a determining factor concerning the PAR transmission within a silvopastoral system.

3.4.3 Soil water content

In a previous study in the same area, Bosi et al., 2020 evaluated soil water of full sun and the silvopastoral system using the same access plastic tubes and the same type of capacitance probe. They found similar results, although at that time, July 2013 to June 2016, the tree population was double of that in present study. They also found that soil water in the zone close to the trees (SP1) was different from the other zones, being drier than the central zone (SP3), mainly because of the faster water uptake close to the trees (Bosi et al., 2020). They also observed lower soil water content at FS than at SP3 and considered as the most determinant factor the highest pasture evapotranspiration due to higher solar radiation and wind speed in this zone.

In another study conducted in the same area after the thinning, during the driest period of the experiment (between May and September 2017) SP3 had higher soil water content than FS and SP1, which had lower values (Pezzopane et al., 2020b). The authors pointed at higher water consumption in the zone close to the trees due to water uptake by the tree roots. After high rainfall, they observed that the soil moisture becomes similar between all assessed zones (Pezzopane et al., 2020b). However, in the present study, we observed a slightly different pattern regarding soil moisture.

The main differences in soil water content were observed during summer and autumn at deeper layers (60 to 100 cm) (Figure 6). That indicates an alteration in the hydrological dynamics compared with the previous studies. Probably the difference between SP1 and the other zones be explained by the faster soil water drainage, which was also observed by Pezzopane et al. (2015), in a silvopastoral system with *Urochloa decumbens* and Brazilian native trees arranged in the North-South orientation 17 m apart. They suggested that the tree roots increased soil aeration and decreased the soil water retention.

There were observed differences between the zones regarding the rainfall recorded in the rain gauges, mainly with less rain registered in the SP zones compared with the FS zone (Figure 6). One possible explanation for those differences in the rainfall is the interception loss, which is the evaporation of the water stored in the tree canopy (Rutter et al., 1975). Even though the interception of rain in the canopy of trees can represent losses by evaporation, part of the

water stored in the canopy may fall to the ground due to the intensity of the rain, wind speed and direction and architecture of the canopy (Xiao et al., 2000). That may explain why during the cycles C6 and C10 the accumulated rainfall in SP1 was greater than in SP3 (Figure 6), especially when there is rainfall events with high wind speed and perpendicular direction in relation to the tree rows (Bosi et al., 2020).

Therefore, the soil water dynamics within a silvopastoral system goes beyond tree population and age. Similar studies also found different relationships between shaded areas and soil moisture. Some found greater soil moisture in more shaded areas, especially in the 0 to 10 cm layer (Nascimento et al., 2019), others observed a decrease in soil water content in shaded areas, which may have been an outcome of greater development of lateral roots of clonal tree plants (Gautam et al. 2003).

3.4.4 Pasture biomass

Tropical pastures such as Brachiarias and Panicums can adapt to a certain level of light restriction, although growth limitations may occur when shade levels are greater than 35 to 40% (Paciullo et al., 2007; Paciullo et al., 2017; Lima et al., 2019). PAR transmission around 60% represented reductions in the forage accumulation (Pontes et al., 2016; Pezzopane et al. 2020a).

Regarding PAR transmission, the most restrictive zone was SP1 that varied from 30 % to 50 %, and the less restrictive zones were SP2 and SP3 (Figure 5). However, no differences were observed on pasture production between the SP zones. During the late spring and summer, the FS zone pasture production was greater than the SP zones (Figure 7), thus demonstrating that the pasture growth is determined by light availability when soil moisture and nutrients were not limiting factors (Pezzopane et al., 2020a).

3.4.5 Tree root influence

The presence of Eucalyptus roots was higher in the zone close to the tree row (SP1), which could represent a risk of competition for soil water within 1.0 m depth (Figure 8). Although, the presence of tree roots in the soil profile doesn't imply water uptake competition (Ehleringer; Dawson, 1992), and the extraction of nutrients is not necessarily proportional to the abundance of roots within a soil layer. Instead, the drier condition in SP1 could be a consequence of an increase in the water infiltration due to soil physical properties modifications

(Vasquez et al., 2020), such as the macropores increase as a function of tree tick root decomposition (Bieluczyk, 2018).

In the period of the present experiment the Eucalyptus trees were eight years old, thus we assume that those trees are capable of extracting water from above 10 m depth (Laclau et al., 2013). *E. grandis* are recognised for its fast exploration of deep soil layers with some fine roots observed at 6 m depth after 12 months of growth, and deepest roots founded at 9.5 m depth in 1.5 years of age (Christina et al., 2011). Trees with deep root systems are believed to represent a low risk of water competition when grasses have shallow roots (Breman; Kessler, 1997; Lehmann et al., 1998).

Despite the FS zone being a treeless area, a small proportion of roots were identified as being Eucalyptus roots. That happens because the technique of carbon isotopes analysis is capable of identifying the proportion of carbon $^{12}\text{C}/^{13}\text{C}$ in the plant material, thus the presence of C3 plants in the FS zone (e.g. weeds) explains why the pasture roots are not 100% (Figure 8).

The observed zones (SP1, SP2, SP3, SP4 and FS) could be interpreted as environments with levels of available soil water and PAR which is more or less suitable for pasture production. Close to the trees (SP1 and SP4), there was less solar radiation incidence, less soil water content (mainly SP1) and a greater presence of tree roots (SP1). Those factors combined could be a reasonable explanation for the FS higher pasture productivity compared to the silvopastoral zones, especially SP1.

3.5 Conclusions

The trees influenced PAR and soil water differently according to the season and the trees proximity. The reduced PAR transmission on the understory of a silvopastoral system may impair pasture production when water and temperature were not limiting factors. The risk of pasture productivity losses is an authentic concern which imposes urgency in tree management such as pruning and thinning to prevent the excess of shade over the grass. The drier condition of soil layers until 1.0 m depth close to the trees may be explained by the higher proportion of Eucalyptus roots. Although, soil water competition is at low risk in a silvopastoral system with eight years old Eucalyptus trees. The question to be addressed regarding the silvopastoral systems is whether and when the trees' presence negatively impacts pasture production as a consequence of resource competition.

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4 SILVOPASTORAL SYSTEM PASTURE GROWTH SIMULATION AND SENSITIVITY ANALYSIS USING APSIM-TROPICAL PASTURE AND SLURP MODELS

ABSTRACT

Silvopastoral systems integrate trees, pastures and animals aiming for sustainable livestock production. This kind of agroecosystem tends to be more biodiverse, which enhances ecological and biophysical interactions amongst its components (animals, pasture, trees, soil, atmosphere). Despite the benefits (animal welfare, soil water infiltration, carbon stocks, etc), there are concerns upon the negative effects of trees on pasture growth caused by the lack of light underneath the trees canopy and the soil water competition under drought conditions. The Agricultural Production Systems Simulator (APSIM) has shown accuracy to simulate crops and pastures within agroforestry systems. Thus, our study aimed to calibrate and validate the APSIM-Tropical Pasture and APSIM-Slurp model combination to simulate Piatã palisade grass growth under a silvopastoral system and analyse its sensitivity concerning nitrogen fertilisation, grazing management and light and water competition. The data used for calibration and validation of APSIM-Slurp and APSIM-Tropical Pasture models were collected in two periods (2014 – 2016 and 2018 – 2019) from a silvopastoral system located at Southeastern Brazil. The APSIM-Slurp model simulated well the light interception ($R^2 = 0.64$ NSE = 0.60). APSIM-Tropical Pasture model showed a good performance to simulate pasture biomass ($R^2 = 0.90$ NSE = 0.72), leaf ($R^2 = 0.82$ NSE = 0.44), stem ($R^2 = 0.82$ NSE = 0.75) and an acceptable performance for pasture leaf area index ($R^2 = 0.76$ NSE = 0.58). Considering the model combination accurate, we performed a multifactorial virtual experiment to simulate the pasture biomass (P) using as input 39 years of weather data from the same location of the field experiment. These factorial simulations considered as factors nitrogen fertilisation (N), tree's canopy leaf area index (L), tree's root water extraction capacity (KL) and grazing severity using pasture stubble mass (kg ha^{-1}) as a parameter (G). We performed a sensitivity analysis using linear regression with the pasture biomass as a response to a combination of factors ($P = N \times L \times KL \times G$). The sensitivity analysis showed that the combination of APSIM-Tropical Pasture and APSIM-Slurp models was sensible to variations among the factors described above, which indicates a great potential for decision making upon silvopastoral system design.

Keywords: model optimisation, livestock-forest integration, solar declination.

4.1 Introduction

The silvopastoral system combines grass, trees, and animals in the same area at the same time. Such combination could improve animal welfare due to a shaded environment (Schutz et al, 2010; Pezzopane et al, 2019), and influence the litter dynamics (Wallace, 2000), soil moisture and nutrients (Sanchez et al., 1997), which contributes to nutrient cycling in these systems (Menezes et al., 2002). Although, the presence of trees into pastureland could impair the pasture biomass due light, nutrients, and water competition between plants, which is a relevant concern among scientists dedicated to silvopastoral systems studies (Rao et al., 1998).

Changes in microclimate are often observed in silvopastoral systems. When trees are arranged in rows, wind speed and photosynthetic active radiation (PAR) are reduced and that promotes changes in air temperature and humidity underneath the tree canopy (Pezzopane et al., 2015). The microclimate under the tree canopy and the organic material arising from the trees reduce evapotranspiration rates, which help to keep water in the soil profile (Siriri et al., 2013).

A silvopastoral system could be designed in a wide range of configurations regarding its botanical composition, trees arrangement and pasture management. Indeed, there is no obvious decision among the myriad of possible combinations and it's hard to predict the outcome trade-offs. While the herbaceous component could be managed with short term planning, the same is not true for the arboreous one. Such a complex system needs an effort on what concerns planning and decision making tied to the main objectives of the agricultural system.

Silvopastoral systems are more complex to be modelled when compared to pasture monoculture. One of the major challenges is how to model the interactions between grass and trees, which are subject to influences from a wide range of combinations of tree types and grass species, soil types, tree arrangements and climate conditions. Models that simulate with good performance the availability of solar radiation for pasture photosynthesis are an important tool for silvopastoral planning.

However, some progress has been made in the simulation of tropical silvopastoral systems. The Agricultural Production Systems Simulator (APSIM) is an open-source platform that can combine different modules to produce precise and accurate predictions. It also allows contributions to source code development and performance of the model (Holzworth et al., 2014).

APSIM has been used to simulate agroforestry systems where trees were windbreaks for crops (Huth et al, 2002), where maize growth is influenced by *Gliricidia* (*Gliricidia sepium*,

Jacquín) trees (Smethurst et al, 2017), with reliable simulations of maize productivity under up to 50% shading (Dilla et al., 2018). The APSIM-Tropical Pasture model, has been used to simulate Piatã palisadegrass (Bosi, 2017) and Marandu palisadegrass (Gomes et al., 2020) under a silvopastoral system with Eucalyptus. The Plant Modelling Framework (PMF), in APSIM Next Generation allows the interaction of different models in one simulation (Brown et al, 2014).

One of the biggest challenges in modelling agroforestry systems lays on local calibrations according to the system design. However, the use of models could take place complementary to field experiments which are usually limited to edaphic and climatic conditions (Probert et al., 1998). The possibility to simulate a wider range of silvopastoral configuration compared to a field experiment might broaden the options to optimise the system, hence increasing the pasture biomass accumulation. The major objective of our study was to calibrate and validate the APSIM-Tropical Pasture and APSIM-Slurp models to simulate Piatã palisadegrass under a silvopastoral system and analyse its sensibility in relation to nitrogen fertilisation, grazing management, light and water competition. Our specific objectives were: (a) calibrate and validate the APSIM-Slurp model to simulate the intercepted solar radiation by Eucalyptus rows in a silvopastoral system; (b) analyse the performance of APSIM-Tropical Pasture model to simulate Piatã palisadegrass biomass and its morphological components in a silvopastoral system under rotational stocking; (c) analyse the sensibility of APSIM-Tropical Pasture to nitrogen, grazing and resource competition.

4.2 Material and Methods

4.2.1 Field data

The observed data comes from a silvopastoral system area located in São Carlos (São Paulo State), Southeast Brazil (latitude 22° 01' S, longitude 47°53' W, alt 860 m). The climate is a Cwa (Köppen) with a cool and dry season, from April to September (average air temperature of 19.9°C and total rainfall of 250 mm), and another warm and wet season, from October to March (average air temperature of 23.0°C and total rainfall of 1100 mm) (Alvares et al., 2013). The soil is an Oxisol with sandy loam texture. The data were collected in two periods, from December 2014 to May 2016 (Period 1) and from April 2018 to May 2019 (Period 2). Nitrogen was applied as urea during the wet season using an application rate of 100 kg ha⁻¹ with five applications in 2013 and 2014, three in 2015, one in 2016 and 2017, two in 2018 and no application for 2019.

The silvopastoral system was composed by *Brachiaria* (syn. *Urochloa*) *brizantha* (Hochst. ex A. Rich.) Stapf ‘BRS Piatã’ and *Eucalyptus urograndis* (*Eucalyptus grandis* x *Eucalyptus urophylla*). The *Eucalyptus* seedlings were transplanted in April 2011 in an East-West orientation, arranged in single rows with 15 m between rows and 2 m between trees (333 trees ha⁻¹). In July 2016 half of the trees were thinned, leaving 4 m between trees (167 trees ha⁻¹). The silvopastoral system was managed at rotational stocking with beef cattle at a 30 days interval with six days of paddock occupation. Data assessments were done at distances of 0.00 m (SP1); 3.75 m (SP2); 7.50 m (SP3) and 11.25 m (SP4) from the North row of trees ([Figure 1](#)).

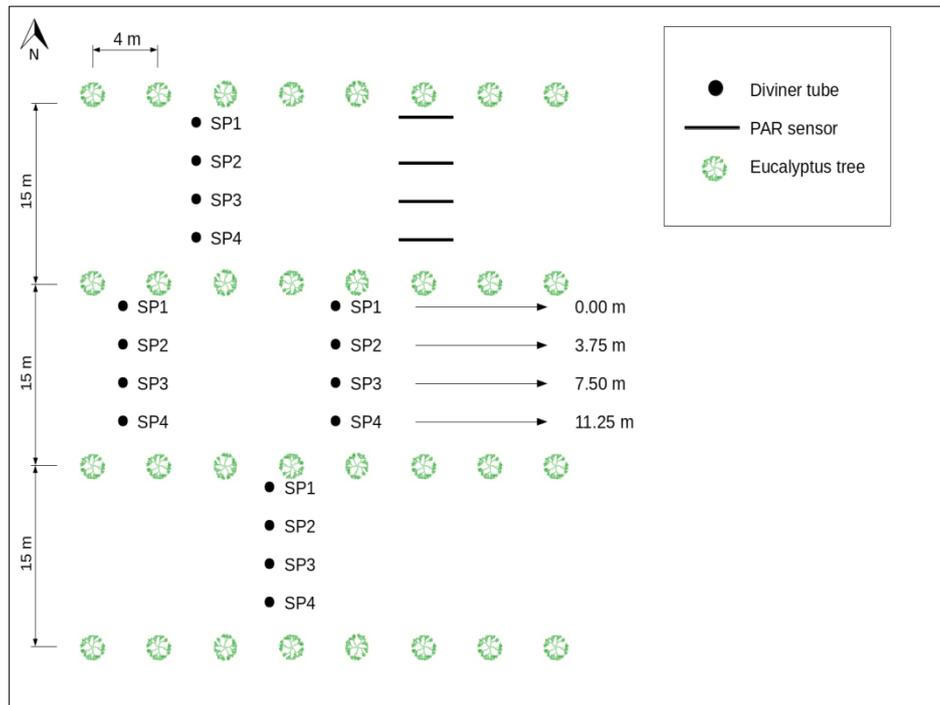


Figure 1: Experimental area scheme representing the tree's row arrangement (after thinning in 2016), zones of pasture sample collection, diviner access tubes and PAR sensors (SP1 = 0.00 m; SP2 = 3.75 m; SP3 = 7.50 m and SP4 = 11.25 m from the North row of trees).

4.2.2 Weather data

The weather data is based on daily records from 1980 to 2019 of global solar radiation (MJ m⁻² d⁻¹), rainfall (mm), maximum and minimum air temperatures (°C) ([Figure 2](#)). Weather variables, further used as input for the simulations, were obtained from different sources according to the period. Data from 1980 to 2009 comes from Xavier et al. (2016), and data from 2010 to 2019 comes from an automatic weather station located at Embrapa Pecuária Sudeste, approximately 1500 m from the experimental field.

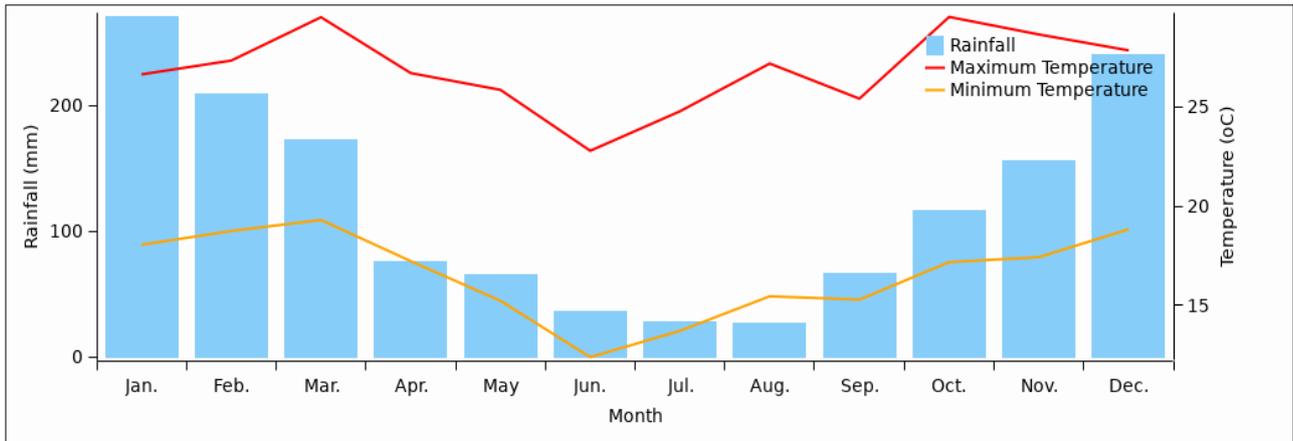


Figure 2: Weather data time series from 1980 to 2019 for São Carlos, São Paulo, Brazil. Blue bars are the average of accumulated rainfall (mm) in each month, the red line is the monthly average of maximum temperature (°C), the yellow line is the monthly average of minimum temperature (°C).

4.2.3 Photosynthetically active radiation

The photosynthetically active radiation (PAR) was measured in all observed zones at a single stationary point. Inside the silvopastoral system, linear quantum sensors (Apogee, Logan, UT, USA) were installed at 0.6 m above the ground at each distance from the Northern Eucalyptus row ([Figure 1](#)). In the area outside of the silvopastoral system, PAR was measured at a single point using a quantum sensor. Those sensors were connected to a data logger (CR3000, Campbell Scientific, Logan, UT, USA), configured to log the data for daily total values of PAR.

4.2.4 Volumetric soil water content

Soil moisture was measured with a portable capacitance probe (Diviner 2000, SENTEK Pty Ltd., Stepney, SA, Australia). There were 16 access tubes distributed in the field with four tubes for each zone ([Figure 1](#)). The soil water content was measured at least once a week at every 0.1 m until 1.0 m depth. The Diviner 2000 probe was calibrated with a soil type similar to the soil of the field experiment (da Cruz et al., 2020).

4.2.5 Pasture biomass assessment

The pasture biomass, its morphological components (leaf, stem and dead material), leaf area index (LAI) and specific leaf area (SLA) were evaluated in all four zones (SP1, SP2, SP3, SP4). Samples were cut with a 0.25 m² (0.5 x 0.5 m) quadrat. Every zone was sampled with four

replicants and each replicant had two subsamples. Subsamples were weighed to obtain the fresh pasture weight, then every pair of subsamples were homogeneously mixed and two parcels were separated. One of the parcels was weighed after oven-dry at 60°C for 72 hours to calculate the dry mass (DM) percentage. The other parcel was used for morphological separation (leaf, stem and dead material) after this parcel was fully separated the leaf amount was passed into the leaf area meter Li-Cor 3100 (Li-Cor, Lincoln, NE, USA). The morphological parts were oven-dried at 60°C for 72 hours and weighed to calculate the percentage of each part of the plant. SLA was calculated dividing the leaf area (m²) by its DM (g). The LAI was calculated by the product between SLA (m² g⁻¹) and leaf DM (g m⁻²).

During the first period (December 2014 to May 2016), pasture was sampled at 0, 9, 16, 23 and 30 days after grazing by cutting the pasture at 10 cm above the ground. Once per season of the year, the pasture was cut at ground level to determine the biomass and plant composition below 10 cm. During the second period (April 2018 to May 2019), pasture was assessed on every cycle at 0 and 30 days after grazing at ground level. Pasture DM productivity was extrapolated to 1 ha (kg ha⁻¹) from the biomass sampled in 0.25 m².

4.2.6 Simulation structure and model calibration

The simulation ran from 2013 to 2019 with a daily output. Four rectangular zones were placed within the simulation structure available in the user interface. Each one of these rectangular zones has APSIM-Tropical Pasture and APSIM-Slurp and the other sub-models necessary to accomplish the simulation ([Figure 3](#)).

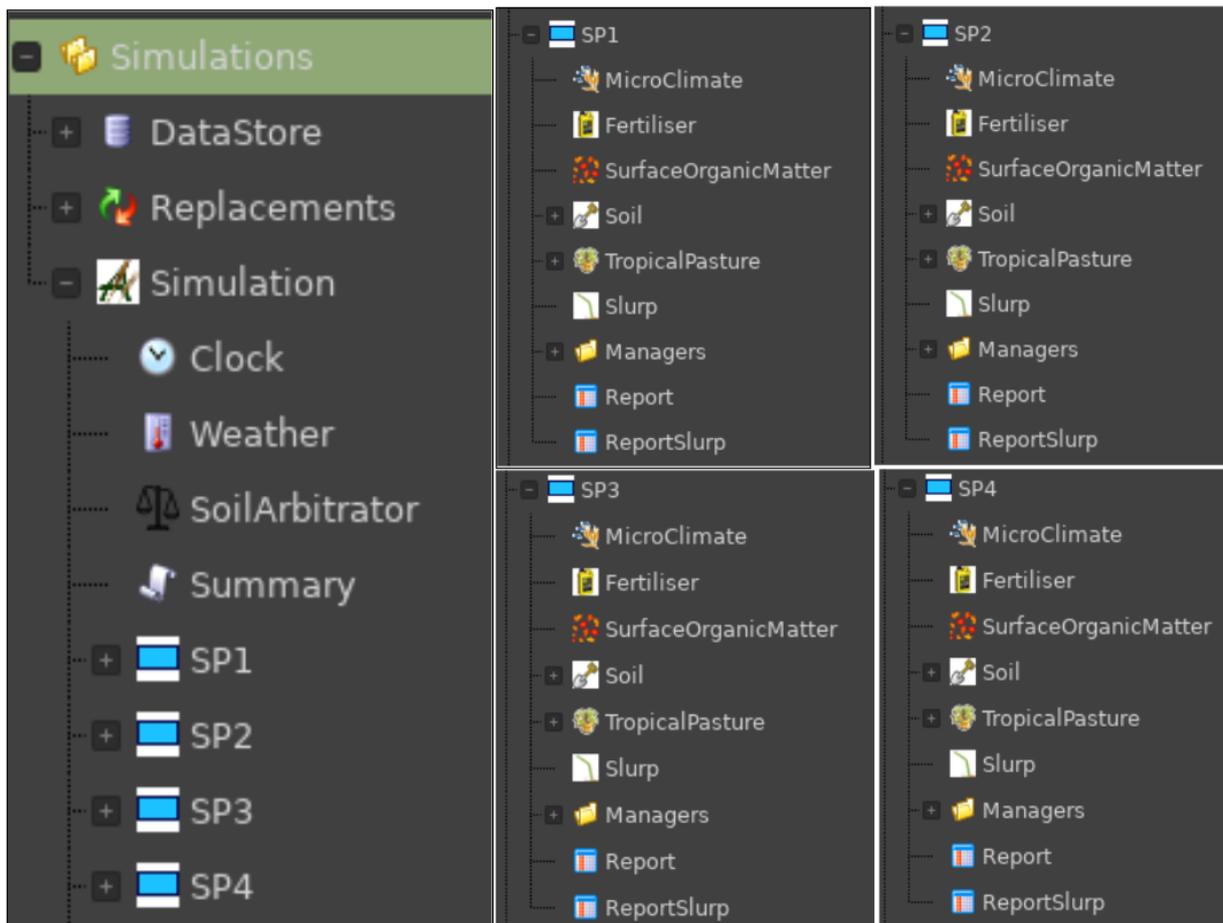


Figure 3: Screenshots of the silvopastoral simulation structure with each rectangular zone (SP1, SP2, SP3 and SP4), Clock (set the simulation period), Weather (import the weather data from .xlsx document), SoilArbitrator (integrates the daily fluxes into crop root systems via a Runge-Kutta calculation) and Summary which produces auto-documentation (left) as it's shown in the APSIM User Interface. Each rectangular zone expanded (middle and right) showing MicroClimate (calculates the potential transpiration for multiple competing canopies), Fertiliser (calculates fertilisers application and flux through the soil), SurfaceOrganicMatter (set the amount and C:N of SOM), Soil (sets the physical and chemical parameters of soil layers), APSIM-Tropical Pasture (set to simulate Piatã palisade grass), APSIM-Slurp (set to simulate Eucalyptus static tree), Managers (a folder containing manager scripts), Report (outputs from Weather, Soil and Tropical Pasture) and ReportSlurp (outputs from Slurp).

4.2.7 APSIM-Tropical Pasture model

APSIM-Tropical Pasture is a generic model that simulates perennial tropical grasses production. It was developed for the APSIM Next Generation (Holzworth et al., 2018) using the APSIM Plant Modelling Framework (PMF), described by Brown et al. (2014). The basic structure of APSIM-Tropical Pasture comes from APSIM-Growth, available in APSIM Classic. New functions for phenology, plant organs, arbitration of resources (biomass and nitrogen), and a factor to consider the effect of CO₂ concentration on pasture growth were added to the model

(Bosi et al., 2020b). The parameterization and calibration of APSIM-Tropical Pasture remained the same as described by Bosi et al., (2020b).

To carry out the management routines specific to pasture rotational stocking we set up a manager script (Moore et al., 2014) that controls the grazing cycle, here called ‘Cutting Management’. The observed residual leaf and stem biomass after each grazing cycle were used as input to set the amount of leaf and stem biomass be removed at the grazing. While ‘Cutting Management’ defines the fraction and the condition for biomass removal, the ‘Operations Manager’ defines the dates and amount of residue of leaf and stem to be left after grazing.

4.2.8 APSIM-Slurp model

The APSIM-Slurp model was developed to mimic a static tree that partially intercepts the solar radiation and extract water from the soil. By default, the APSIM-Slurp comes with canopy LAI set to 5, the canopy extinction coefficient (K) set to 0.65 and the plant tallness was 5 m. With that configuration, the intercepted radiation by the tree canopy was around 95%, which hinders the pasture growth. Therefore, we changed the canopy parameters to increase the accuracy of APSIM-Slurp simulating a Eucalyptus tree.

The canopy K values for the Eucalyptus trees were daily calculated by Eq. (1) and monthly averaged. PAR measurements taken beneath the tree’s canopy in each zone (SP1, SP2, SP3, SP4) were considered as the transmitted radiation (I_i) and the measurements outside the silvopastoral system were considered as the total radiation (I_o) above the tree’s canopy. The Eucalyptus LAI (3.28) was calculated by Bosi (2017), which considered the tree’s population and the tree canopy covered area. The Eq. (1) assumes that the solar zenith angle is incorporated in K, which represents a temporal and spatial variation on K values (Zhang et al, 2014). Intercepted PAR was calculated by the difference between I_o and I_i and was used as observed data to compare with the tree’s canopy radiation interception simulations.

$$K = -\ln(I_i/I_o)/LAI \quad -1$$

The potential water uptake resulted from the product of the available water in the layer (water above LL limit) and a factor controlling the rate of extraction (KL). The KL factor takes into account the soil hydraulic conductivity and the root length density for each soil layer that the roots have extended into (Teixeira et al., 2018). The values of KL are set as a soil physical property inside the APSIM-Soil model (Table 2) and it can be modified according to the plant species that is being represented by APSIM-Slurp. The APSIM-Slurp potential root water uptake

was changed due to simulating different levels of soil water competition, the higher was the KL the stronger was the challenge for the pasture to compete with the trees. The roots were set up to 2.0 m depth as an effort to represent the Eucalyptus root depth extension. The APSIM-Slurp canopy height was set to 30 m which was the actual tree average height.

4.2.9 APSIM-Soil model

The soil physical properties inside the APSIM-Soil were calibrated according to the soil water content measured with the Diviner probe. The drained upper limit (DUL), the 15Bar lower limit (LL15), the soil water saturation (SAT), and the soil air dry (AIR) were calibrated according to the field measurements of soil moisture. The maximum values for each layer were considered the SAT, the minimum was the AIR, the first quartile was the LL15 and the third quartile was DUL (Table 1). The soil bulk density (BD) was the same used by Bosi (2017). The fraction of water above DUL that drains per day (SWCON) was estimated considering 30% of drainage.

Despite the soil water content measures being at 100 cm depth, soil physical properties were set up to 200 cm. We believed that setting deeper layers would help the model to simulate water dynamics around the deeper tree's roots. As soon as we didn't measure the soil physical properties below 100 cm, the values in layers 100-150 cm and 150-200 cm were considered the same as in the layer 90-100 cm.

Table 1. Soil physical properties by layer. BD = bulk density, AIR = air dry soil, LL15 = lower limit or permanent wilting point at -15 bar, DUL = drained upper limit or field capacity, SAT = saturated soil limit, SWCON = fraction of water above DUL that drains per day.

Depth cm	BD g cm-3	AIR mm mm-1	LL15 mm mm-1	DUL mm mm-1	SAT mm mm-1	SWCON Fraction d-1
0-10	1.28	0.13	0.15	0.27	0.34	0.300
10-20	1.48	0.14	0.16	0.29	0.31	0.300
20-30	1.53	0.14	0.15	0.23	0.28	0.300
30-40	1.44	0.13	0.14	0.24	0.28	0.300
40-50	1.38	0.18	0.18	0.24	0.29	0.300
50-60	1.36	0.17	0.18	0.25	0.30	0.300
60-70	1.36	0.16	0.17	0.25	0.33	0.300
70-80	1.36	0.16	0.17	0.26	0.33	0.300
80-90	1.36	0.16	0.17	0.26	0.31	0.300
90-100	1.36	0.16	0.17	0.27	0.30	0.300
100-150	1.36	0.16	0.17	0.25	0.30	0.300
150-200	1.36	0.16	0.17	0.25	0.30	0.300

Some soil physical properties are related to the plant model and its root system, in that case, APSIM-Tropical Pasture and APSIM-Slurp have different characteristics regarding soil water dynamics and water fluxes through the soil profile (Table 2).

Table 2. Soil physical properties by layer according to each plant model. LL = lower limit or permanent wilting point for the crop, KL = water extraction coefficient, XF = root exploration factor.

Depth cm	APSIM-Tropical Pasture			APSIM-Slurp		
	LL mm mm-1	KL fraction d-1	XF 0-1	LL mm mm-1	KL fraction d-1	XF 0-1
0-10	0.150	0.070	1.000	0.150	0.060	1.000
10-20	0.160	0.070	1.000	0.160	0.050	1.000
20-30	0.150	0.090	1.000	0.150	0.050	1.000
30-40	0.140	0.080	1.000	0.140	0.050	1.000
40-50	0.180	0.070	1.000	0.180	0.050	1.000
50-60	0.180	0.070	1.000	0.180	0.050	1.000
60-70	0.170	0.050	1.000	0.170	0.050	1.000
70-80	0.180	0.040	1.000	0.180	0.050	1.000
80-90	0.190	0.030	1.000	0.190	0.050	1.000
90-100	0.170	0.020	1.000	0.170	0.050	1.000
100-150	0.170	0.010	1.000	0.170	0.050	1.000
150-200	0.170	0.010	1.000	0.170	0.050	1.000

4.2.10 APSIM-Tropical Pasture and APSIM-Slurp validation

Several statistics were used to validate the APSIM-Tropical Pasture and APSIM-Slurp simulating the pasture biomass, leaf, stem, dead material, LAI and SLA of Piată palisade grass under the silvopastoral system environment. The coefficient of determination (R^2) from the linear regression between observed (O) and estimated (E) values of each tested variable, was used as an indicator of precision. The precision was classified as unsatisfactory ($R^2 \leq 0.6$), satisfactory ($0.6 < R^2 \leq 0.7$), good ($0.7 < R^2 \leq 0.8$) and very good ($R^2 > 0.8$). (Bosi et al., 2020a).

The Nash-Sutcliffe Efficiency (NSE) was used to evaluate the model's accuracy and was classified as unsatisfactory ($NSE \leq 0.5$), satisfactory ($0.5 < NSE \leq 0.65$), good ($0.65 < NSE \leq 0.75$) and very good ($NSE > 0.75$), following the criteria of Moriasi et al. (2007):

$$NSE = 1 - \frac{\sum_{i=1}^n (E_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (2)$$

Mean absolute error (MAE)

$$MAE = \left(\frac{1}{n} \right) - \sum_{i=1}^n |E_i - O_i| \quad (3)$$

Mean error (ME)

$$ME = \left(\frac{1}{n} \right) - \sum_{i=1}^n (E_i - O_i) \quad (4)$$

Root mean square error (RMSE)

$$RMSE = \sqrt{\left[\left(\frac{1}{n} \right) \sum_{i=1}^n (O_i - E_i)^2 \right]} \quad (5)$$

The ratio between RMSE and SD (RSR)

$$RSR = \frac{RMSE}{SD} = \frac{\sqrt{\left[\left(\frac{1}{n} \right) \sum_{i=1}^n (O_i - E_i)^2 \right]}}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (6)$$

4.2.11 Factorial experiment simulation and sensitivity analysis

The multifactorial simulation tested scenarios of silvopastoral system arrangement and management. We tested the model sensibility regarding the competition for PAR and soil water between trees and pasture, the effect of nitrogen fertilisation and grazing severity upon the pasture biomass accumulation. The first factorial experiment, henceforth tagged as Run1, was arranged as a central composite design (CCD). Then, we went further adding levels to the factors that appeared more sensitive regarding the pasture biomass accumulation. Thus we performed the second (Run2) and the third (Run3) factorial experiments. All factors had their levels transformed into coded units due to give them the same weight within the linear regression model used to proceed with the sensitivity analysis (Table 3).

The factorial experiment Run1 has five factors and three levels per factor (35) resulting in 243 simulations per year for 39 years (from 1980 to 2019). The pasture biomass obtained in Run1 was calculated as the accumulated biomass in each cycle of 30 days. Then, the monthly average of the accumulated pasture was computed considering the whole period of 39 years. The linear regression model was performed according to the equation (7).

$$P = a + b1Ni + b2La + b3Kl + b4Gr + b5Se + b6NiLaKlGrSe + e \quad (7)$$

Where P is the pasture biomass (kg ha^{-1}), a is the intercept, bi is the angular coefficient. The factors are described in equation (7) as follows. Ni is Nitrogen, La is TreePopLai, Kl is TreeRootKl, Gr is Grazing, Se is Season and e is the error.

Based on the first sensitivity analysis (Run1), we redesigned the factorial simulations and proceeded other two runs (Run2 and Run3) adding one level on factors TreePopLai and Nitrogen in each run, while the other factors were set to the level corresponding to code 0 (Table 3).

Table 3. The factors and its levels descriptions for Run1. TreePopLai, three levels of APSIM-Slurp canopy LAI (2, 3 and 4), representing the tree's population. TreeRootKl, three levels of APSIM-Slurp KL (0, 1 and 2), where each level represented a multiplier factor applied to the APSIM-Tropical Pasture soil KL, thus the first level (0 times APSIM-Tropical Pasture KL) represents the absence of competition for soil water between trees and pasture. While the factor rises it increases the water competition between trees and pasture. Nitrogen, three levels of N fertilisation (0, 100, 200 kg ha⁻¹y⁻¹) distributed in five applications throughout the year. Grazing, three levels of pasture biomass residue post grazing (500, 1000, 1500 kg ha⁻¹). Season, those three levels (Winter, Transition, Summer) represent the major variation of weather through the year. New levels and coded units, where Run1 used the coded levels (-1, 0, 1); Run 2 (-2, -1, 0, 1, 2); Run3 (-2, -1, 0, 1, 2, 3).

Factors		Levels						
		Run1						
Code	-3	-2	-1	0	1	2	3	4
Nitrogen (kg ha y-1)	-	-	0	100	200	-	-	-
TreePopLai	-	-	2	3	4	-	-	-
TreeRootKl	-	-	0	1	2	-	-	-
Grazing (kg ha-1)	-	-	500	1000	1500	-	-	-
Season	-	-	Winter	Transition	Summer	-	-	-
		Run2						
Code	-3	-2	-1	0	1	2	3	4
Nitrogen (kg ha y-1)	-	-	0	100	200	300	-	-
TreePopLai	-	1	2	3	4	-	-	-
TreeRootKl	-	-	-	1	-	-	-	-
Grazing (kg ha-1)	-	-	-	1000	-	-	-	-
Season	-	-	Winter	Transition	Summer	-	-	-
		Run3						
Code	-3	-2	-1	0	1	2	3	4
Nitrogen (kg ha y-1)	-	-	0	100	200	300	-	500
TreePopLai	0	1	2	3	4	-	-	-
TreeRootKl	-	-	-	1	-	-	-	-
Grazing (kg ha-1)	-	-	-	1000	-	-	-	-
Season	-	-	Winter	Transition	Summer	-	-	-

4.3 Results

4.3.1 Tree canopy light transmission simulation

APSIM-Slurp's leaf extinction coefficient (K) was calibrated with a monthly value calculated using the Eq. (1) for each observed zone (Table 5). For SP1 the lower K values were found in March and September (equinox) and the higher values in June and July (winter). For the SP2 lower values were found in January and December (summer) and the higher values were found in May and July (autumn and winter). For the SP3 lower values were found in January, February, December and November (spring and summer) and the higher values in May, June and July (autumn and winter). For SP4 the lower values were found in February, March and October (spring and summer) and the higher values in June and July (winter). Considering the whole year, zone SP1 had an average K of 0.30 whereas the other zones had an average of 0.25.

Table 5. APSIM-Slurp monthly average K values for 2018 according to each observed zone (SP1, SP2, SP3 and SP4).

Month	SP1	SP2	SP3	SP4
Jan	0.26	0.14	0.17	0.21
Feb	0.29	0.20	0.17	0.15
Mar	0.18	0.26	0.28	0.16
Apr	0.32	0.24	0.25	0.27
May	0.32	0.34	0.34	0.27
Jun	0.37	0.29	0.34	0.36
Jul	0.34	0.31	0.36	0.34
Aug	0.32	0.28	0.25	0.25
Sep	0.19	0.20	0.27	0.24
Oct	0.25	0.27	0.20	0.14
Nov	0.31	0.18	0.17	0.23
Dec	0.27	0.11	0.15	0.32

The solar radiation interception was simulated with a satisfactory performance considering all zones together ($R^2 = 0.64$, $NSE = 0.60$). Although the simulations with SP1 and SP4 had a better performance than SP2 and SP3 zones ([Figure 4](#)).

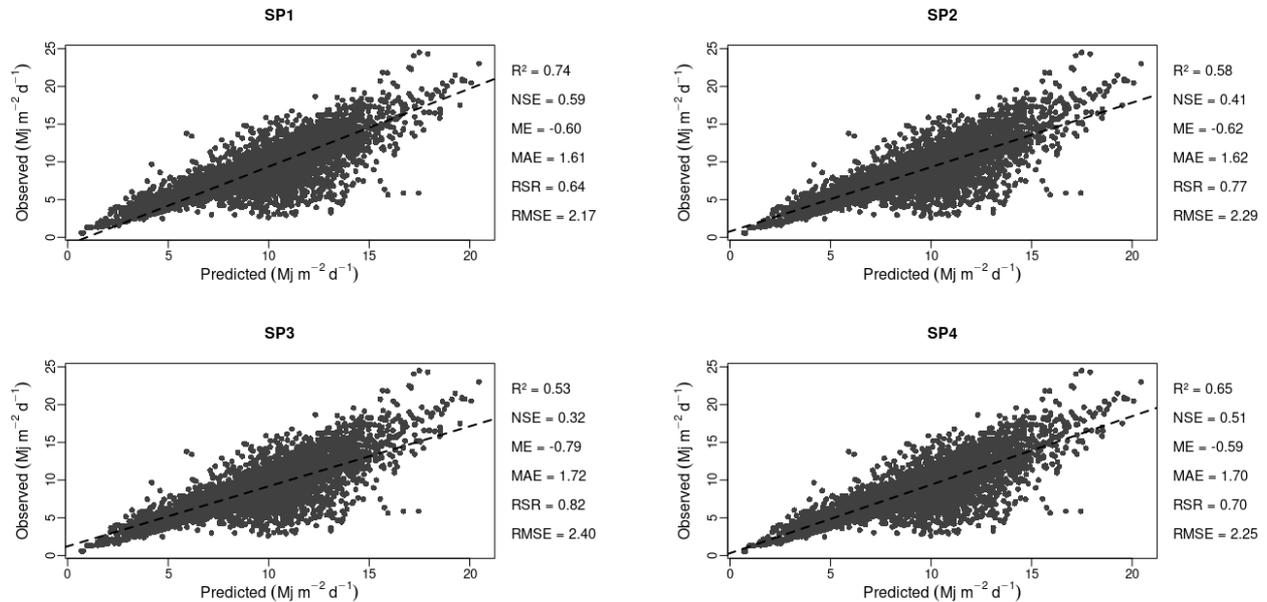


Figure 4: Relationship between observed and predicted values of the tree canopy radiation interception in the four observed zones (SP1 = top left, SP2 = top right, SP3 = bottom left, SP4 = bottom right). The statistics are presented on the right side of each graph. R^2 = coefficient of determination, NSE = Nash-Sutcliffe Efficiency, ME = mean error, MAE = mean absolute error, RSR = ratio between RMSE and SD, RMSE = root mean square error.

4.3.2 Pasture biomass simulation

For both periods of observation (2015 – 2016 and 2018 – 2019), the pasture biomass, leaf stem and LAI was simulated by APSIM-Tropical Pasture with a good to very good performance. Despite the overestimation during the summer ([Table 6](#)), the simulation well represented the pasture biomass trends during the whole year. ([Figure 5](#)).

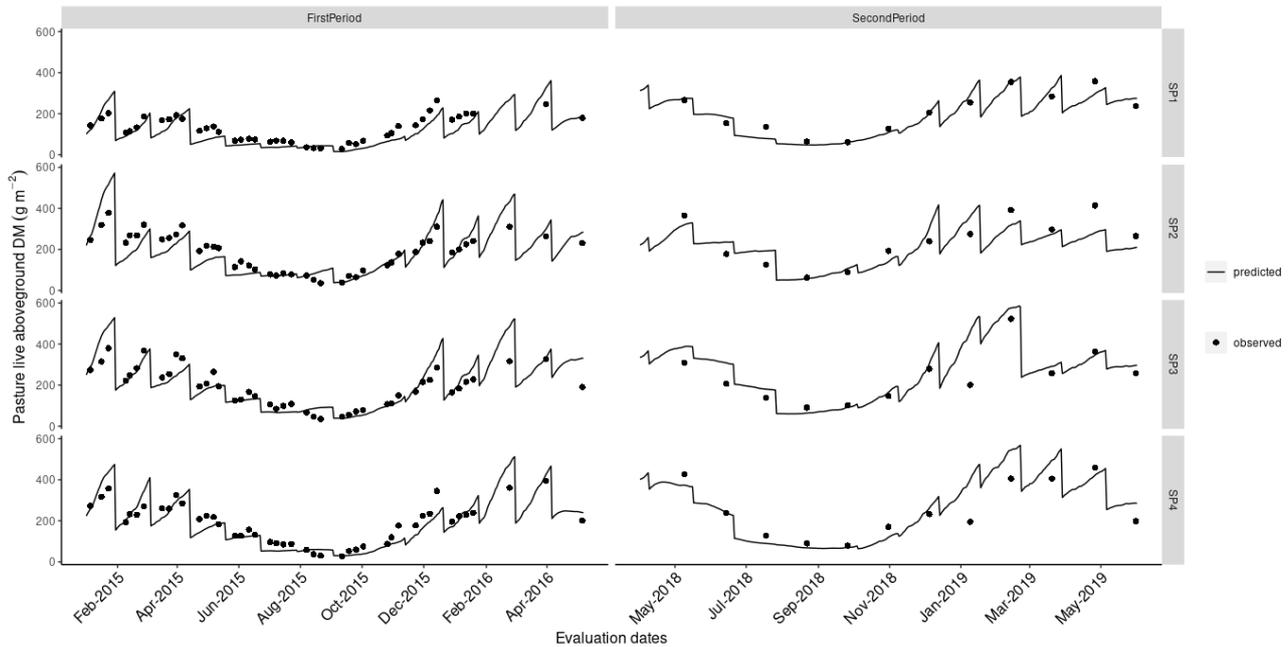


Figure 5: Pasture biomass simulated (black dots) and observed (line) throughout the two periods of evaluation First Period (2014 to 2016) and Second Period (2018 to 2019) for each observed zone (SP1, SP2, SP3, SP4).

It was considered an overestimation when the difference between predicted and observed values of pasture biomass was positive and greater than the MAE. When the summation of predicted minus observed plus MAE was negative, it was considered an underestimation. A great part of the overestimations occurred during the summer. Although underestimation was less frequent, it most occurred during autumn ([Table 6](#)).

Table 6. Percentage of overestimation and underestimation of pasture biomass simulation according to the season of the year.

Season	Underestimated (%)	Overestimated (%)	within MAE boundaries (%)
Autumn	22	20	58
Winter	4	10	86
Spring	14	14	72
Summer	18	43	39

APSIM-Tropical Pasture model performed well predicting the pasture biomass, leaf, stem and LAI, considering the four zones together ([Figure 6](#)). Although, the simulations were unsatisfactory for SLA and dead material ([Table 7](#)).

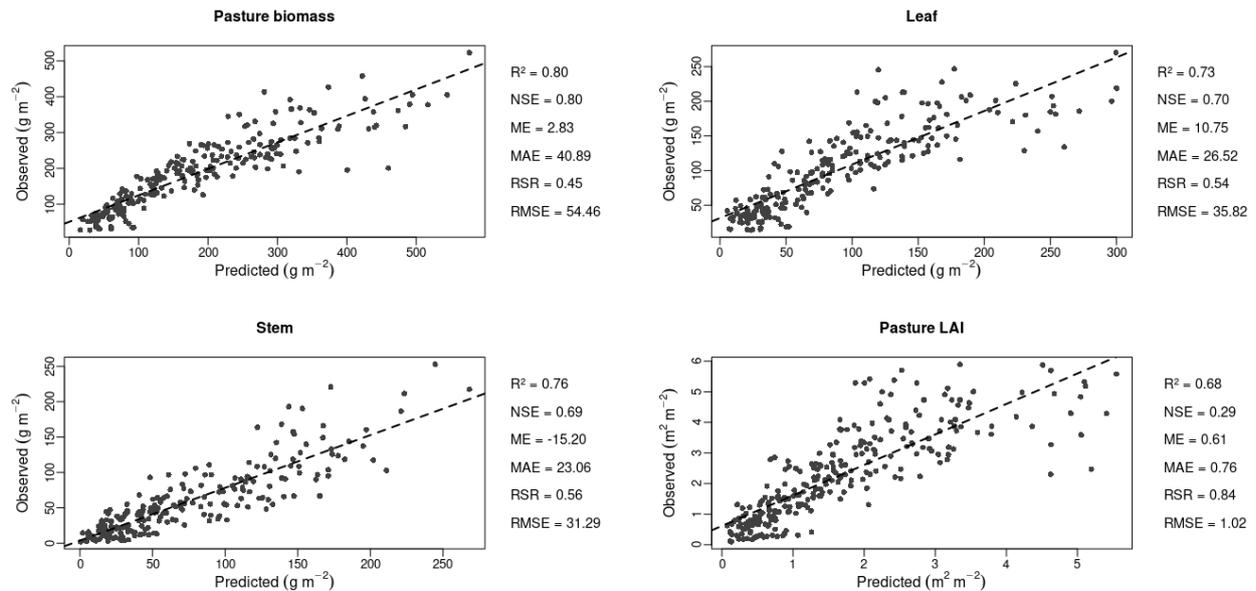


Figure 6: Linear regression between Observed vs. Predicted values evaluating all zones together. Each graph represents a single variable. Top left = Pasture biomass, top right = leaf mass, bottom left = stem mass, bottom right = pasture LAI. The statistics are presented on the right side of each graph. R² = coefficient of determination, NSE = Nash-Sutcliffe Efficiency, ME = mean error, MAE = mean absolute error, RSR = ratio between RMSE and SD, RMSE = root mean square error.

The relationship between observed and predicted values had some differences for each observed zone ([Table 6](#)). The zones SP1 and SP4 were simulated with better performance than zones SP2 and SP3 for pasture biomass, leaf, stem and LAI. The pasture biomass simulation had good (SP2 and SP3) to very good precision (SP1 and SP4) and good (SP2) to very good (SP1, SP3 and SP4) accuracy.

The leaf simulation had satisfactory (SP2 and SP3) to good (SP4) and very good precision (SP1), besides it had satisfactory (SP2 and SP3) to good (SP1) and very good (SP4) accuracy. The stem simulation had satisfactory (SP2) to good (SP1, SP3 and SP4) precision, and satisfactory (SP2 and SP3) to good (SP4) and very good (SP1) accuracy. The dead material simulation was unsatisfactorily precise and accurate for all zones, except for SP1 zone, which was satisfactorily simulated. The LAI simulation had satisfactory (SP2 and SP3) to good (SP1 and SP4) precision and unsatisfactory accuracy for all zones. The SLA simulation was

unsatisfactorily performed in all observed zones (Table 7). Although, when we split the simulation and analyse the two periods separately, whereas the first period indeed had a poor performance, the second period had a satisfactory performance for SLA simulation (SP1: $R^2 = 0.69$, $NSE = 0.64$; SP2: $R^2 = 0.22$, $NSE = 0.04$; SP3: $R^2 = 0.75$, $NSE = 0.61$; SP4: $R^2 = 0.54$, $NSE = 0.50$) for all observed zones, except for the SP2 zone.

Table 7: Statistical indexes for pasture biomass, leaf, stem, dead material, LAI and SLA for each zone.

Zones	R^2	NSE	ME	MAE	RSR	RMSD
Pasture biomass						
SP1	0.86	0.82	18.77	32.96	0.43	38.62
SP2	0.73	0.73	6.61	45.50	0.52	56.81
SP3	0.78	0.76	-15.13	43.19	0.49	63.32
SP4	0.84	0.82	1.36	41.76	0.41	55.74
Leaf						
SP1	0.84	0.74	14.44	19.98	0.51	23.99
SP2	0.68	0.58	16.77	29.80	0.65	40.74
SP3	0.66	0.65	4.15	30.20	0.58	40.97
SP4	0.78	0.77	7.75	26.01	0.47	34.76
Stem						
SP1	0.80	0.76	-7.00	14.80	0.48	21.27
SP2	0.62	0.51	-14.35	25.34	0.70	32.49
SP3	0.77	0.65	-19.86	25.80	0.58	34.84
SP4	0.80	0.70	-19.38	26.10	0.55	34.37
Dead material						
SP1	0.60	0.23	-17.48	33.79	0.87	67.54
SP2	0.07	-3.57	-90.20	92.20	2.12	101.00
SP3	0.03	-3.54	-114.49	121.14	2.11	129.86
SP4	0.11	-2.40	-105.15	111.40	1.83	122.36
SLA						
SP1	0.10	-0.49	0.00	0.01	1.21	0.01
SP2	0.00	-0.26	0.00	0.00	1.12	0.01
SP3	0.03	-0.62	0.00	0.01	1.26	0.01
SP4	0.03	-0.85	0.00	0.01	1.35	0.01
LAI						
SP1	0.72	0.00	0.61	0.67	0.99	0.87
SP2	0.64	0.01	0.71	0.89	0.99	1.17
SP3	0.63	0.39	0.48	0.73	0.78	1.00
SP4	0.74	0.41	0.64	0.76	0.76	1.02

4.3.3 Soil water simulation

Due to comparing simulated and observed values of soil water content, the soil layers were aggregated as 0 to 30 cm, 30 to 60 cm, 60 to 100 cm and 0 to 100 cm (Figure 7). The shallow layer (0 to 30 cm) was the one with the best performance followed by the mid-layer (30 to 60 cm) and the bottom layer (60 to 100 cm). Considering the whole soil profile and all zones together, the simulation performed well.

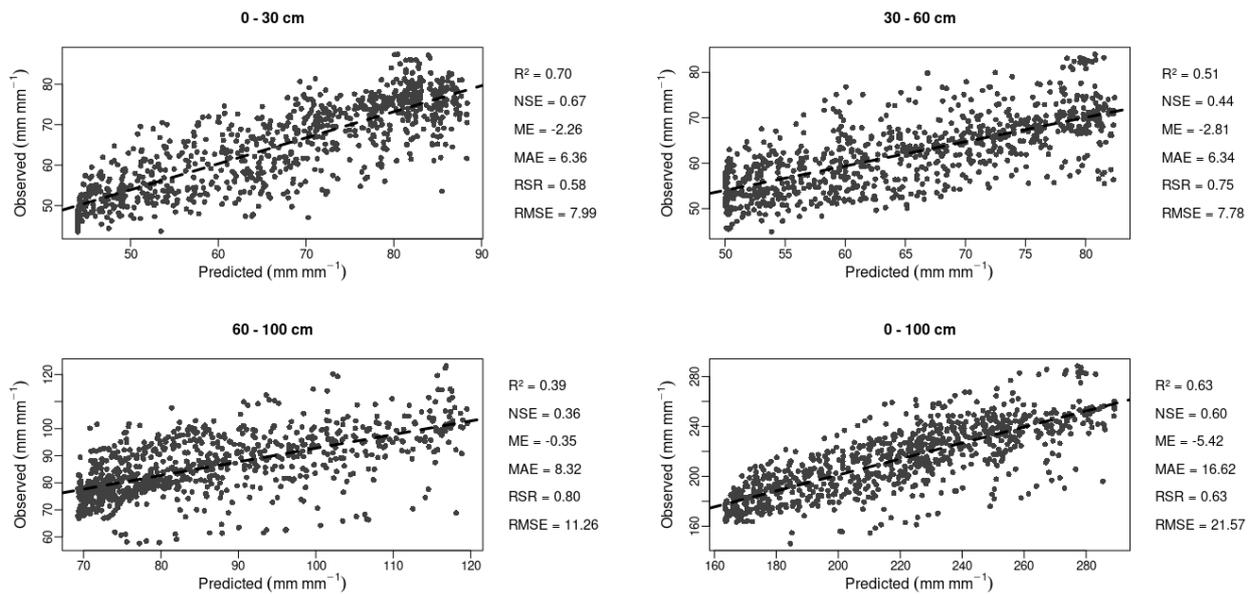


Figure 7: Linear regression between Observed vs. Predicted values evaluating all zones together. Each graph represents an aggregation of soil layers. Top left = 0 to 30 cm, top right = 30 to 60 cm, bottom left = 60 to 100 cm, bottom right = 0 to 100 cm. The statistics are presented on the right side of each graph. R² = coefficient of determination, NSE = Nash-Sutcliffe Efficiency, ME = mean error, MAE = mean absolute error, RSR = ratio between RMSE and SD, RMSE = root mean square error.

When the soil water was evaluated separately by zone, we identified some differences regarding precision and accuracy on the simulations. The shallow layer (0 to 30 cm) simulation had good precision and accuracy in all zones, except for SP1 which had an unsatisfactory accuracy. The mid-layer (30 to 60 cm) simulation had unsatisfactory precision in all zones, except for SP4 which was satisfactory. Moreover, the mid-layer simulation accuracy was unsatisfactory for SP1 and SP2 whereas it was satisfactory for SP3 and SP4. The bottom layer (60 to 100 cm) simulation had unsatisfactory precision and accuracy in all zones, except for SP2 and SP3 which had a satisfactory accuracy. The whole soil profile (0 to 100 cm) simulation had good precision for all zones, except for SP1. The whole soil profile simulation accuracy was satisfactory (SP2) to good (SP3 and SP4), however unsatisfactory for SP1 (Table 8).

Table 8. Statistical indexes for soil water content (mm mm⁻¹) for each observed zone within the silvopastoral system (SP1, SP2, SP3 and SP4). The statistics presented are: R² = coefficient of determination, NSE = Nash-Sutcliffe Efficiency, ME = mean error, MAE = mean absolute error, RSR = ratio between RMSE and SD, RMSE = root mean square error. The soil profile was stratified as a shallow layer (0 - 30 cm), mid-layer (30 - 60 cm), bottom layer (60 - 100 cm) and the whole profile (0 - 100 cm).

Zones	R ²	NSE	ME	MAE	RSR	RMSD
0 - 30 cm						
SP1	0.72	0.47	-6.76	8.16	0.72	10.12
SP2	0.78	0.71	-3.07	5.75	0.53	7.10
SP3	0.73	0.71	0.92	5.97	0.54	7.46
SP4	0.79	0.77	-0.14	5.54	0.48	6.83
30 - 60 cm						
SP1	0.53	0.17	-6.23	7.61	0.91	9.54
SP2	0.59	0.38	-4.47	6.56	0.79	7.65
SP3	0.55	0.55	-0.23	5.61	0.67	6.85
SP4	0.60	0.59	-0.30	5.57	0.64	6.78
60 - 100 cm						
SP1	0.11	-0.20	-4.94	10.28	01.09	14.81
SP2	0.59	0.52	-3.84	7.45	0.69	10.08
SP3	0.58	0.53	2.55	6.90	0.68	8.67
SP4	0.52	0.39	4.80	8.64	0.78	10.54
0 - 100 cm						
SP1	0.52	0.24	-17.92	22.19	0.87	29.72
SP2	0.77	0.64	-11.38	16.45	0.60	20.15
SP3	0.75	0.74	3.24	13.57	0.51	16.69
SP4	0.78	0.75	4.36	14.29	0.50	17.14

4.3.4 Factorial experiment and sensitivity analysis

The sensitivity analysis evidenced that the Season (S) factor had a relevant influence on the pasture biomass accumulation ([Figure 8](#)). Thus, we isolated the S factor by analysing each season (Summer, Transition and Winter) separately. That procedure was done in each run (Run1, Run2 and Run3) of factorial simulation.

Regardless of the season, the TreeLai factor (L) had the highest effect upon the pasture biomass. During the Winter the L factor was nearly the only relevant factor. During the

Transition season, the L factor affected pasture biomass approximately twice the K factor, which was the second most relevant factor in all the three factorial simulation runs.

During the Winter the N factor had less relevance than it had during the Summer or Transition seasons, probably due to the low water availability in the soil and the lower temperatures. During the Summer season, the K factor had less importance, probably due to the high availability of soil water. The N factor was the second most relevant factor during the Summer of Run1, besides it presented an important interaction with the L factor. The G factor doesn't seem to be very important regardless of the season analysed.

The Run2 analysis differs from Run1 by adding one level (LAI = 1) to the L factor and one level (N = 300 kg ha⁻¹ y⁻¹) to the N factor. The Run3 added one more level (LAI = 0) to the L factor and one more level (N = 500 kg ha⁻¹ y⁻¹) to the N factor. In both runs (Run2 and Run3) the sensitivity analysis showed an interaction between N and L factors, which had more influence than the N factor alone independently of the season. In Run 3, the influence of K factor during the Summer season was greater than in the Run 1 and Run2.

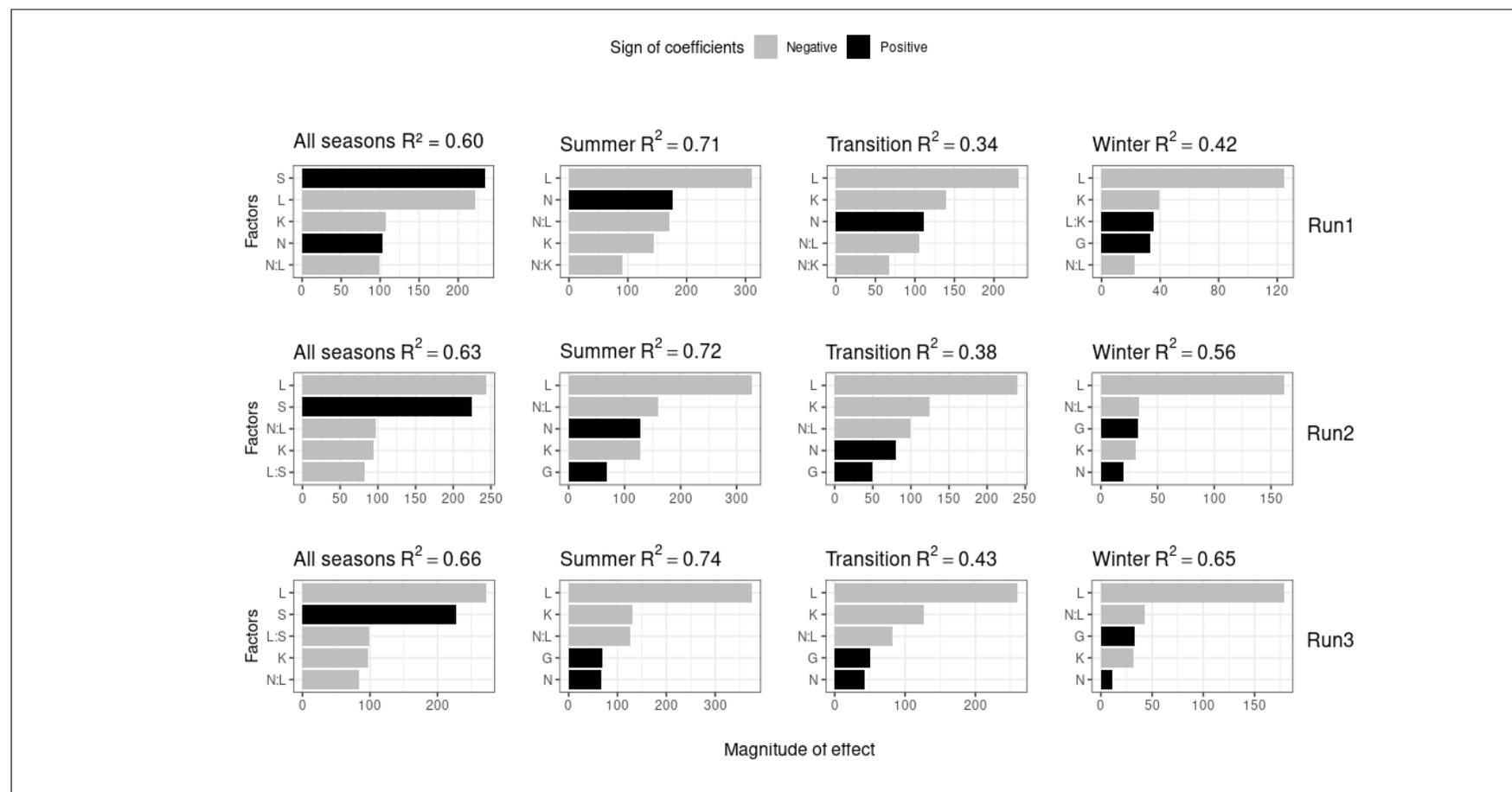


Figure 8: Sensibility analysis for all seasons and each season (Summer, Winter and Transition). In the x-axis are indicated the magnitude of the effect of one coded unit upon the pasture biomass. In the y-axis are the factors (N = Nitrogen, L = TreeLai, S = Season, K = TreeKl, G = Grazing). When two letters are separated by : it means an interaction between those factors. The values of factor coefficients could be negative (grey bars) or positive (black bars). The graphs aligned in the same row belong to the same run of factorial simulation. Run1 (N = 0, 100, 200; L = 2, 3, 4; K = 0, 1, 2; G = 500, 1000, 1500; S = Summer, Transition, Winter), Run2 (N = 0, 100, 200, 300; L = 1, 2, 3, 4; other factors remained the same as in Run1), Run3 (N = 0, 100, 200, 300, 500; L = 0, 1, 2, 3, 4; other factors remained the same as in Run1).

The sensibility analysis showed that at a certain level of shade (higher L factor) the pasture response to nitrogen fertilisation was reduced. Even the season effect was diminished as the L factor increased ([Figure 9](#)).

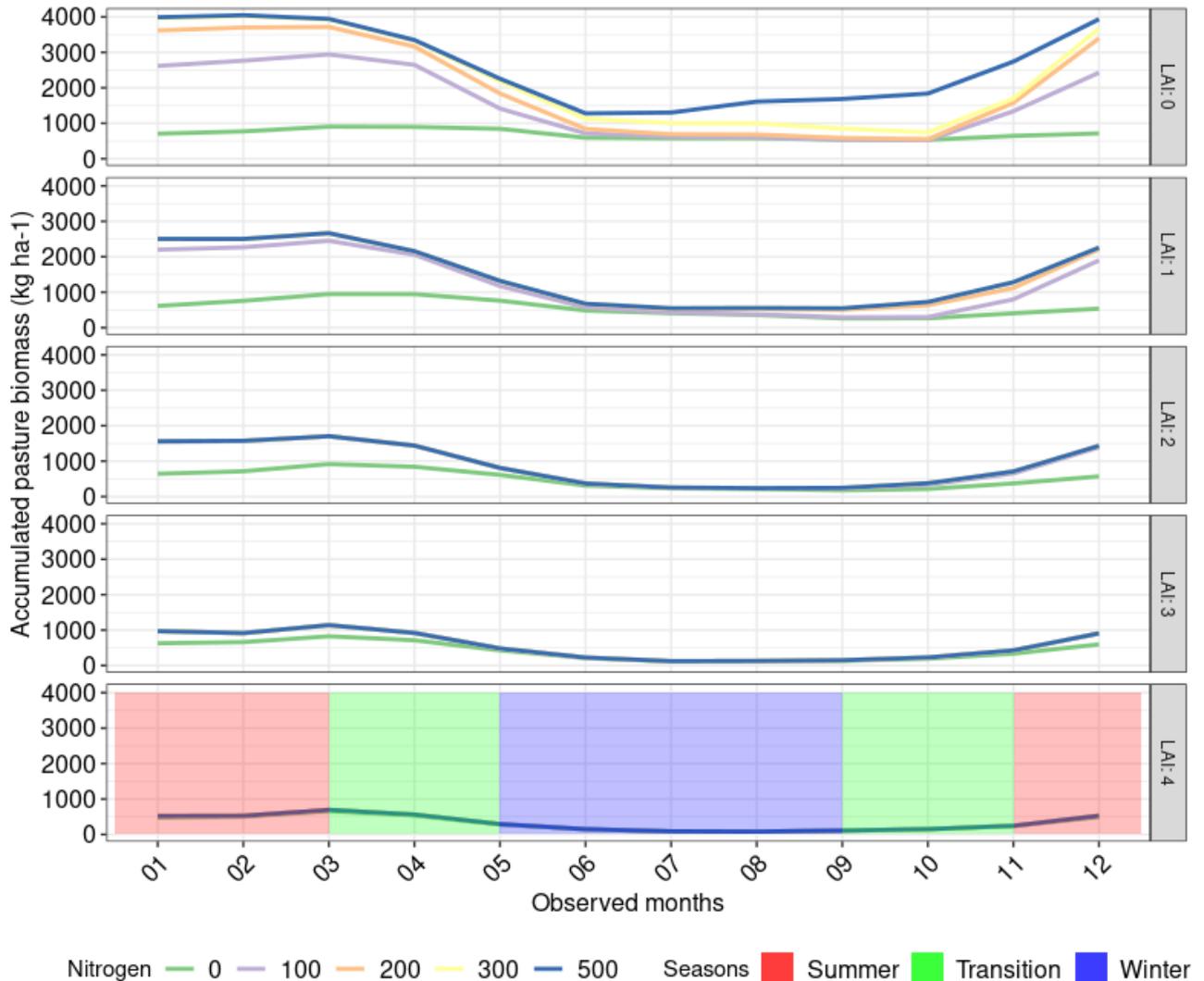


Figure 9: Monthly average accumulated pasture biomass (kg ha-1) according to the Nitrogen fertilisation level (different line colours), each graph is under a Tree LAI level (0, 1, 2, 3, 4).

4.4 Discussion

4.4.1 Light extinction simulation

The K values estimated in this study tend to represent better the tree canopy structure and the effect of solar declination when the shade projection was under the tree canopy perimeter (SP1 and SP4). When the shade projection was far from the trees (SP2 and SP3) the

simulation showed less accuracy, probably due to the variability in the shade projection and the overlapping effect that comes from the adjacent northern tree row. Since half of the trees were cut in 2016, there may be more lateral branch development in the Eucalyptus trees due to the increase in solar radiation incidence. That lateral branch expansion probably makes the K values increase throughout the years. Thus, a model that can simulate the tree canopy structure modifications resulting from the management practices such as pruning and thinning probably will be more accurate in long term simulations.

4.4.2 Pasture biomass simulation

The simulated pasture biomass follows the same seasonal trends found in the observed data, which showed the model's reliability to simulate the pasture production seasonality within a silvopastoral system ([Figure 5](#)). The performance of the simulations were similar to that found by Bosi (2017) ($R^2 = 0.69$ to 0.88 ; $NSE = 0.51$ to 0.85) and Gomes et al. (2020) ($R^2 = 0.76$ to 0.93 ; $NSE = 0.70$ to 0.84) simulating pasture growth under tree canopies using the APSIM-Tropical Pasture model. The main difference between those studies and the present one is the use of APSIM-Slurp to simulate the tree influence upon the pasture growth. In the study conducted by Bosi (2017), APSIM-Slurp was used just in the zone closest to the tree's row, thus the direct influence of shade doesn't affect the other zones, here we made different placing the APSIM-Slurp model in each zone. In the study conducted by Gomes et al. (2020) the radiation interception was not simulated, but measured in the different distances from the trees and used directly as an input. Therefore, the most important achievement in our study is to set a capability to simulate the light environment beneath the trees inside a silvopastoral system.

The overestimation observed during the summer probably was determined by two major factors, the abrupt changes regarding the biomass partition among the plant organs during the reproductive phase and the cattle trampling effect upon the pasture stubble. The large duration of reproductive period (almost five months) of Piatã palisade grass (Bosi et al., 2020a), which mainly happens during the summer (Valle et al., 2010), must negatively impact the pasture biomass accumulation. Thus, during the peak of the reproductive phase, the demand for photoassimilates must be greater than the APSIM-Tropical Pasture simulated. Another effect related to the reproductive phase is the stem elongation, which causes the leaf/stem ratio reduction, thus reducing the pasture photosynthetic efficiency (Euclides et al., 2008). The level of shading in the pasture also could be a factor that promotes stem elongation (Crestani et al., 2017). Although depending on the level of shade the flowering process could be retarded, this

fact must explain the better performance observed in the zone close (SP1) to the trees. Using the CROPGRO-Perennial Forage model, Bosi et al. (2020a) also found an issue related to the simulation during the reproductive phase, however, they reported an underestimation whereas we observed an overestimation.

Another possible factor affecting the simulation is the grazing damage caused by cattle trampling; part of the material collected in the field considered as live plant parts actually could be already a dead material in the early stages of decomposition. Thus, the sampling of the stubble biomass just after the cattle leaves the paddock could lead to an overestimation of the residual leaf area attached to the pasture tillers. Because of that, residual leaf area was used as an input it could also lead to an overestimation regarding the rate of pasture growth.

The live plant parts (leaf and stem) simulation showed good fitness, suggesting that biomass partitioning among aboveground plant organs is well calibrated within the APSIM-Tropical Pasture model. However, the dead material was not simulated properly, probably due to a problem related to the detachment rate of dead tissues (leaf and stem). The dead material detachment rate was happening faster in the model than it happened in our field experiment observations. This dyssynchrony between the model and the reality must have to be given more attention in further experiments and model calibration. Regarding the dead material sampling method, it must be adopted for more precise segregation between which is dead material attached to the pasture and the surface organic matter. On the other hand, a function that can change the plant tissue senescence and the dead material detachment according to the pasture phenological phase and the weather conditions must be implemented in APSIM-Tropical Pasture. For example, during the dry season of the year the dead:live ratio is greater than in the rainy season, however, this ratio could change abruptly due to the heavy rains at the beginning of the rainy season.

The tropical grasses are likely to have some plasticity regarding the SLA, with the tendency to increase the SLA under shaded environments when compared to open pasture (Santos et al., 2016). That phenotypic adaptation occurs mainly as a mechanism to compensate for the reduction of PAR availability; larger leaves have more chance to intercept the solar beams (Paciullo et al., 2007). Also, there is a difference between the dry and rainy season, with greater SLA during the rainy season (Santos et al., 2016; Gomes et al., 2019). Reducing the SLA is a strategy to reduce the leaf transpiration rate, smaller leaves have less contact with the atmosphere. The SLA simulation presented differences between the two periods of observation. Probably the main reason that explains the difference between the two observed periods is the amplitude and the variability of the observed data, which were greater for the first period. The leaf sub-model within APSIM-Tropical Pasture calculates the SLA through a function. That

function results in a product of three factors, plant age where older plants have greater SLA, drought stress that reduces the SLA when plants are under stress and the radiation factor where plants submitted to a light regime below 15 MJ m⁻² day⁻¹ has an increase in the SLA.

4.4.3 Soil water simulation

In general, the soil water content was simulated with good performance ($R^2 > 0.74$, $NSE > 0.39$, RSR from 0.77 to 0.64) in every zone considering the whole observed soil profile (0 to 100cm), except for the SP1. For SP1 soil water content simulation, the model just had a precise prediction ($R^2 = 0.72$) in the top layer (0 to 30 cm). However, the NSE was equal to 0.04, which means that the predictive power of the model is barely the same as the observed mean (Nash; Sutcliffe, 1970). For the other observed layers (30 to 60 cm, 60 to 100 cm), the SP1 simulation performance was also poor ($R^2 = 0.53$, $NSE = -1.06$) and ($R^2 = 0.11$, $NSE = -1.17$). Those negative values of NSE could be explained by the large variation of the data. Another important question to be discussed concerns the soil physical properties calibration, which should be different for the SP1 concerning the other zones. This particular calibration for SP1 makes sense if we think about the likely stronger influence of the tree roots in the zones closer to the tree row (Bieluczyk, 2018).

The difference in the simulation accuracy among the zones suggests that different soil parameters should be used for zones closer to the trees. The tree roots have the potential to accelerate the rate of soil water infiltration (Lima et al., 2018), also the evapotranspiration near the trees is potentially higher than the zones farther from the tree trunk (Gyenge et al., 2002). On top of that, during the dry season, the soil water content may become relatively lower near the trees (Crestani et al., 2017).

4.4.4 Factorial experiment and sensitivity analysis

Some constraints appeared when the long term simulation was set to run the factorial experiments. The defoliation manager that was responsible to simulate the grazing routine has a population decrease function. This function reduces the initial population every grazing cycle ending with the pasture population after a decade of simulation. Thus, we turned off the population decrease function within the defoliation manager to overcome that issue. The APSIM-Tropical Pasture hadn't implemented a population dynamic yet. It could be an indicator

to add this kind of feature in the model when the objective is to run long term simulations, or when the population dynamics is a concern.

Another issue was the “Leaf Kill function for frost”; it was set to kill the leaves when the minimum temperature reaches zero °C; all the pasture was killed when the temperature reached below zero. To rapidly resolve this situation, a workaround was done setting the temperature to kill the leaves at minus five °C. Although, another solution might be implemented, perhaps some function that considers the air relative humidity and dew formation over the leaves. However, the occurrence of frost does not necessarily mean the death of all plants, even tropical grasses from *Brachiaria* genus have a level of frost tolerance and can recover after sporadic frost (Ludlow, 1980; Argel et al., 2005). Thus, the “Leaf Kill function for frost” must be calibrated to kill just a fraction of the leaves according to the frost intensity.

The nitrogen fertilisation response shown by the sensitivity analysis when considered all levels (0, 100, 200, 300 and 500 kg ha⁻¹ y⁻¹) of application and TreeLai = 0, was similar to found in other studies that compared the pasture biomass production regarding the nitrogen application. A quadratic effect ($P < 0.05$) was verified for nitrogen levels on the production of total and green leaf blade dry matter, with the optimum at a mean nitrogen application level between 380 kg ha⁻¹ (Dourado et al., 2015) and 450 kg ha⁻¹ (Zanine et al., 2020). Although, when the TreeLai was 1 or greater the differences between the levels of nitrogen application regarding the pasture biomass production became smaller. Indeed, the interaction between nitrogen and light resources is expected for tropical grasses. In a study with *Panicum maximum* cultivars, Paciullo et al. (2017) verified a pasture biomass linear response to N under full sun and moderate (37%) shading and a quadratic effect under intense (58%) shading. Therefore, the level of shade in a pasture under a silvopastoral system must be considered when applying nitrogen fertiliser.

Looking at the sensitivity analysis in an optimisation perspective, the best attainable pasture production was obtained with the absence of trees, in other words, no shade effect and no water competition. Although, tropical grasses are likely to exhibit shade tolerance due to phenotypic plasticity and produce as much as a pasture in an environment without trees (Geremia et al., 2018; Pezzopane et al., 2020). Comparing the PAR reduction between TreeLai 0 and TreeLai 1, the reduction was between 20 and 30% and the reduction of pasture biomass was 50% which was an overestimated reduction when compared with other studies. Another study has shown that a reduction in approximately 20% of PAR availability for the pasture does not represent a decline in *Brachiaria brizantha* cv. Marandu biomass accumulation (do Nascimento et al., 2019). Although, when the shade provided by the tree’s canopy is around 21% and 51% the pasture accumulation decreased by 39% to 68% respectively (Crestani et al., 2017).

The water competition between trees and pasture in a silvopastoral system is a controversial theme. Some studies suggest that the competition is likely to occur during the dry season (de Castro Santos et al., 2016) whereas other states that the competition depends on the microclimatic conditions promoted by the trees to the understory (Pezzopane et al., 2015; Bosi et al., 2019) and the potential reduction in the system evapotranspiration (Menezes et al., 2002). Indeed, other factors will determine whether and when the water competition happens, the soil type, the climatic conditions and the management.

With a simplification of the water competition dynamics, the sensitivity analysis takes into account just the water coefficient extraction (KL). The KL factor showed a relevant influence during the Transition and Winter seasons, which is explained by the lower plant available water in the soil during this period. Even though the KL factor is crucial to control water uptake by roots, there are species that deep spread its roots through the soil profile (e.g. Eucalyptus and perennial forages) the KL parameter is hard to be set (Teixeira et al., 2018). Although, the KL parameter can be set according to each soil layer which gives the possibility to simulate the soil water extraction by multiple plant species that explore different soil depths. Moreover, in long term simulations, it should be interesting to understand whether the KL values change across time. Probably two main factors will make the KL change, one is the alterations in the soil physical structure (Vasquez et al., 2020), increase in macropores due root development and senescence, decomposition (Bieluczyk, 2018). Another reason to modify the KL in long term simulations is the likely increase of Eucalyptus (Pinheiro et al., 2016) and *Brachiaria* (Vieira et al., 2019) root length and deep zone exploration.

In our sensitivity analysis, we focused just on the detrimental effect of Eucalyptus upon the Piatã water supply, however in the early stages of the silvopastoral system the opposite may occur more often. In an experiment conducted during the implementation of a silvopastoral system with *E. urograndis* and *Brachiaria decumbens*, the best results regarding the Eucalyptus development was achieved when a crown of two meters diameter was cleaned around the Eucalyptus plants (Machado et al., 2013). The critical phase is during the first two years of Eucalyptus growth where *Brachiaria* species could impair the Eucalyptus growth (Toledo et al., 2003). That competition for water and subsequent impact in Eucalyptus growth may happen regardless of the water level in the soil, and it's assumed that the *B. brizantha* was more competitive in the early stages than *E. citrodora* and *E. grandis* species (Silva et al., 2000).

The grazing severity, represented by the level of factor G (residue after grazing kg ha⁻¹), had little effect upon the accumulated pasture biomass. However, considering that defoliation severity impacts plant tillers population (da Silva et al., 2017), it was expected that the different levels (500, 1000, 1500 kg ha⁻¹) of grazing stubble must have affected the pasture biomass

accumulation. Probably the effect of grazing severity upon the pasture biomass accumulation was overlaid by the undoubted effect of the L factor. Despite the insensitivity of APSIM-Tropical Pasture concerning the grazing severity effect, until now we did not identify a paper that describes an experiment comparing different post-grazing stubbles under a silvopastoral system.

The grazing management is considered the touchstone upon sward structure, which can affect patterns of herbage accumulation (Silva et al., 2009). Theoretically, a lower pos-grazing stubble represents lower residual LAI, than a long process of regrowth, sward canopy LAI recovery compared to a higher pos-grazing stubble. When the grazing severity is changed in the APSIM-Tropical Pasture model, it doesn't take into account the structural modifications at the sward level.

4.5 Conclusions

The implementation of a variable tree canopy extinction coefficient (K) rather than a static value to the APSIM-Slurp, was an important improvement for light interception simulation. The assembling of APSIM-Tropical Pasture and APSIM-Slurp models produced a sound tool to simulate the pasture production under a silvopastoral system in different environments and management. The silvopastoral system modelling also could provide valuable information about how to optimise the system when a biophysical limitation is faced (light, water and nutrients competition). A model designed to simulate a silvopastoral system must be capable to highlight the ecological relations within the system. In this way, it's possible to address issues related to the resources competition.

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