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

Understanding the Brazilian silvopastoral systems based on experimental data and functional-structural modeling

Nilson Aparecido Vieira Junior

Thesis presented to obtain the degree of Doctor in Science. Area: Agricultural Systems Engineering

Piracicaba
2022

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
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2022

Dados Internacionais de Catalogação na Publicação
DIVISÃO DE BIBLIOTECA – DIBD/ESALQ/USP

Vieira Junior, Nilson Aparecido

Understanding the Brazilian silvopastoral systems based on experimental data and functional-structural modeling / Nilson Aparecido Vieira Junior. - - versão revisada de acordo com a resolução CoPGr 6018 de 2011 -- Piracicaba, 2022.

119 p.

Tese (Doutorado) - - USP / Escola Superior de Agricultura “Luiz de Queiroz”.

1. Pecuária-floresta 2. Modelagem de culturas 3. Sombreamento 4. Arranjo 5. Manejo das árvores 6. Consócio de culturas I. Título

ACKNOWLEDGEMENTS

Firstly I thank God for my life, health, all opportunities, and being able to carry out this research.

To my wife, Dândara Vieira, for her love, support, comprehension, and belief in me during all these years of study. To all my family for their support.

To my advisor Professor Dr. Fábio Ricardo Marin, for his assistance in the development of this study, as well, for teaching, motivational support, and friendship. Furthermore, for the opportunities provided, for sharing his knowledge and experience that contributed to me becoming a meticulous researcher.

To my supervisor, Dr. Jochem Evers, for his assistance, teaching, and mentoring during my abroad internship at Wageningen University & Research. To Dr. Bruno Pedreira and Dr. Murilo Viana for their support, friendship, and contribution to the development of this thesis.

To the São Paulo Research Foundation (FAPESP), by the financial support (18 months) through my P.h.D scholarship (grant: 2018/15355-2) and scholarship to abroad internship (12 months) at Wageningen University & Research (grant: 2019/21277-7). To Coordination for the improvement of Higher Education Personnel (CAPES) for the scholarship (12 months).

To the "Luiz de Queiroz" College of Agriculture, University of São Paulo, for the infrastructure and opportunity to develop my P.h.D and improve my skills in research and teaching at the Biosystem Engenireeing Department. To all professors and employees for their teaching and support.

To the GEPEMA/AGRIMET group to provide teaching and mentoring experiences with undergraduate students, research, and field practices which improved my skills as a researcher. To all members of the group, especially Evandro Moura da Silva and Juliano Mantellato Rosa for their friendship, professional support, and good experiences.

To everyone that contributed to my personal e professional development, helping to finish my thesis and obtain the degree of Doctor in Agricultural Systems Engineering. Thank you very much.

EPIGRAPH

“I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.”
Isaac Newton

CONTENTS

RESUMO

Entendendo os sistemas silvipastoris brasileiros com base em dados experimentais e modelagem funcional-estrutural

Nos últimos anos, estudos vem mostrando o potencial dos sistemas silvipastoris em elevar a sustentabilidade da produção pecuária por meio da integração de árvores, pastagem e animais. Porém a adição de árvores no sistema pode desfavorecer o crescimento da pastagem, tornar mais complexas as operações de manejo e planejo e assim limitar sua adoção. O objetivo desse estudo foi avaliar a incidência de radiação solar em sistema silvipastoril por meio de um dados experimentais previamente coletados e um modelo funcional e estrutural de plantas. Para isso foram coletados 50 pontos de radiação fotossinteticamente ativa entre os renques de árvore, além de amostras da forragem em 3 diferentes tratamentos; 2 distâncias entre os renques de árvores (4m e 15 m) e a pleno sol. A orientação do renque de árvores e a posição do sol ao longo do ano influenciou na qualidade e na produção da forragem. A produção de forragem foi menor mais próximo ao renque das ávores, enquanto que mais ao centro houve menor teor de fibra e maior produção em todas as estações do ano. Posteriormente foi desenvolvido uma abordagem em que se acoplou um modelo funcional-estrutural de plantas para simular a interceptação de radiação pelas árvores em diferente idades, com um modelo baseado em processo para simulação da produção da forragem. Ambos os modelos foram calibrados com dados previamente coletados. Para simular os diferentes arranjos e manejos no sistemas determinou-se 29 zonas agroclimáticas para representar toda a região produtora pecuária brasileira. Os sistemas silvipastoris simulados foram selecionados pelas combinações de espaçamentos entre renques (15, 30 e 45 m), duas orientações (Norte-Sul e Leste-Oeste) e renques simples ou triplos. As simulações foram replicadas para diferentes idades das árvores (2, 4, 6, 8, 10 e 12 anos). Simulou-se quatro cenários de manejo das árvores com base nas práticas mais adotadas pelos produtores. Para sistemas silvipastoris com renques simples, foram simulados dois manejos: (i) poda de 40% da copa e desbaste alternada de 50% das árvores (M1) e (ii) poda de 40% da copa das árvores (M2). Para renques triplos, simulou-se os seguintes manejos: (i) poda de 40% da copa e desbaste alternada de 50% das árvores (M3) e (ii) poda de 40% da copa e desbaste das árvores externas (M4). Verificou-se que todos os arranjos de sistemas silvipastoris apresentaram uma produção satisfatória nos primeiros anos de implantação do sistema. Simulações para árvores com 2 anos de idade indicaram que os níveis de produção de biomassa forrageira variaram de 16.000 a 18.000 kg ha^{-1}. Verificou-se a necessidade de práticas de manejo das árvores após 6 anos da implantação dos sistemas silvipastoris com 15 m de espaçamento. A poda ou desbaste são recomendados após 8 anos para sistemas com espaçamento de 30 m e após 10 anos nos sistemas com espaçamento entre renques de 45 m. Essa abordagem apresentou resultados satisfátorios e pode ser aplicada para outras espécies ou até mesmo outros tipos de sistemas agrossilvipastoris, se mostrando uma ferramenta importante para auxiliar no planejamento e tomada de decisão.

Palavras-chave: Pecuária-floresta, Modelagem de culturas, Sombreamento, Arranjo, Manejo das árvores, Consócio de culturas

ABSTRACT

Understanding the Brazilian silvopastoral systems based on experimental data and functional-structural modeling

Currently, studies have shown the potential of silvopastoral systems to increase the sustainability of livestock production through the integration of trees, pastures, and animals. However, the addition of trees to the system can decrease pasture growth, make management and planning operations more complex, and thus limit its adoption. This study aimed to evaluate the incidence of solar radiation in silvopastoral systems and, based on experimental data and a functional-structural model, to evaluate different arrangements and management of trees in Brazil. For this, 50 photosynthetically active radiation points were glued between the tree rows, in addition to forage samples in 3 different treatments; 2 distances between rows of trees (4 m and 15 m) and full sun. It was found that the tree row orientation and the sun position throughout the year influenced the quality and production of forage. Forage production was lower closer to the tree row, with lower fiber content and higher production in all seasons in the center of rows. An approach was developed in which a functional-structural plant model was coupled to a process-based model for simulating the intercepted radiation by trees at different ages and forage production. Both models were calibrated with previously collected data. To simulate the different arrangements and managements in the systems, 29 agroclimatic zones were determined to represent the entire Brazilian livestock producing region. The simulated silvopastoral systems were selected by the combinations of spacing between rows (15, 30, and 45 m), two orientations (North-South and East-West), and single or triple rows. The simulations were replicated for different tree ages (2, 4, 6, 8, 10, and 12 years). Tree management scenarios were simulated based on the most adopted practices by producers. For silvopastoral systems with simple rows, two managements were simulated: (i) pruning of 40% of the canopy and alternate thinning of 50% of the trees (M1) and (ii) pruning of 40% of the canopy of the trees (M2). For triple rows, the following managements were simulated: (i) pruning of 40% of the canopy and alternate thinning of 50% of the trees (M3) and (ii) pruning of 40% of the canopy of trees and thinning of external trees lines (M4). It was verified that all the silvopastoral systems arrangements showed satisfactory production in the first years of system implantation. Simulations for 2 year old trees indicated that forage biomass production levels ranged from 16,000 to 18,000 kg ha^{-1}. The need for tree management practices was required 6 years after the implantation for arrangements with 15 m spacing between rows. Pruning or thinning was recommended after 8 years for systems with a spacing of 30 m and after 10 years for systems with a tree row spacing of 45 m. This approach showed satisfactory results, being dan important tool to assist in planning and decision-making in these types of systems.

Keywords: Livestock-forest, Crop modeling, Shading, Arrangement, Tree management, Intercropping

1. INTRODUCTION

Silvopastoral systems are a kind of agroforestry that associates trees, pastures, and animals (Paciullo *et al.*, 2017). This type of system combines the conservation of natural resources with animal production, resulting in more sustainable livestock (Franchini *et al.*, 2014). In this sense, some benefits have been described in the literature, as the optimization of the land use (Alao and Shuaibu 2013), improvement of physical and chemical soil conditions (Lemaire *et al.*, 2014), as well as higher animal thermal comfort (Magalhães *et al.*, 2020; Pezzopane *et al.*, 2019; Morales *et al.*, 2017).

Shading caused by trees when in satisfactory quantity and quality has been shown to be an economically viable option for animal production based on grazing (Paciullo *et al.* 2014). It is important to remark that to achieve adequate levels of forage production is necessary to provide enough radiation incidence. For this, the forage species in these systems depends on their adaptability to grow and develop under environmental conditions altered by the presence of trees (Soares *et al.*, 2009), since the shading change the microclimate (Pezzopane *et al.*, 2015) and affects the quantity and quality of the forage produced (Gobbi *et al.*, 2009).

The success of livestock production in silvopastoral systems is determined, mainly, by the radiation availability within the system. Shading caused by trees has a huge impact on the equilibrium of the microclimatic conditions, which can result in benefits or damage to all system components (Geremia *et al.*, 2018). The effects of radiation incidence on the production of forage, in general, is conditioned by the management of four factors: (i) row spacing, through tree density and planting arrangement; (ii) selection of tree species with an open canopy, the gender Eucalyptus are the most cultivated in Brazil, followed by Pinus, Acacia, and Tectona (Andrade *et al.*, 2012); (iii) thinning and pruning of trees; (iv) forage species tolerant to shading (Oliveira Neto and Paiva, 2010). According to the climatic conditions of each region, the interactions between these factors may result in the different performance of pasture production. In this sense, the adoption of silvopastoral systems should be evaluated and planned specifically for each location (Soares *et al.*, 2009).

If the silvopastoral systems are arranged to guarantee sufficient radiation availability, shade tolerance mechanisms allow pastures to sustain productivity at levels equivalent to those of pastures without shade (Gomes *et al*., 2020), resulting in similar livestock productivity (Carvalho *et al*., 2019). Grasses adapted to shading change their carbon translocation, prioritizing shoot growth to increase leaf area index and to improve radiation use efficiency (Gomes *et al*., 2019).

The proper management of trees is fundamental for capitalizing on existing synergies supporting forage growth and, consequently, livestock productivity (Carvalho *et al.*, 2019). In this sense, pruning places a role to regulate the structure of trees and contribute to the growth of forage (Ortega-Vargas *et al.*, 2019), while thinning might reduce the light, water, and nutrient intraspecies competition, favoring the tree growth and avoiding depletion of the pasture production (Nicodemo *et al.*, 2016).

In this way, if the silvopastoral system is not properly scaled and managed the potential advantages and benefits provided for the addition of the tree can become a factor prejudicial and negatively affect the physiological responses of the pastures and decrease herbage accumulation (Zhang *et al.*, 2018). To understand the dynamics and interactions between trees and pasture species that occur in this system it is necessary to apply tools to assess impacts caused by micrometeorological and management factors. Crop modeling is able to represent and describe the relationship between the components, expressing the hypothesis, and suppositions idealized about the real system (Lara; Rakocevic, 2014).

Functional-structural plant (FSP) modeling, also known as 3D modeling, has been applied for assess tree rows and arrangements effects on pasture production because it can simulate light competition by different species in a mixture. Mao *et al.* (2016) used the FSP modelling to determine the optimum row spacing and population density in wheat (*Triticum aestivum*) crop, in association with cotton (*Gossypium* L.), considering the radiation interception by the plants to define the arrangement that reduced the competition. In this way, Zhu *et al.* (2015) studied plant plasticity in a mixture of wheat and maize (*Zea mays*), testing the adaptation capacity of these crops at different population density and arrangements, as well as effects on the radiation interception.

Crop models have been used to simulate the growth of forage species and the biomass production in systems conducted at the full sun (Pedreira *et al*., 2011; Pequeno *et al*., 2014; Pequeno *et al*., 2018), but few studies were realized aiming to calibrate models and simulate the forage biomass production in silvopastoral systems (Bosi *et al*., 2020; Gomes *et al*., 2020). In general, these studies carried out in silvopastoral systems employed just one calibration to represent the pasture, even with different conditions of solar radiation incidence. In addition, process-based models do not consider the interactions between species that composed the system. In this sense, FSP models are capable of representing the structure of trees of different ages and calculate the amount of solar radiation intercepted by them.

Therefore, the 3D modeling of the production, structure, and functionality of pastures was not properly explored in reason of the complexity in representation of the architecture of plants, heterogeneity vertical and horizontal in the canopy and the dynamic of growth and effects of grazing in the forage development (Verdenal, 2009). Then, it emphasizes the need for new research aiming to apply the functional-structural plant modeling for optimizing the arrangements production in the silvopastoral systems, and reducing uncertainties associated with tree arrangements for a more productive and sustainable livestock production systems.

1.1 OBJECTIVES

The main objective of this study was to understand the effects of solar radiation interception by trees in the pasture growth into silvopastoral systems based on experimental data and functional-structural simulations.

1.1.1 SPECIFIC GOALS

a) Evaluating the forage mass and nutritive value across a shade gradient in a silvopastoral system

b) Developing a model capable of simulating the radiation interception in a silvopastoral system considering the structural aspects of trees.

c) Calibrating a process-based to simulate the forage biomass production, then couple it to simulations of solar radiation incidence above the pasture.

d) Simulating different arrangements for trees in silvopastoral systems for Brazil.

e) Simulating the pruning and thinning impacts on the forage biomass production in several arrangements of silvopastoral systems.

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2. FORAGE MASS AND NUTRITIVE VALUE OF TIFTON 85 GRASS IN A SILVOPASTORAL SYSTEM WITH EUCALYPTUS IN SOUTHERN BRAZIL

ABSTRACT

Silvopastoral systems are efficient alternatives to increase animal production, improve thermal comfort, and enhance weight gain. The addition of the tree component changes the solar radiation incidence, and high levels of shading can limit forage production. We evaluated the effects of Eucalyptus shading on the forage mass and nutritive value of Tifton 85 grass in a silvopastoral system. This study was conducted in Ibiporã, Paraná, Brazil (23.16° S; 51.01° W; 484 m a.s.l), in a silvopastoral system of eucalyptus (*Eucalyptus grandis*) with Tifton 85 bermudagrass (*Cynodon* spp). The trees were planted in single rows (north-south) with 30 m between rows. To verify the influence of shading on forage mass and nutritive value, three treatments were considered: below the tree canopy (4 m), in the center of the row spacing (15 m), and in the pasture in full sun (FS). Photosynthetically active radiation (PAR) was measured at 50 points per experimental unit in all four seasons. There were changes in the PAR incidence throughout the year due to solar inclination and PAR interception by trees. The lowest forage mass was observed at 4 m for all seasons. Also, the greatest forage mass and the lowest fiber content were found at 15 m. Moderate shading did not negatively affect the Tifton 85 characteristics in this silvopastoral system.

Keywords: Bromatological composition; Cynodon spp.; Livestock-forest; Photosynthetically active radiation.

2.1. INTRODUCTION

Projections show that the world population will reach 9.3 billion inhabitants by 2050 (Nations 2019), and hence, food demand would increase by 60%. Nowadays, global meat production is 288 million Mg, and an increasing population will demand that the livestock sector produces nearly 463 million Mg (OECD-FAO 2016). In this context, Brazil has an important position as the largest beef producer and exporter in the world (ABIEC 2018); livestock production is carried out in forage-based systems mostly in full sun, on an area occupying 23% of the national territory (Neely, Bunning & Wilkes 2009).

Inadequate pasture management can result in soil degradation and decreased forage quality and quantity, explaining the current low productivity. Besides, tropical livestock is highly influenced by thermal stress, limiting weight gain (Moura *et al.*, 2010). In this sense, it is necessary to adopt practices that enhance livestock efficiency, increasing beef production without expanding the pasture areas (Garcia *et al.*, 2017).

Silvopastoral systems are viable alternatives to intensify livestock production, associating trees, pastures, and animals (Carvalho *et al.*, 2019). The trees in the system reduce the impacts of high temperatures and radiation, enhancing animal welfare (Vieira Junior *et al.*, 2019) and increasing system productivity (Pezzopane *et al.*, 2019). Such systems also can improve soil physical and chemical characteristics throughout the years (Gatto *et al.*, 2010), mainly because of the increase in soil organic matter and improved nutrient cycling (Souza *et al.*, 2010). Consequently, the environmental impact of livestock breeding is decreased, while, at the same time, animal thermal indices are reduced, allowing a more sustainable production.

However, the integration of the different components in a silvopastoral system can result in positive, neutral, or negative interactions, depending on the level of competition among components. The ideal design of such a system might be an interaction between tree and forage components, optimizing the production (Geremia *et al.*, 2018). Tropical forages, in general, are better adapted and more efficient in full-sun systems (Santos *et al.*, 2017), but some shade-tolerant species can also be used. However, even forages considered tolerant to shading show a decrease in dry matter production when exposed to intense shading (Faria *et al.*, 2018), which is associated with morphologic and physiologic responses of the forage to maximize radiation uptake (Gomes *et al.*, 2019; Nascimento *et al.*, 2019).

The lack of information about the optimal spacing and arrangement of trees in such systems is one of the challenges, making it necessary to investigate the potential interactions among different species in silvopastoral systems. We hypothesize that shading intensity in a silvopastoral system has an impact on pasture productivity, contributing to the development of a sustainable production system. To test this hypothesis, we studied a eucalyptus-Tifton 85 silvopastoral system to evaluate forage mass and nutritive value by clipping across a shade gradient in a silvopastoral system with *Eucalyptus urograndis* in Southern Brazil.

2.2. MATERIAL AND METHODS

Site characteristics and fertilization management

This study was conducted at the Agronomic Institute of Paraná (IAPAR) experimental station, located in the municipality of Ibiporã, Paraná, Brazil (23.16° S; 51.01° W; 484 m a.s.l.). The climate is subtropical humid (Cfa), according to the classification of Köppen, with hot summers and an undefined dry season (Nitsche *et al.*, 2019). The soil was classified as Red Nitosol (EMBRAPA 2018).

Soil samples were collected at the 0–20-cm layer in December 2016, with the following basic soil properties: pH in $CaCl_2$ = 4.9, organic matter = 37.1 g dm^{-3}, P = 12.1 mg dm^{-3}, Ca = 8.0 $cmol_c$ dm^{-3}, Mg = 2.63 $cmol_c$ dm^{-3}, K = 0.33 $cmol_c$ dm^{-3}, Al = 0.05 $cmol_c$ dm^{-3}, H+Al = 7.2 $cmol_c$ dm^{-3}, sum of bases = 10.96 $cmol_c$ dm^{-3}, effective cation exchange capacity = 18.2 $cmol_c$ dm^{-3}, and base saturation = 60.4%. To correct soil acidity and increase calcium and magnesium levels, 4.75 Mg ha^{-1} of limestone was applied (RTNP = 75.2), taking as a criterion the increase in base saturation to 80%. As a low stocking rate was maintained in the area, 80 kg of N per ha and 20 kg of K_2O ha were applied per year.

Silvopastoral system and treatment description

The experimental area was composed of a silvopastoral system of eucalyptus (*Eucalyptus grandis*) with Tifton 85 bermudagrass (*Cynodon* spp.) in an area of 1.6 ha, which had been implemented in 2011. The trees were planted in simple rows of 60 m, with a row spacing of 15 m. At an age of 4 years, the trees were thinned to reduce the length of the rows to 30 m and to increase the spacing between rows to 30 m. Trees were planted in north-south rows with an intra-row spacing of 3 m (112 trees ha^{-1}). At the beginning of this study, the trees were around 20 m tall.

The area was used for the low-intensity management of Holstein cows, with an average grazing interval of around 25 days and an instant stocking rate of 30 animal unit (AU) per ha. A pasture plot in full sun was used for comparison. The experiment was carried out from March 2017 to February 2018 in a randomized complete block design under a strip-split-plot arrangement, with 10 replications for the photosynthetically active radiation (PAR) and 5 for the forage characteristics (Fig. 1).

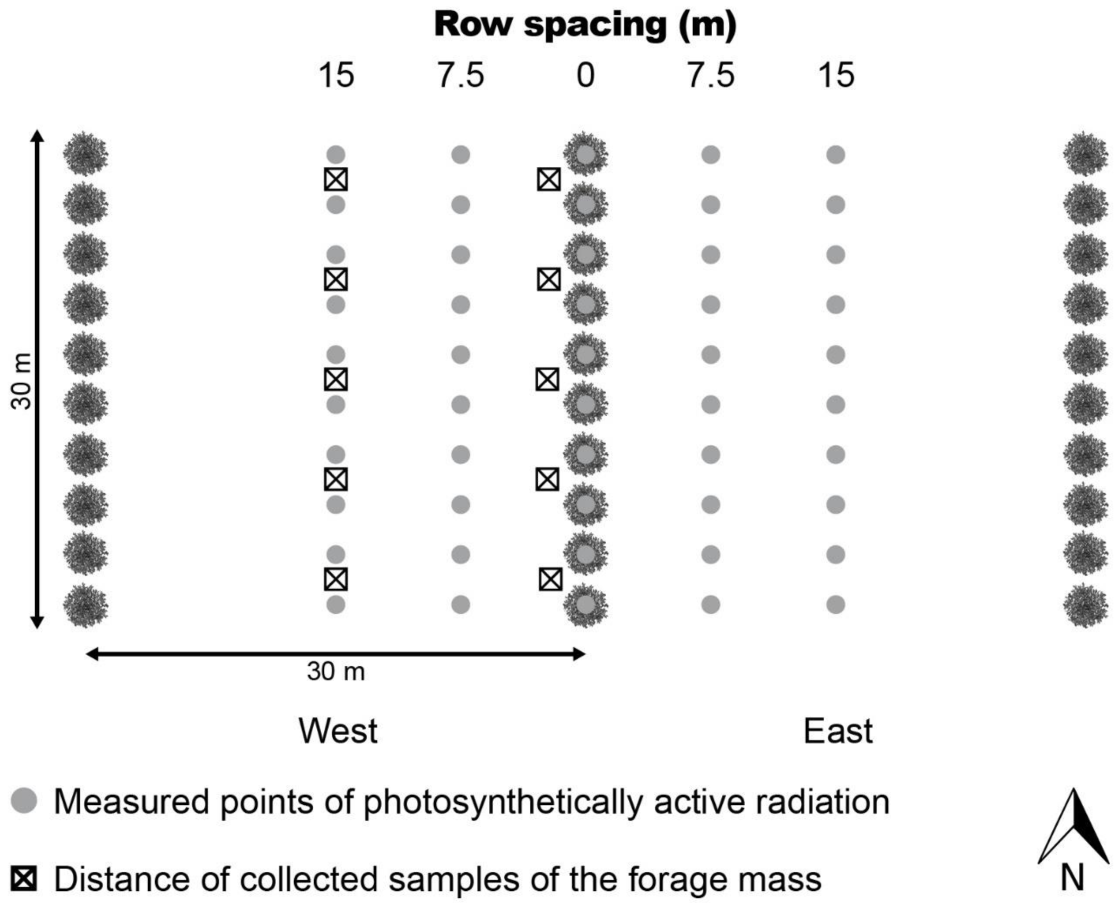

Fig. 1. Schematic representation of the silvopastoral system with the measured points of photosynthetically active radiation and collected samples of the forage mass.

Light environment

The PAR was measured with a ceptometer (1-m bar with 80 sensors) (Accupar lp-80, Decagon). Measurements were taken monthly on days without clouds, with hourly measurements from 08:00 to 17:00 h. The PAR was collected in 5 distances between the trees rows, starting from the closest distance from the trees (0m) and two more measurements on each side (7.5 m west, 15 m west, 7.5 m east, and 15 m east). for each distance, 10 sites were evaluated, at a spacing of 3 m, creating a 5 x 10-m grid, totaling 50 measures hourly (Fig. 1). Assuming that the measurements at 15 m for both sides represented the same microclimatic conditions, PAR for this distance was analyzed using the average of both samplings. For comparative purposes, one measure was also performed in the full-sun pasture, just after taking measurements in the silvopastoral system.

The PAR data collected in each month were grouped by mean values for each season. Interpolation between distances by inverse-distance weighting (IDW) was performed to visualize and identify the trends during each season of the year. In addition, the length of the shade was measured in 10 points (at a spacing of 3 m) every hour for the same period of the PAR analysis, using a tape measure.

Forage mass and nutritive value

To represent the effects of the PAR distance in the pasture growth, samples were collected in three different treatments: in the silvopastoral system, under the canopy of trees, considering a distance of 4 m from the row trees (4 m), in the center of the row spacing (15 m, Fig. 1), and in an adjacent full-sun pasture (FS). Sampling was performed for each season on the following dates: 05/16/2017 (autumn), 07/17/2017 (winter), 11/14/2017 (spring), and 02/09/2018 (summer).

A sampling square of 0.5 m^2 was used, which was randomly launched at five replications for each treatment to obtain a representative sample of the forage in each microclimate. The samples were cut at 5 cm above the ground, packed in a paper bag, and submitted to drying in a forced air circulation oven for 72 hours at a temperature of 65°C.

The chemical composition of the forage samples was obtained through analysis of the neutral detergent fiber (NDF), acid detergent fiber (ADF), mineral content (MC), and crude protein (CP), following the methodology described by Silva and Queiroz (1981). To determine the forage mass per hectare (FM), the samples were weighed after cutting to quantify the green mass and subsequently oven-dried at 55ºC until constant weight to obtain the dry mass.

Statistical analysis

Data were analyzed using the method of generalized linear mixed models with parametric structure; for evaluation and to generate the interaction plot, we applied R 3.6.3 (R Core Team 2018), using the agricolae package (Mendiburu 2014). The average values of PAR, FM, and nutritive values (NDF, ADF, MC, and CP) were estimated and the comparisons were performed using the Tukey test at the 5% significance level.

For the PAR measurements, the replications (block) were considered as random effect. The distances (0 m, 7.5 m east, 7.5 m west, and 15 m), seasons (autumn, winter, spring, and summer), and their interactions were considered fixed effects. The following model was used:

$$Y_{ijk} = \mu + D_i + b_j + a_{ij} + S_k + (DS)_{ik} + \varepsilon_{ijk} \tag{1}$$

where Y_{ijk} = expected response; μ = general average; D_i = fixed parameter associated with distance (0 m, 7.5 m East, 7.5 m west, and 15 m) i; b_j = random parameter associated with block $j \sim$ NID (0, $^o\sigma^2$ b); a_{ij} = error associated with distance i, in block $j \sim$ NID (0, $^o\sigma^2$ a); S_k = fixed parameter associated with season (autumn, winter, spring, and summer) k; DS_{jk} = interaction (distance x season) ik; ε_{ijk} = experimental error associated with distance i, season k, and its interaction, in the block $j \sim$ NID (0, $^o\sigma^2$ ε).

For the forage variables, FM, and nutritive values, the replications (block) were considered as random effect. The treatments (FS, 15 m, and 4 m), seasons (autumn, winter, spring, and summer), and their interactions were considered fixed effects. The model was as follows:

$$Y_{ijk} = \mu + T_i + b_j + a_{ij} + S_k + (TS)_{ik} + \varepsilon_{ijk} \tag{2}$$

where Y_{ijk} = expected response; μ = general average; T_i = fixed parameter associated with treatment (FS, 15 m, and 4 m) i; b_j = random parameter associated with block $j \sim$ NID (0, $^o\sigma^2$ b); a_{ij} = error associated with treatment i, in block $j \sim$ NID (0, $^o\sigma^2$ a); S_k = fixed parameter associated with season (autumn, winter, spring and summer) k; TS_{jk} =

interaction (treatment x season) ik; ε_{ijk} = experimental error associated with treatment i, season k, and its interaction, in the block $j \sim$ NID (0, ºσ^2 ε).

2.3. RESULTS

The PAR incidence was affected by season ($p < 0.0001$), distance ($p < 0.0001$), and season x distance interaction ($p < 0.0001$, Table 1). The higher incidence of PAR occurred in the summer for all distances, except for 0 m. Overall, lower values were observed in autumn and winter. The highest incidence of PAR at 15 m occurred in the summer, and no differences were observed between 15 m and 7.5 m west. In autumn, the highest PAR incidence was recorded at 7.5 m west, which was similar to 15 m and differed from 7.5 m east and 0 m, with no differences verified between distances in winter (Table 1).

Table 1. Photosynthetically active radiation (μmol m^{-2} s^{-1}) across distances (15 m, 7.5 m West, 7.5 m East and 0 m) and seasons (autumn, winter, spring, and summer) in Ibiporã-Paraná, between 2017 and 2018.

Season	**Distance**				SE
	0 m	**7.5 m east**	**7.5 m west**	**15 m**	
	μmol m^{-2} s^{-1}				
Autumn	684 Bb†	662 Cb	978 Ca	838 Cab	790.1‡
Winter	638 Ba	700 Ca	857 Ca	781 Ca	743.1
Spring	882 Ac	1363 Bb	1842 Ba	1921 Ba	1502.3
Summer	875 ABc	2257 Ab	2166 Ab	2570 Aa	1966.7
SE	601.2	1100.9	1359.8	1378.4	

†Uppercase letters compare seasons within distances and lowercase letters compare distances within seasons by t-test ($p < 0.05$). ‡ SE: standard error.

The tree-row orientation and the sun trajectory throughout the day in the different seasons determined the PAR availability inside the system (Fig. 2). The incident PAR at noon showed the lowest value in the winter at 7.5 m east. The highest values were verified at distances close to 7.5 west. In summer, a higher PAR incidence occurred between tree rows (from 7.5 to 15 m); the lowest values were recorded in a small area close to the tree row (0 m). In autumn and spring, shading resulted in a lower incidence of PAR on the eastern side, exceeding 15 m in both seasons. The highest values were verified close to the tree row on the western side, ranging from 2,155 to 3,762 μmol m^{-2} s^{-1}.

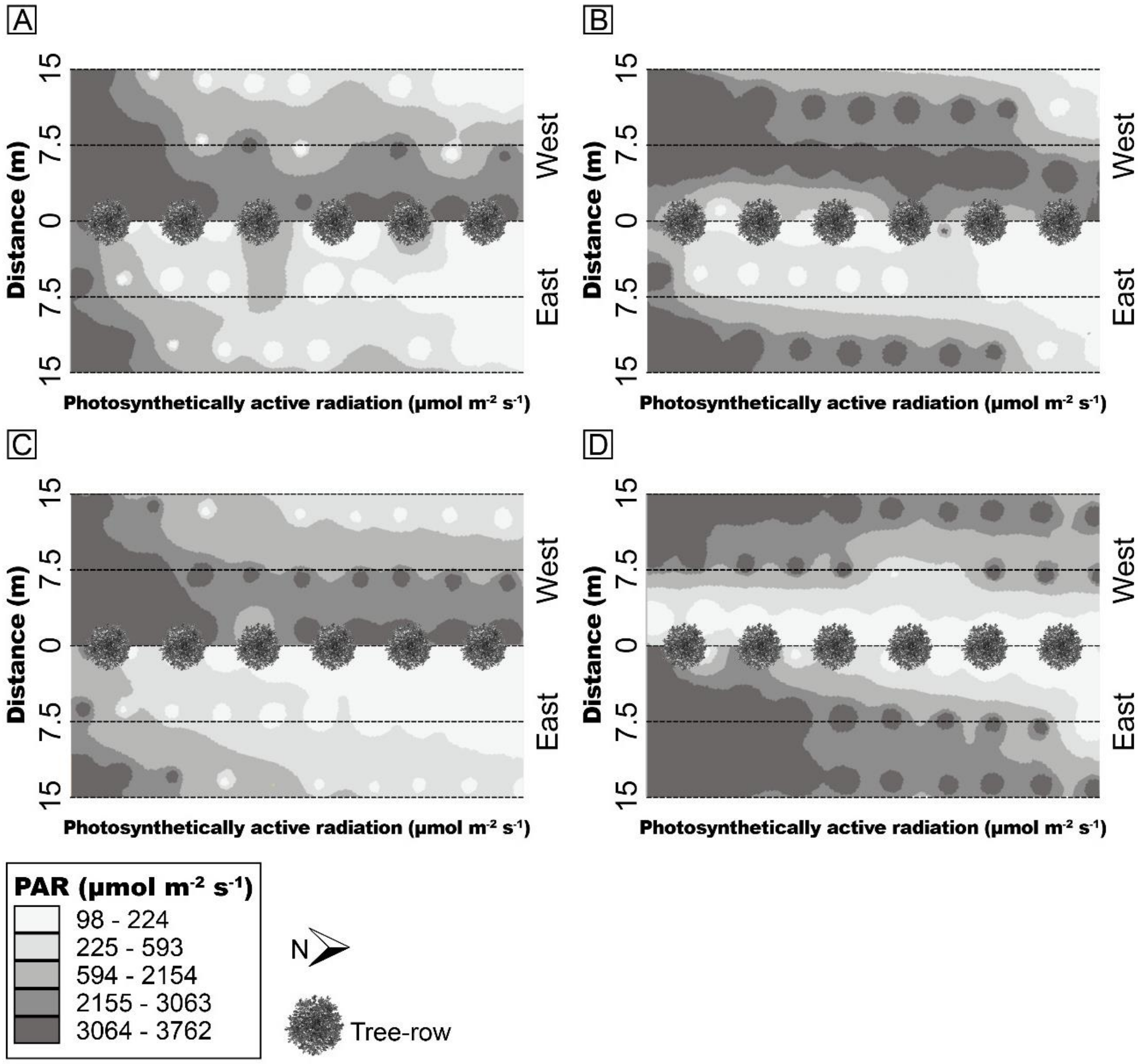

Fig. 2. Spatial and temporal incidence of photosynthetically active radiation (μmol m^{-2} s^{-1}) in inter-row of the silvopastoral system at 12:00 pm for a day of measurements for the seasons (A – autumn; B – winter, C – spring and D – summer), in Ibiporã-Paraná, in 2017 and 2018.

Solar inclination had a direct effect on shade projection and corroborated with the trends measured in the PAR incidence inside of the silvopastoral system. Shade projection was evaluated from 8:00 to 17:00 h on 1 day for each season (Fig. 3). In the winter, the shade was projected to the western side until 9:00 and did not exceed 7.5 m. After 13:00 h, the shade exceeded 15 m and covered all the spacing between the tree rows towards the eastern side. In the summer, the opposite effect was observed, with shade projection to the western side, covering almost all pasture in the first hours of the day and decreasing gradually until 13:00 h. Then, the shade was projected to the eastern side and achieved 15 m only at 16:00 h, not covering the spacing between the tree rows. In autumn and spring, similar trends were registered, when the length of the shade covered the row spacing at around 14:00 h.

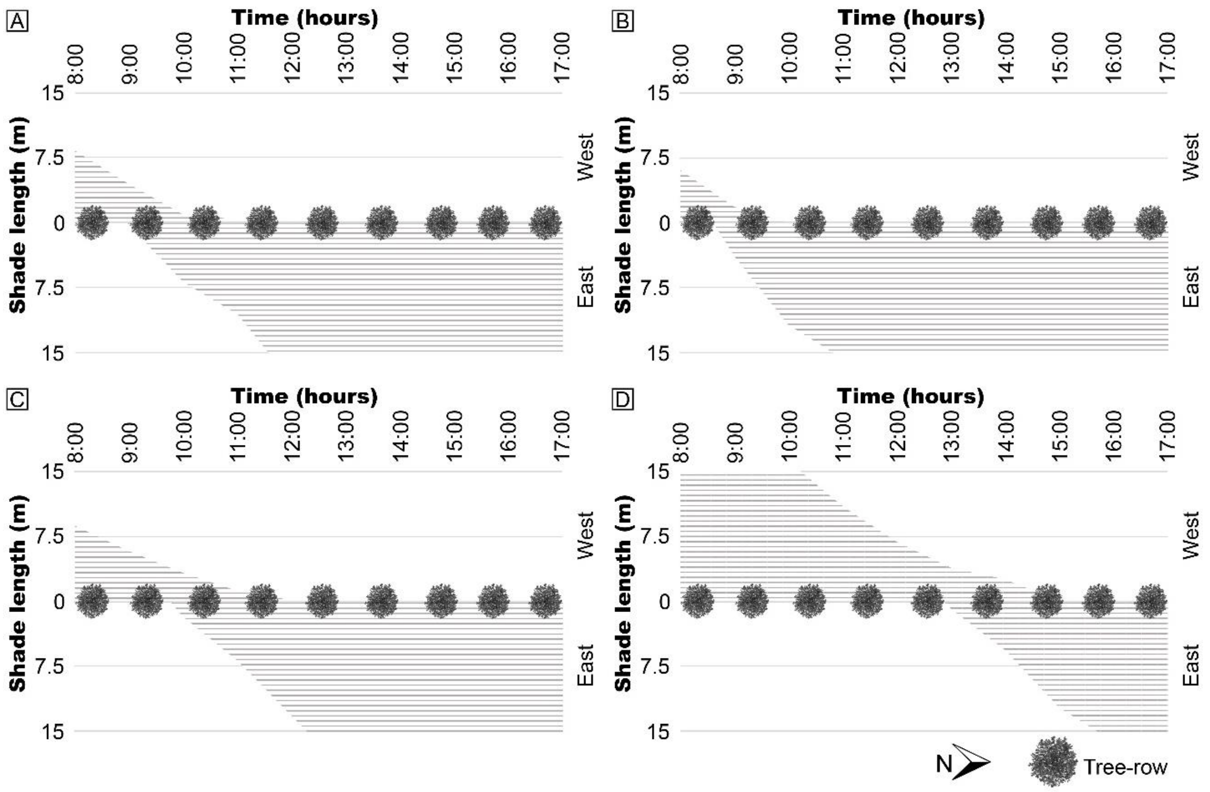

Fig. 3. Shade projection in the silvpastoral system for the seasons (A – autumn; B – winter, C – spring and D – summer), in Ibiporã-Paraná, between 2017 and 2018.

The PAR interception was higher at 0 m in all seasons, with values above 60% (Fig. 4). High values were also observed at 7.5 m west in autumn (61%) and winter (60%). Comparing the PAR interception between the seasons, we found the highest average of the interception in winter (58%). In contrast, the lowest average was observed in summer (37%), and even at 0 m, the trees intercepted 72% of the PAR incident, the highest value observed; for the other distances, interception was below 30% (Fig. 4).

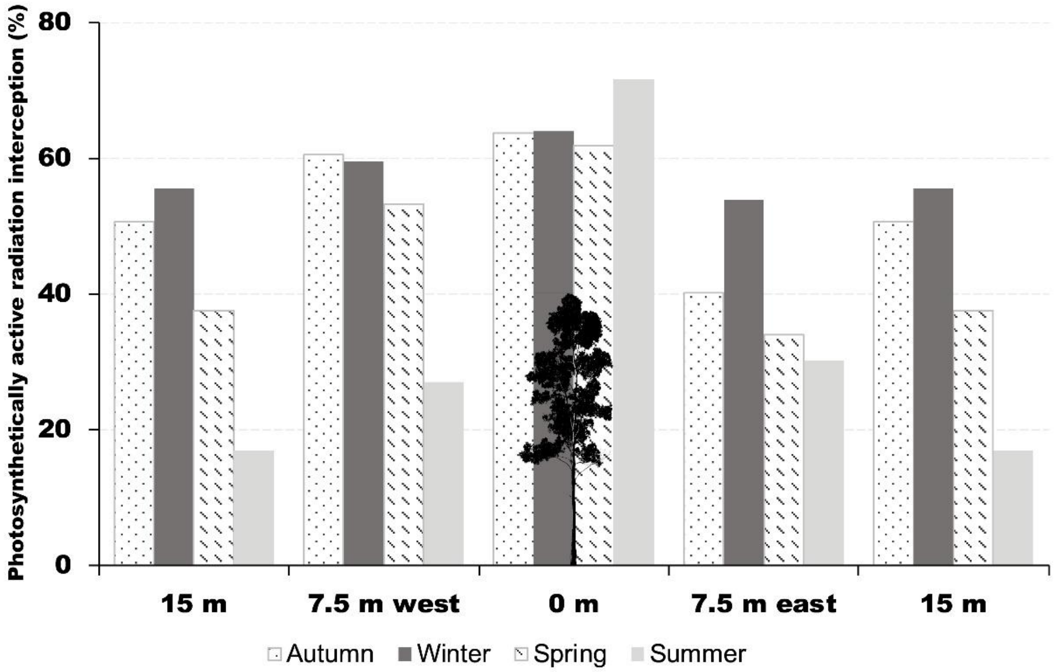

Fig. 4. Mean of the photosynthetically active radiation interception (%) in the silvopastoral system for the seasons (A – autumn; B – winter, C – spring and D – summer), in Ibiporã-Paraná, between 2017 and 2018.

The shade caused by the trees on the pasture resulted in changes in forage mass and chemical composition. The effects of shading on the forage characteristics were modified across seasons and distances (Table 2). The greatest FM was observed for summer, decreasing in spring and autumn, and the smallest value occurred in winter. The highest CP content was observed in autumn and the lowest in summer. Regarding MC, the highest value was observed in winter, the spring and summer values were similar, and the lowest value occurred in autumn. The NDF content was higher during winter and lower in autumn and spring. Regarding ADF, higher values occurred in autumn and summer; the lowest values were observed in winter. Analyzing the treatments, the greatest FM was observed in FS, followed by 15 m, and the smallest value was measured at 4 m. Higher NDF contents were observed in the FS and at 4 m; the other variables were not affected by the treatment (Table 2).

Table 2. Forage mass (FM), mineral content (MC), neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude protein (CP) for each season (autumn, winter, spring, and summer) and treatment (FS, 15 m, and 4 m), for a silvipastoral of eucalyptus (*Eucalyptus grandis*) with Tifton 85 bermudagrass in Ibiporã-Paraná, between 2017 and 2018.

	FM	**MC**	**NDF**	**ADF**	**CP**
	kg ha^{-1}	g kg^{-1}			
		Season			
Autumn	3157 b	87 c	799 c	437 a	126 a
Winter	2325 c	103 a	817 a	417 c	109 b
Spring	3141 b	92 b	800 c	423 b	92 c
Summer	4293 a	91 b	808 b	439 a	84 d
MSE	914	8	17	16	17
p-value	< 0.0001***	< 0.0001***	0.0012**	0.0028**	< 0.0001***
		Treatment			
FS	3816 a	91	813 a	429	95
15 m	3454 b	95	794 b	426	110
4 m	2418 c	94	811 a	432	106
MSE	993	9	16	19	23
p-value	< 0.0001***	0.2299 ^{ns}	< 0.0001***	0.6799 ^{ns}	0.0713^{ns}

The values of FM (p = 0.0440), NDF (p < 0.0001), and MC (p < 0.0001) were affected by season x treatment interaction (Table 3); FM production was greatest in FS during winter and summer. In autumn and spring, FM was greatest at 15 m. The FM production was lowest at 4 m in all seasons when compared with the other treatments. The greatest FM values were found for summer in all treatments, whereas the lowest ones were observed in winter at 15 and 4 m and in autumn in FS (Table 3).

Table 3. Forage mass (FM), neutral detergent fiber (NDF) and mineral content (MC) and across seasons (autumn, winter, spring, and summer), treatments (FS, 15 m and 4 m) and interaction (season x treatment), for a silvopastoral system of of eucalyptus (*Eucalyptus grandis*) with Tifton 85 bermudagrass in Ibiporã-Paraná, between 2017 and 2018.

	Season				
Treatment	Autumn	Winter	Spring	Summer	SE
			FM (kg ha^{-1})		
FS	3272 Bd†	3296 Ac	3312 Bb	5384 Aa	1145‡
15 m	3536 Ac	2368 Bd	3592 Ab	4320 Ba	978
4 m	2664 Cb	1312 Cd	2520 Cc	3176 Ca	858
SE	785	948	722	1201	
			NDF (g kg^{-1})		
FS	839 Aa	799 Bc	802 ABc	812 Ab	19
15 m	805 Ba	781 Cd	792 Bbc	797 Bab	15
4 m	805 Ba	815 Aa	809 Aa	814 Aa	13
SE	19	9	13	14	
			MC (g kg^{-1})		
FS	86 ABb	101 ABa	89 Bb	88 Bb	8
15 m	93 Ab	110 Aa	88 Bb	91 ABb	7
4 m	82 Bb	99 Ba	98 Aa	96 Aa	10
SE	7	8	8	6	

†Uppercase letters compare seasons within treatments and lowercase letters compare treatments within seasons by t-test ($p < 0.05$). ‡ SE: standard error.

In autumn, the highest content of NDF was verified in FS, whereas in spring and summer, the value was similar to that at 4 m. In contrast, the NDF content was higher at 4 m than at the other treatments in winter. The NDF content was lower at 15 m in all seasons, except autumn. The highest contents of NDF occurred in autumn at FS and

15 m. For 4 m, we found no statistically significant difference among seasons (Table 3).

The MC content was higher at 15 than at 4 m and similar to that of FS, during autumn and winter. In the spring, the content was higher at 4 m than in the other treatments, whereas in summer, it was higher at 4 m than at FS, but was similar to that at 15 m. For the treatments FS and 15 m, the highest MC contents were observed in winter. At 4 m, the values were similar in all seasons, except for autumn, when the lowest MC value was recorded (Table 3).

In spring, the average PAR incident at 15 m was similar to that of FS in winter, but FM production was greater at 15 m than at FS (Fig. 5). In autumn, we found a lower average PAR incidence at 15 m (838 μmol m^{-2} s^{-1}) than at FS (1,895 μmol m^{-2} s^{-1}); FM production was greater at 15 m. At 4 m, the average PAR incidence was lower than 900 μmol m^{-2} s^{-1} in all seasons, imped the FM production (Fig. 5).

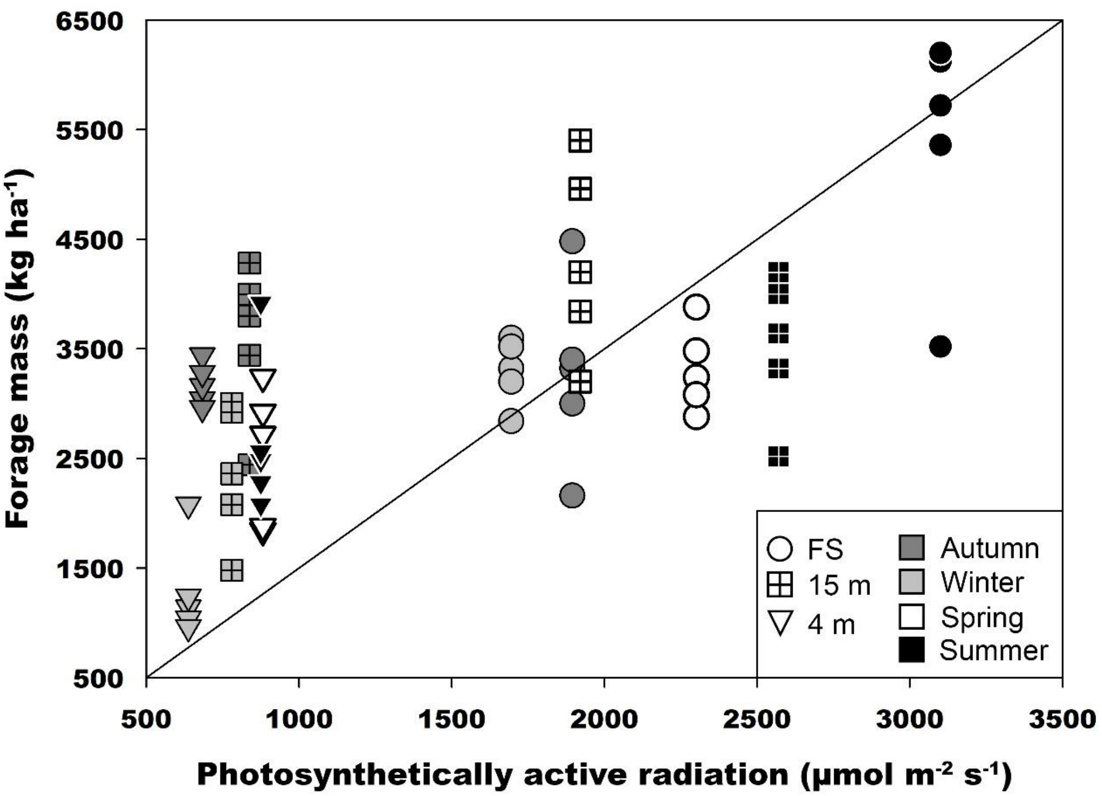

Fig. 5. Relationship between the forage mass (kg ha^{-1}) and photosynthetically active radiation incident (μmol m^{-2} s^{-1}) for the seasons (autumn, winter, spring, and summer) in each treatment (FS, 15 m and 4 m), in Ibiporã-Paraná between 2017 and 2018.

2.4. DISCUSSION

The silvopastoral system was able to maintain its FM at 15 m, surpassing that of full-sun pastures in some seasons (Fig. 5). Shading of up to 51% of the PAR did not negatively influence the growth of Tifton 85 bermudagrass in autumn and spring, when the FM was higher at 15 m than at FS. In summer, even with lower FM values, the moderate shading allowed adequate conditions for the growth of the pasture at 15 m (Fig. 4 and Table 3). During winter, the shading was higher than 50%, decreasing the FM in all silvopastoral treatments (4 and 15 m) when compared to FS (Tables 2 and 3). The decrease in FM was a result of the lower PAR incidence and the longer shading period between the tree rows (Figs. 2 and 3), whereas this effect was observed in all seasons at 4 m (Table 2). Even for shade-tolerant tropical grasses, the production can be reduced by light limitation because of a significant decrease of the photosynthetic rates in C_4 species (Faria *et al.*, 2018). In this regard, the advantage of Tifton 85 bermudagrass as a component of silvopastoral systems must be highlighted when it is compared to other pastures of the genus *Brachiaria*. Previous studies have shown important productive losses by *Brachiaria decumbens* growing under shading higher than 39% (Bosi *et al.*, 2014). In a previous study, *Brachiaria decumbens* cv. Basilisk under shading between 29 and 45% (Castro *et al.*, 2010) and *Brachiaria brizantha* cv. Marandu under shading higher than 30% resulted in production losses (Cabral *et al.*, 2017). Nascimento *et al.*, (2019) suggested that *Brachiaria brizantha* cv. Marandu can tolerate PAR reductions in silvopastoral systems of up to ~ 20% without a negative impact on pasture production.

The lower PAR availability increased NDF, specifically in treatment 4 m in winter, spring, and summer (Tables 2 and 3). This can be attributed to the higher stem proportion as a response of grasses to maximize radiation absorption (Castro *et al.*, 2010). High levels of PAR incidence can result in an increase in the proportion of sclerenchyma tissue, whose cells have thicker walls than under shading conditions (Paciullo *et al.*, 2007). Thus, no differences were verified in the NDF contents between FS and 4 m in spring and summer, with higher values in FS than at 4 m in autumn. Similar results have been reported by Paciullo *et al.* (2009) and Sousa *et al.* (2007), with no differences in the fiber contents between pastures under high shading and under FS. Besides, we highlight a decreased fiber (NDF) content at 15 m (Tables 2 and 3). All treatments provided CP levels greater than those recommended for grazing beef cattle (>70 g kg^{-1}; Minson 1990).

The addition of the tree component requires a more complex management. The shading level caused by the trees determines the success of the livestock production in a silvopastoral system, requiring an equilibrium of the microclimatic conditions to allow the growth of all system components (Geremia *et al.*, 2018). In this context, the heterogeneity of the PAR incidence throughout the year (Table 1) is a factor to be considered during the planning phase of a silvopastoral system. The proper arrangement of system components is fundamental for capitalizing on existing synergies ensuring forage growth and, consequently, livestock productivity (Carvalho *et al.*, 2019). Pruning and thinning can be efficient alternatives to increase the PAR incidence inside the systems and to provide favorable conditions for the grasses (Nicodemo *et al.* 2016).

Another important aspect to be considered is the change in the carbon translocation by the grasses in the understory, prioritizing shoot growth (i.e., leaves) to increase leaf area index (Nascimento *et al.* 2019) and to improve PAR use efficiency (Gomes *et al.* 2019). Based on that, grazing management must be carried out to avoid pasture depletion and to allow adequate regrowth. If the silvopastoral systems are arranged to guarantee sufficient PAR, shade tolerance mechanisms (e.g., increases in specific leaf area and leaf proportion) allow shaded pastures to sustain productivity at levels equivalent to those of pastures without shade (Gomes *et al.* 2020), resulting in a similar livestock productivity (Carvalho *et al.* 2019).

Shading also plays a significant role in providing thermal comfort, protecting the animals from the direct incidence of solar radiation, even if there are no changes in the temperature and relative humidity of the silvopastoral system (Karvatte Junior *et al.* 2016). The addition of trees creates a more favorable environment, facilitating idleness and rumination (Domiciano *et al.* 2018), which results in greater animal weight gain (Pezzopane *et al.* 2019). In the same area, a previous study reported that the animals preferred to take refuge in the understory during the winter in the hottest hours of the day, whereas in summer, they stayed in the shade from the early hours of the morning, spending more than 70% under the shade throughout the analyzed period, from 08:00 to 17:00 h (Vieira Junior *et al.* 2019). However, in the hottest hours of the summer, the animals were exposed to higher levels of radiation (Fig. 2) and the shade projection was small, around 7 m from 11:00 am to 2:00 pm (Fig. 3). The tree row orientation was also determinant for the shading availability in terms of providing an area large enough for the animals (Silva *et al.* 2014), reducing their cardiac frequency due to the need of dissipation of corporal heat (Garcia *et al.* 2011) and, consequently, leading to higher animal productivity. This highlights the necessity of adequate planning in the implementation of the system to maximize the benefits of the shade projection for the animals.

Tifton 85 bermudagrass can be an alternative as a component of a silvopastoral system in Southern Brazil, providing throughout the year (Tables 2 and 3). Besides, several studies have shown that silvopastoral systems can contribute to the recovery of degraded pastures (Lira Junior *et al.* 2020), increase carbon sequestration (Cárdenas *et al.* 2019), and enhance livestock production and income due to timber production, thereby increasing the economic stability of farmers (Leal *et al.* 2019).

2.5. CONCLUSION

The addition of trees to a pasture system affected the incidence of the photosynthetically active radiation, which varied according to the solar inclination. Rows need to be adequately arranged and managed to provide suitable conditions for pasture growth. Moderate shading had no negative effect on Tifton 85 bermudagrass forage mass, although a decrease in fiber content was observed. Overall, the nutritive value and forage mass were adequate to support grazing animals throughout the year. Thus, in the analyzed arrangement, the integration of Tifton 85 bermudagrass with *Eucalyptus* can be recommended as a suitable silvopastoral system in Southern Brazil.

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3. IMPROVING THE ARRANGEMENT OF EUCALYPTUS-MARANDU PALISADE GRASS SILVOPASTORAL SYSTEMS IN BRAZIL

ABSTRACT

Limited land availability and an increasing global population are challenges faced by the agricultural sector in the coming decades. The silvopastoral system is an efficient alternative to full sun pastures that could be used to sustainably intensify animal and crop production. However, the adoption of this system is being held back by a lack of knowledge on how the trees in such a system should be arranged in order to avoid detrimental effects on pasture growth. The aim of this study was to test different arrangements of trees in the Eucalyptus-Marandu palisade grass silvopastoral system and to evaluate its performance in different regions of Brazil. METHODS: A functional-structural plant model was developed to simulate radiation interception by trees and was then coupled to the CROPGRO-Perennial Forage model to simulate the production of forage biomass. The models were calibrated with experimental data collected in silvopastoral systems in Brazil. The silvopastoral systems were selected according to a combination of tree row spacing (15, 30, and 45 m), two row orientations (north-south and east-west), and single or triple rows. Simulations were replicated for different tree ages (2, 4, 6, 8, 10 and 12 years) representing different levels of shading. Our simulations show that the tree arrangement has a significant effect on the incidence of radiation on the pasture, resulting in different levels of forage production. Row spacing of 30 and 45 m is suitable for providing forage for the animals for several years. In contrast, tree arrangements with a row spacing of 15 m or triple lines demand more careful planning and management, taking into account the soil and climatic characteristics of each region. The approach used in this study can be extended to other combinations of species and environments to aid the planning and management of this kind of system.

Keywords: Functional-Structural Plant Modeling; CROPGRO-Perennial Forage; Livestock-forest; Intercropping.

3.1. INTRODUCTION

Silvopastoral systems are a kind of agroforestry that combines trees, pastures, and animals (Paciullo *et al*., 2017). This system can combine the conservation of natural resources with animal production, resulting in more sustainable livestock (Franchini *et al*., 2014). Previously reported benefits include the optimization of land use (Alao and Shuaibu, 2013), improvement of physical and chemical soil conditions

(Lemaire *et al*., 2014), as well as higher animal thermal comfort (Magalhães *et al*., 2020; Pezzopane *et al*., 2019; Tarazona Morales *et al*., 2017).

When in satisfactory quantity and quality shading caused by trees has been shown to be an economically viable option for animal production based on grazing (Paciullo *et al*., 2014). It is important to note that to achieve adequate levels of forage production it is necessary to provide sufficient incident radiation. The type of forage species that can grow in these systems depends on their adaptability to the edaphoclimatic conditions, which are altered by the presence of trees (Soares *et al*., 2009) since shading changes the microclimate (Pezzopane *et al*., 2015) and affects the quantity and quality of the forage produced (Gobbi *et al*., 2009).

The integration of components in the silvopastoral system can result in positive, neutral, or negative interactions, depending on the outcome of competition. In the planning of the system, the main objective is that the tree and forage components interact successfully, optimizing production (Nicodemo *et al*., 2004). The system can be composed of several kinds of forage and tree species, with one of the greatest difficulties in the planning and adoption of such systems being determining the optimal row spacing. The tree density is an important factor in the success of the silvopastoral system (Geremia *et al*., 2018; Santos *et al*., 2016).

If silvopastoral systems are not properly scaled and managed, the potential advantages and benefits provided by the addition of the trees can be negated due to competition for water or radiation. This negatively affects the physiological responses of the pastures and decreases herbage accumulation (Zhang *et al*., 2018). To understand the dynamics and interactions between trees and pasture species that occur in this system, it is necessary to analyze the impacts caused by micrometeorological and management factors. Crop modeling can be used to represent and describe the relationship between the components of the silvopastoral system, testing hypotheses and suppositions about the real system (Lara and Rakocevic, 2014).

The lack of information about the optimal spacing and arrangement of trees in such systems is one of the challenges holding back their adoption. Studies on the effects of shading on the system components are necessary to reduce the uncertainty associated with its implementation and management. We hypothesize that incident radiation will affect pasture growth differently depending on the layout and arrangement of the system. To test this hypothesis, we: (i) developed and tested a structural plant model to simulate the amount of radiation intercepted by trees in different row spacing and orientation arrangements; (ii) calibrated and evaluated the CROPGRO-Perennial Forage model under silvopastoral conditions; and (iii) coupled the simulations of both structural (tree) and functional (pasture) models to simulate and assess the production of forage biomass in different arrangements of the eucalyptus-Marandu palisade grass silvopastoral system across Brazil.

3.2. MATERIAL AND METHODS

An approach was taken that combined structural and functional aspects of the trees and the pasture in the system. A 3D model of the arrangement of trees in a silvopastural system was developed to simulate radiation interception by the trees. Focusing on solar radiation as the resource under competition within the tree-pasture system, the forage component was represented only by functional aspects. Therefore, a process-based model, CROPGRO-Perennial Forage (Rymph *et al*., 2004), implemented in the DSSAT (Decision Support System for Agrotechnology Transfer) platform (Jones *et al*., 2003), was coupled to solar radiation simulations composing the functional-structural plant (FSP) model framework to simulate forage biomass production (Fig. 1).

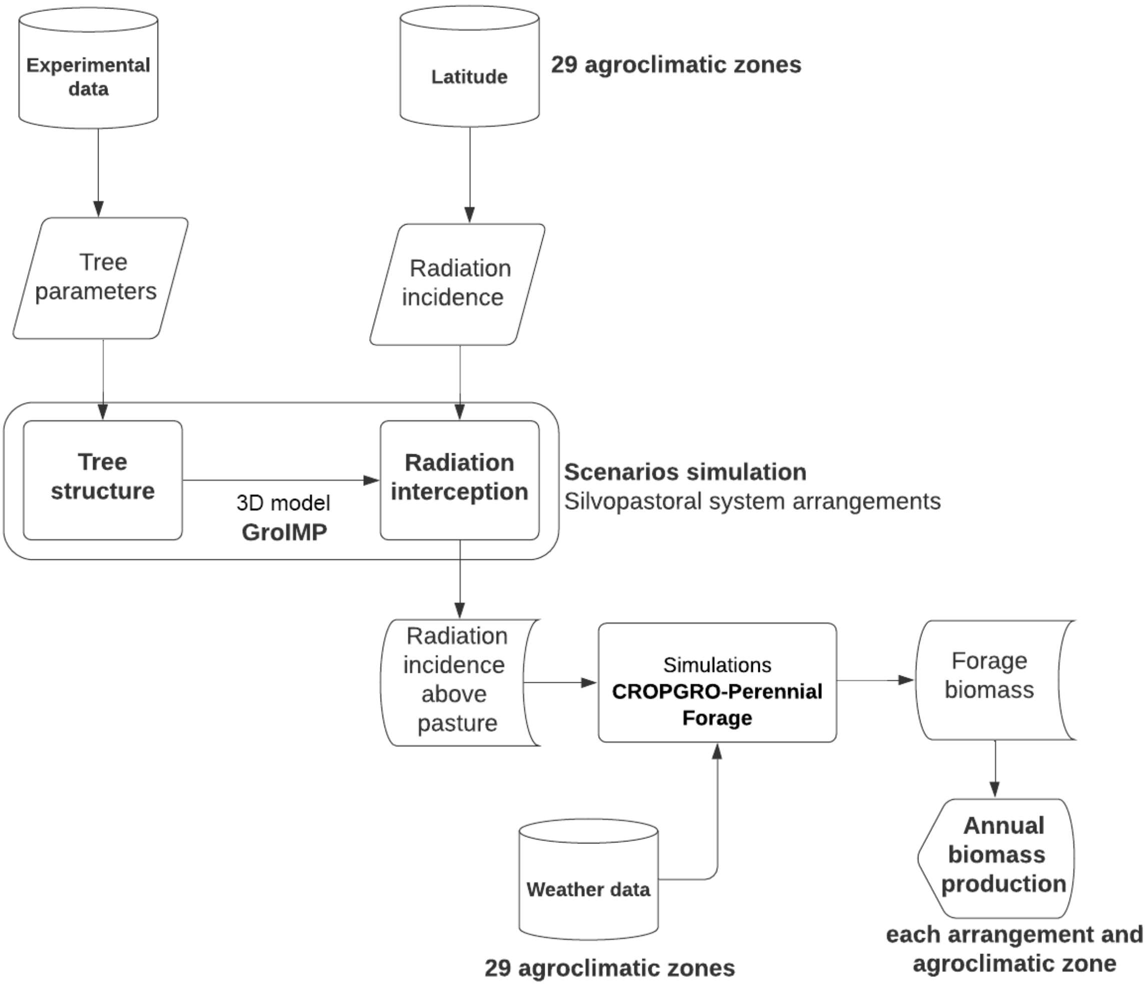


Fig. 1. Flowchart of the approach employed to simulate the forage biomass production in different arrangements and scenarios of silvopastoral systems.

Functional-structural plant model development

The model was written in the programming language XL (eXtensible Language), which is rule-based, and all the routines were implemented in GroIMP v1.5 (Growth Grammar-related Interactive Modelling Platform), a 3D modeling platform (Hemmerling *et al*., 2008). Direct radiation was simulated using a matrix of 24 sources of light, representing the sun's trajectory (Evers *et al*., 2010; Buck-Sorlin *et al*., 2011). Considering the latitude and the day of the year as input, the azimuth modified the position of each light source and solar inclination angle (Goudriaan and Van Laar, 1994). The diffuse radiation was simulated using 72 directional lights arranged in a hemisphere, composed of six concentric rings each consisting of two lights (Evers *et al*., 2010). The time step of the radiation model was daily.

The trees were represented only by structural aspects. To recreate trees of different ages we applied growth rules. The growth of the trees was represented by the rate of trunk length increment, branch length increment, leaf appearance, and senescence of the branches, which were determined by the accumulated degree-days. The basic unit plant structure is called the metamer, which in this model consisted of a trunk with an apical meristem, axillary buds, branches, and leaves. Metamers are the basic entities for modeling plant architectural development (Diao *et al*., 2012). The time between the appearance of two successive metamers of the trunk was defined as the time step of the model. Eucalyptus trees have low growth compared to annual crops, so the time step defined was 1 month.

The growth of the trunk is controlled by the apical meristem, and the axillary buds control the growth of the branches and leaves. So, the apical meristem produces new trunk segments and axillary buds produce new branch segments and leaves. At each time step, the age and rank (number of the position in relation to the first apical bud) of the organs is updated. A probability is attributed for each axillary bud to define the maintenance or senescence of the branches. The senescence of the branches can happen when the age of the axillary bud is higher than 5 (time step) and rank is higher than 4. So, at each time step, an axillary bud can produce a new metamer or die. We defined the parameters to describe the architecture and growth of eucalyptus trees based on data from several experiments (Table 1).

Table 1. Parameters to represent the growth and architecture of *Eucalyptus* trees.

Parameter	Value	Unit	Source
Trunk length increment	0.5	m / time step	Diao *et al.*, 2012
Trunk thickness increment	0.05	m / time step	Carr, 1998
Branch length increment	0.33	m / time step	Pinkard, 2002
Branch thickness increment	0.02	m / time step	Carr, 1998
Branch insertion angle	45	°	Pinkard, 2002
Mean leaf width	3.9	cm	James and Bell, 1995
Mean leaf length	12.12	cm	James and Bell, 1995
Number of leaves per branch	7	-	Carr, 1998
Increment number of leaves per day	1.66	leaves / time step	Carr, 1998
Phyllotaxis	150	°	Carr, 1998
Basal temperature	11.5	°C	Freitas *et al.*, 2017
Probability of branches senescence	0.357	-	Diao *et al.*, 2012

Dataset for models calibration and evaluation

The dataset for model calibration and evaluation was collected in Sinop, Mato Grosso, Brazil (11°51' S, 55°35' W, 384 m elevation) between December 2015 and April 2018. Köppen classified the climate as Am, a tropical climate with a dry winter (Alvares *et al*., 2013). The soil was classified as Ferralsol. The silvopastoral system was composed by *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf. cv. Marandu (palisadegrass) with *Eucalyptus urograndis* (clone H13). The row spacing was 30 m, the arrangement was a grove of triple rows with 3.0 m between trees and 3.5 m between rows; 270 trees ha^{-1}. The rows were oriented in the east-west direction (Fig. 2). To complement this dataset for calibration of tree architecture we used data collected by Attia *et al.* (2019).

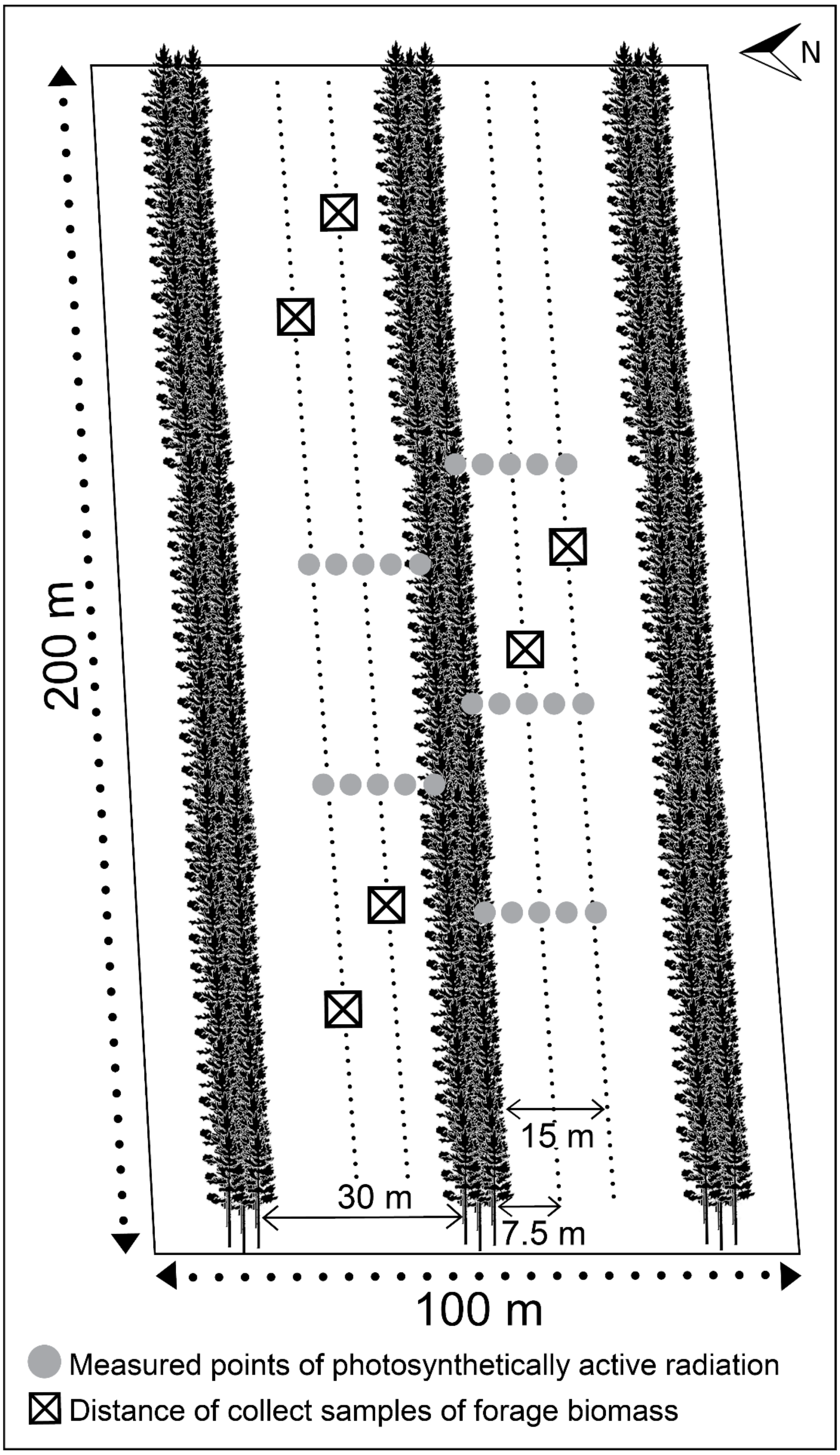


Fig. 2. Schematic representation of the experiment field with the measured points of photosynthetically active radiation and collected samples of the forage mass.

Calibration and evaluation of the functional-structural model

To calibrate the radiation model, we used daily data about photosynthetically active radiation (PAR) measured at five distances from (0, 4, 7.5, 11, and 15 m) and on both sides of (north and south) the rows of trees (Fig. 2). The measurements were taken every 15 minutes in the period from December 2015 to March 2017. To evaluate the ability of the model to simulate the daily radiation interception we used data from the same experiment and distances for the period between April 2017 and April 2018. The structure of trees was calibrated with height (m), diameter at breast height (m), and leaf area index (m) from a dataset collected by Attia *et al.* (2019). To evaluate the ability of the model to simulate the tree architecture and growth we used a dataset composed of height (m), diameter at breast height (m), and leaf area index (m2 m-2) collected in Sinop, MT, between 2012 and 2017.

The CROPGRO-Perennial Forage model simulates the storage and transport of carbon and nitrogen reserves and allows the inclusion of a live biomass residue after a forage cut, along with its morphological composition and number of leaves (Bosi et al., 2020). The parameterization of Pequeno *et al*. (2018) for Marandu palisade grass (*Brachiaria brizantha* cv. Marandu) was used as a reference to start the calibration process. All simulations in this study were carried out using DSSAT version 4.7.5.0. The planting method used for simulations was transplanting, which simulates an already established pasture.

For pasture production calibration, we used data about forage biomass accumulation at different distances from (7.5 and 15 m) and on both sides (north and south) of the tree rows collected monthly from December 2015 to May 2017 and from April 2017 to April 2018 for evaluation (Fig. 2). The model was also calibrated for a system in full sun, to be used as a reference comparison for forage production within the silvopastoral system (Appendix B - Table 1, 2, 3, and 4).

The performance of both structural (GroIMP) and functional (CROPGRO-Perennial Forage) models in simulating radiation interception by the trees and the production of forage biomass at different distances was evaluated by the root mean squared error (RMSE), determination index (r2), and the Willmot index (d), which was calculated for the average of the simulations (Wallach *et al*., 2006).

Determination of representative agroclimatic zones

We used the official statistical data on livestock production and area in Brazil provided by the Brazilian Institute of Geography and Statistics (IBGE, 2016). We selected all the municipalities with registered production. Following the protocol described by Van Wart *et al*. (2013), we defined 29 agroclimatic zones representing the production area in the country (Fig. 3). This classification was based on three factors: (i) crop degree days, calculated using basal temperature fixed at 0°C; (ii) annual dryness index, calculated by the ratio between annual average total rainfall and the yearly average of potential crop evapotranspiration; and (iii) seasonality of air temperature.

The municipality with the highest cattle population per agroclimatic zone was chosen to represent its climatic and soil characteristics (Appendix C - Table 1). The climatic dataset was obtained from the NASA POWER API Client (Sparks, 2018), for the period 1984 to 2017, containing daily data on solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), precipitation (mm), wind speed (m s^{-1}), and relative humidity (%). The dominant soil type for each zone was defined according to regional soil analyses developed by the Radam-Brazil Project (RADAMBRASIL, 1973), and based on the dominant soil type for each agroclimatic zone, we selected the corresponding soil profile from the WISE (World Inventory of Soil Emission Potentials) database available at the International Soil Reference and Information Centre (ISRIC, http://www.isric.org).

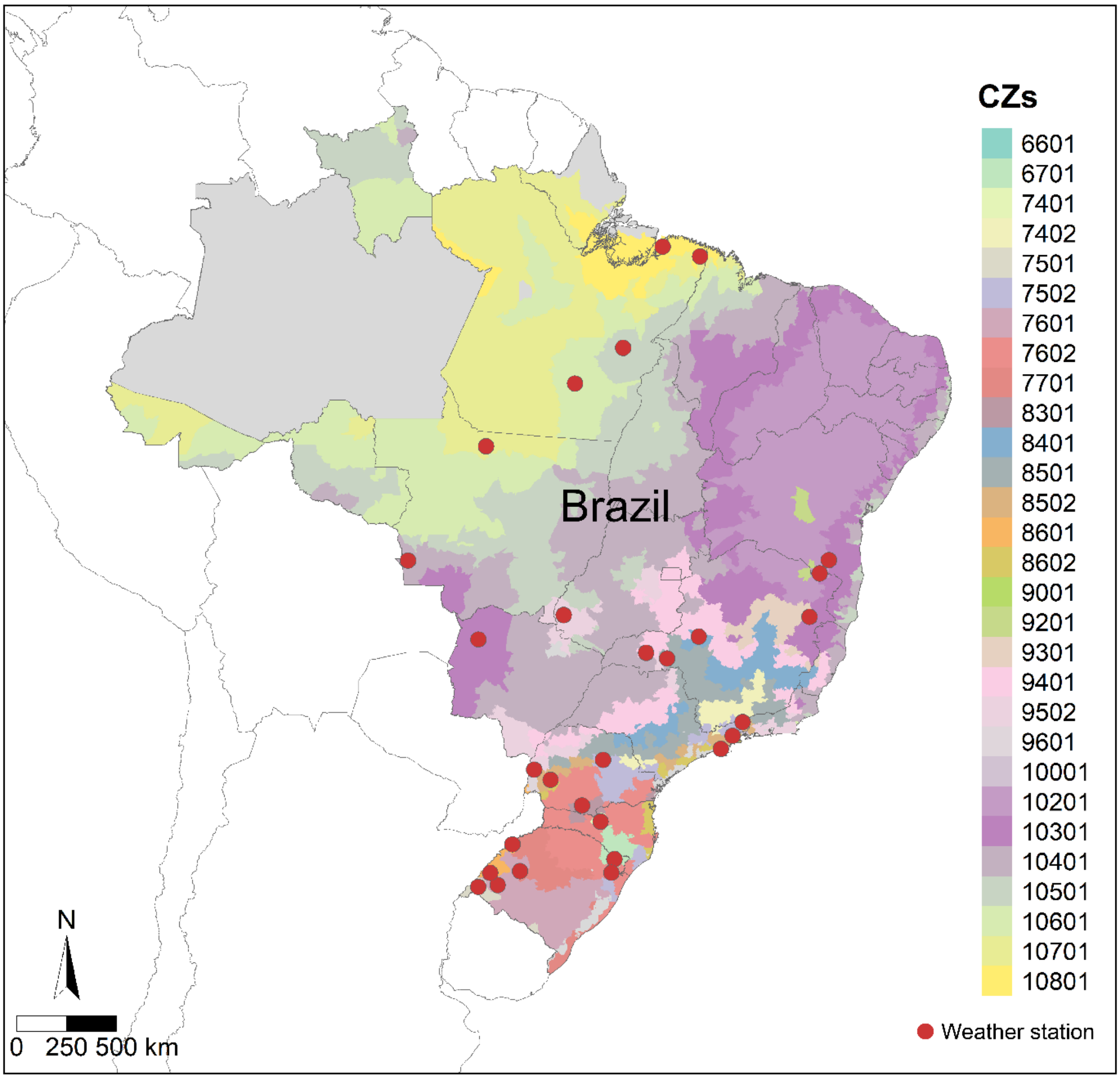


Fig. 3. Spatial representation of 29 agroclimatic zones (CZs) of all livestock producing municipalities in Brazil. Weather stations are indicated for the red dots.

Simulations of different silvopastoral tree arrangements across Brazil

We defined several tree arrangements based on the most adopted silvopastoral systems in Brazil (Porfírio-da-Silva *et al*., 2009; Oliveira Neto and Paiva, 2010), aiming to evaluate the performance of Marandu palisade grass in producing forage biomass in each arrangement. The silvopastoral systems were selected based on combinations of the following factors: (i) tree row spacing of 15, 30, and 45 m; (ii) row orientation (north-south and east-west); (iii) number of rows (single and triple rows). The descriptions of and abbreviations for these systems are shown in Table 2. See more details in the Appendix A (Fig. 1 and 2).

Table 2. Description of the arrangements of silvopastoral systems simulated.

Abbreviation	Row orientation	Row spacing (m)	Number of rows
NS15m1R	north-south	15	1
NS30m1R	north-south	30	1
NS45m1R	north-south	45	1
NS15m3R	north-south	15	3
NS30m3R	north-south	30	3
NS45m3R	north-south	45	3
EW15m1R	east-west	15	1
EW30m1R	east-west	30	1
EW45m1R	east-west	45	1
EW15m3R	east-west	15	3
EW30m3R	east-west	30	3
EW45m3R	east-west	45	3

For each silvopastoral system arrangement, we simulated the radiation intercepted by trees at different ages (2, 4, 6, 8, 10, and 12 years old), with the aim of representing forage production years after the adoption of the system. The framework used to simulate the forage biomass in different arrangements of silvopastoral system first required the simulation of the tree structure for each age of tree. Thereafter we simulated the daily amount of incident radiation for each agroclimatic zone, using latitude as an input. Then, the radiation intercepted at five different distances between the tree rows and for each year of silvopastoral system implementation was simulated.

The next step was to couple the data on incident radiation in the systems simulated by the FSP model for each agroclimatic zone with a weather file from CROPGRO-Perennial Forage. We used the climatic data for each year from 1984 to 2017 to simulate different scenarios for each arrangement and each age of tree. The forage biomass was simulated using three calibrations (7.5 m north, 7.5 m south, and

15 m) and matching by the mean incident radiation for each distance (Fig. 2). The final forage biomass was obtained by calculating the mean of the production simulated for the five distances. We also simulated production in a full sun system to be utilized as a reference for comparison to the different silvopastoral system arrangements.

Clustering the agroclimatic zones

Based on the mean annual forage biomass simulated we defined five levels of production, aiming to guarantee sufficient forage to feed the animals during the year (Nascimento *et al*., 2021): (i) High (> 18000 kg ha^{-1}); (ii) Good (16000–18000 kg ha^{-1}); (iii) Moderate (14000–16000 kg ha^{-1}); (iv) Low (12000–14000 kg ha^{-1}); (v) Very Low (< 12000 kg ha^{-1}). Ward's Hierarchical Clustering (Murtagh and Legendre, 2011) was applied as the algorithm for the clustering of agroclimatic zones. The similarity was calculated by Euclidean distance. The separation between groups was determined by the Phenon line. Clustering was presented as a dendrogram by grouping similar production levels.

3.3. RESULTS

Models calibration and evaluation

The radiation model showed satisfactory performance in simulating the daily incident radiation within and outside the silvopastoral system for the period from April 2017 to April 2018 (Fig. 4). We observed a tendency for simulations to underestimate the PAR for the full sun system while overestimating for distances 7.5 m north, 7.5 m south, and 4.5 m north. The precision of the model varied between 0.72 and 0.83, for the full sun and 7.5 m north respectively. The model showed good accuracy, with d higher than 0.90 at all distances. The error was highest at 7.5 m, with an RMSE of 87.49 and 68.79 for the north and south sides, respectively (Table 3).

The FSP model showed a tendency to overestimate the tree's leaf area index and diameter at breast height, and to underestimate the height of the trees (Fig. 5). The leaf area index was the variable for which the model presented the least optimal performance, with $r^2 = 0.82$ and $d = 0.79$. The r^2 and d were higher than 0.90 for the other variables (Table 3).

The calibrations for the CROPGRO-Perennial Forage resulted in satisfactory accuracy and precision for simulations at all distances in the silvopastoral system and full sun. We observed a tendency to overestimate the observed data in the system in full sun, at distances of 15 m and 7.5 m north (Fig. 6). The d values were higher than 0.90 for all calibrations. The precision was highest at 15 m ($r^2 = 0.90$) and lowest at 7.5 m north ($r^2 = 0.79$, Table 3).

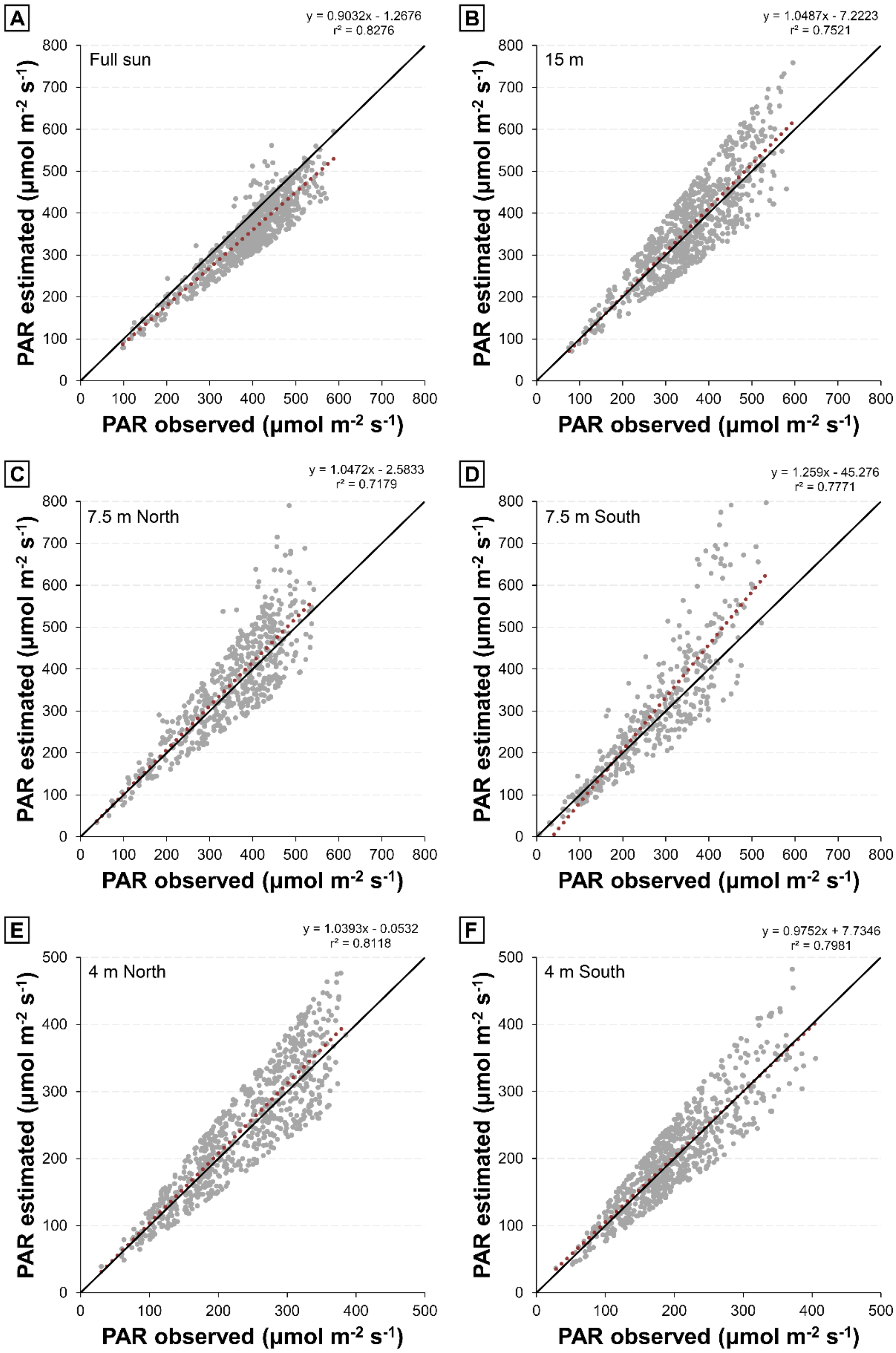


Fig. 4. Relationship between the average of daily photosynthetically active radiation (PAR) observed and estimated for Sinop-MT in silvopastoral system and at the full sun (A – Full sun; B – 15 m; C – 7.5 m North; D – 7.5 m South; E – 4 m North; F – 4 m South) between April 2017 to April 2018.

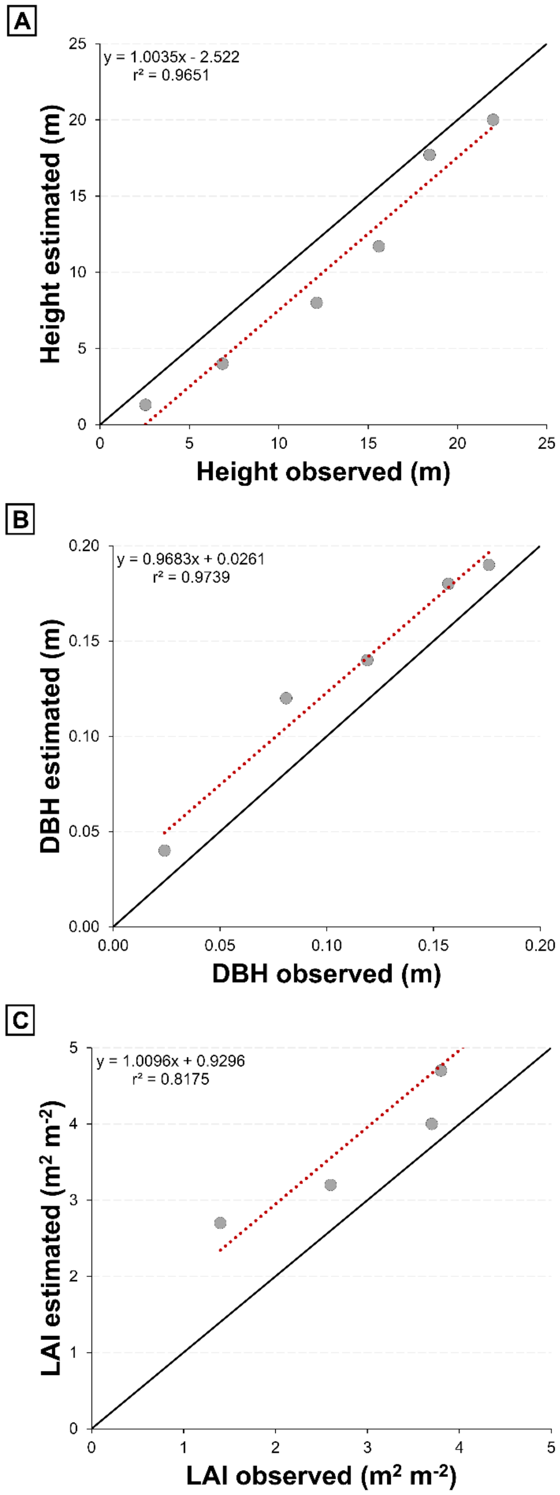


Fig. 5. Relationship between tree's height (A), diameter at breast height (DBH, B) and leaf area index (LAI, C) observed and estimated for Sinop-MT in silvopastoral system between 2012 and 2017.

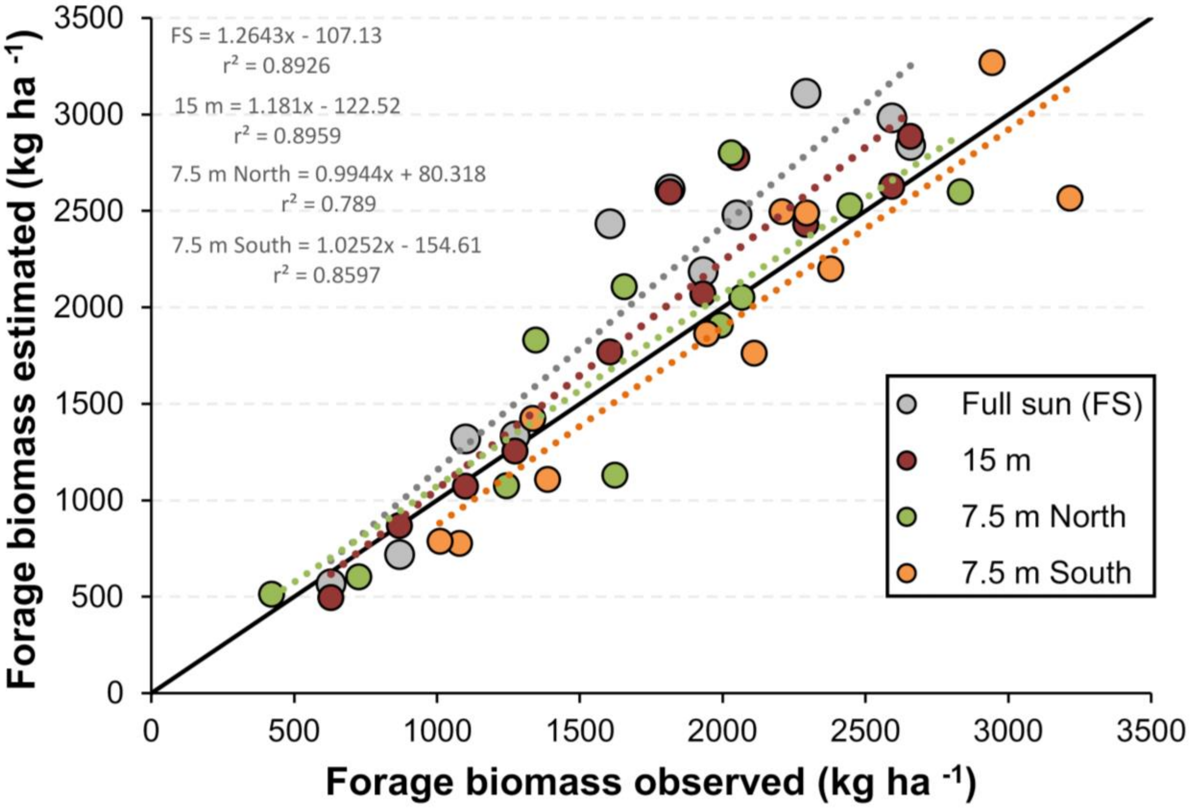


Fig. 6. Relationship between forage biomass observed and estimated for Sinop-MT in silvopastoral system and at the full sun (A – Full sun (FS); B – 15 m; C – 7.5 m North; D – 7.5 m South) between April 2017 to April 2018.

Table 3. Statistical indexes for the simulations performed in the evaluation process of the models (FSP and CROPGRO-Perennial Forage) for the photosynthetically active radiation, tree structure, and forage biomass from April 2017 to April 2018.

Variable	**RMSE**	**r²**	**d**
Photosynthetically active radiation (μmol m^{-2} s^{-1})			
Full sun	55.75	0.83	0.90
15 m	59.44	0.75	0.92
7.5 m North	68.79	0.72	0.90
7.5 m South	87.49	0.78	0.90
4 m North	40.73	0.81	0.94
4 m South	32.62	0.80	0.94
Tree structure			
Height (m)	6.55	0.97	0.96
Diameter at breast height (m)	0.12	0.95	0.97
Leaf area index	2.19	0.82	0.79
Forage biomass (kg ha^{-1})			
Full sun	478.86	0.89	0.90
15 m	342.17	0.90	0.94
7.5 m North	356,53	0.79	0.94
7.5 m South	306.29	0.86	0.95

Simulations of different silvopastoral system arrangements

The interaction between the shading caused by trees over the years and the different silvopastoral system arrangements simulated directly influenced the incident radiation on the pasture. Comparison of the amount of incident radiation in each arrangement with the availability in the full sun system showed higher radiation interception where rows were spaced 15 m apart, with a mean percentage radiation interception varying from 39 to 45% (Fig. 7). There was also a higher percentage of radiation interception in systems with triple rows than in systems with single rows, while the north-south orientation resulted in lower radiation incidence within the system than east-west orientation. The mean ranged between 39 and 54% in arrangements with rows spaced 45 m apart 12 years after implementation of the system. In systems with rows spaced 15 m apart, radiation interception was higher than 39% when the trees were 8 years old, but lower than 18% until the 4th year after implementation.

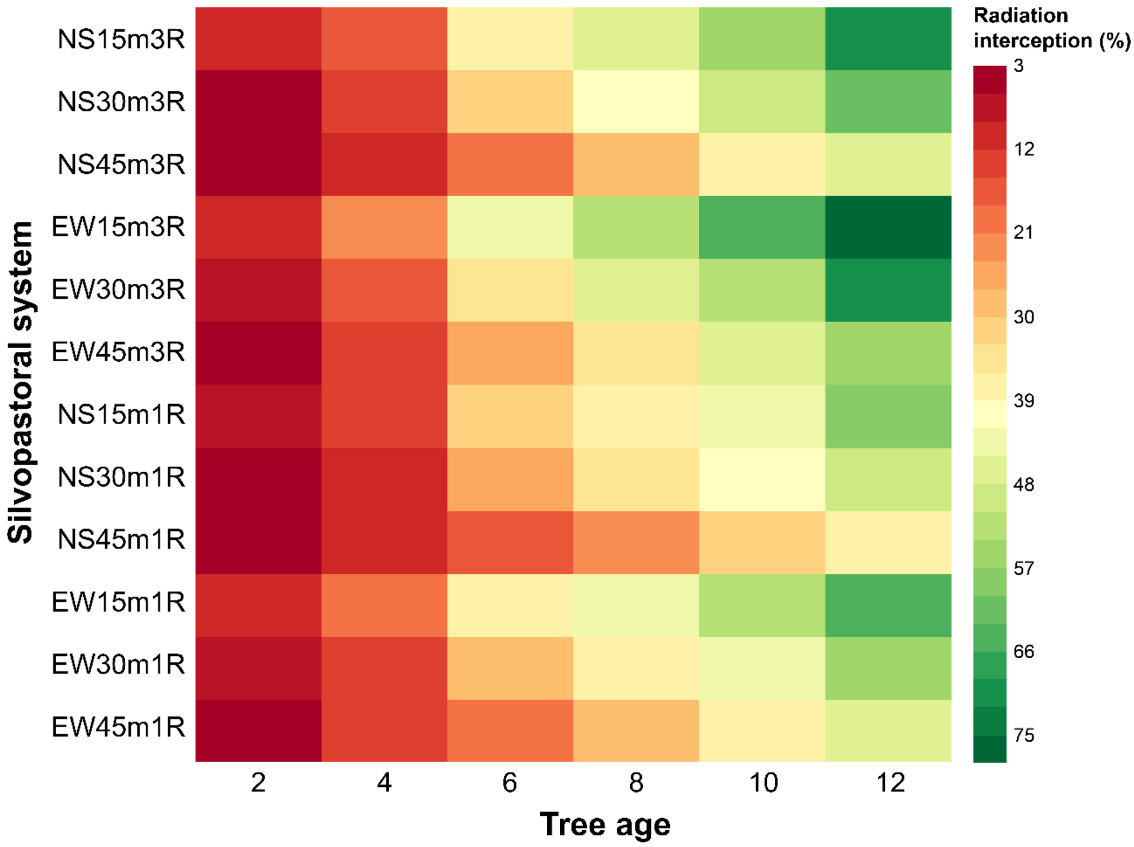
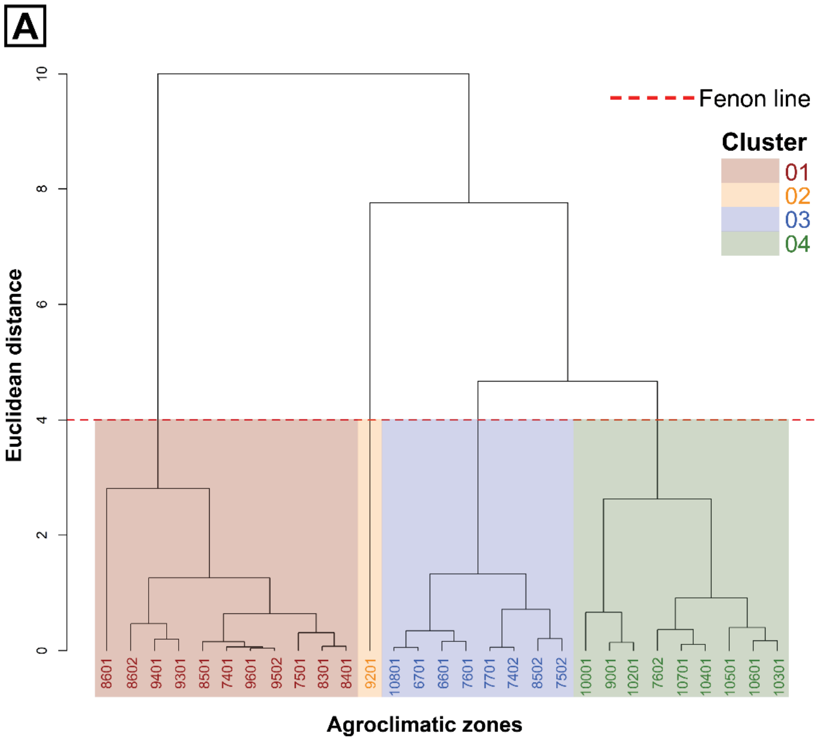


Fig. 7. Average radiation intercepted (%) for each silvopastoral system arrangement simulated for the agroclimatic zones between 1984 and 2017.

Beyond changes in incident radiation caused by the arrangement of trees, other factors can affect the growth of Marandu palisade grass in silvopastoral systems, such as soil and climate. Thus, the level of forage biomass production varied according to the agroclimatic zone. Based on the livestock production in the silvopastoral systems simulated for each agroclimatic zone we grouped the producer regions into four clusters (Fig. 8). Systems with 45 m between rows showed higher levels of production regardless of row orientation or number of rows. The production level was classified as Good in Cluster 01 and Moderate in Cluster 03. Cluster 01 is composed of agroclimatic zones located mainly in the midwest and southeast and cluster 03 is located in the south (Fig. 3). The worst arrangement was EW15m3R, with a production level of Low in cluster 01 and Very Low in the other clusters. In cluster 04 the production level was lower than Moderate, varying from 10573 to 13200 kg ha^{-1}. In cluster 02 the production level was classified as Very Low in all arrangements, being lower than 9000 kg ha^{-1}. The agroclimatic zones of clusters 02 and 04 are located mainly in the northeast of Brazil.



B

Silvopastoral system	Cluster 1	Cluster 2	Cluster 3	Cluster 4
	Mean of annual forage biomass (kg ha^{-1})			
NS15m3R	14545	6903	12851	10573
NS30m3R	15417	7546	12975	11148
NS45m3R	17257	8450	14278	12441
EW15m3R	13499	6648	11189	10503
EW30m3R	15183	7320	13035	11132
EW45m3R	17270	8370	15273	12958
NS15m1R	14742	7024	12955	10889
NS30m1R	16644	7668	15199	12907
NS45m1R	17600	8553	15072	13200
EW15m1R	14520	6758	13118	10732
EW30m1R	15335	7445	12916	11009
EW45m1R	17458	8368	15266	12862

Level of forage biomass production
- High
- Good
- Moderate
- Low
- Very Low

Fig. 8. Hierarchical cluster analysis among the mean of annual forage biomass in silvopastoral system arrangements for each agroclimatic zone for the period of 1984 to 2017(A). Production levels for each silvopastoral system and cluster (B): High (> 18000 kg ha^{-1}); Good (16000 - 18000 kg ha^{-1}); Moderate (14000 - 16000 kg ha^{-1}); Low (12000 - 14000 kg ha^{-1}); Very Low (< 12000 kg ha^{-1}).

Changes in the architecture of the trees over the years influence the incidence of radiation within the system, and as a result, can affect pasture growth. We verified that all silvopastoral system arrangements showed satisfactory production in the first years of implementation. The simulations for 2-year-old trees indicated that the levels of forage biomass production were High or Good for each silvopastoral system (Fig. 9). Even 6 years after the implementation of the silvopastoral systems there were adequate levels of forage biomass production, classified as Moderate in all arrangements, except in EW15m3R. After the 6th year, the differences in forage production between the silvopastoral systems became more evident. In the 8th year, only the arrangements with a row spacing of 45 m maintained forage production at a moderate level. Once trees were 12 years old production was classified as Very Low in all arrangements.

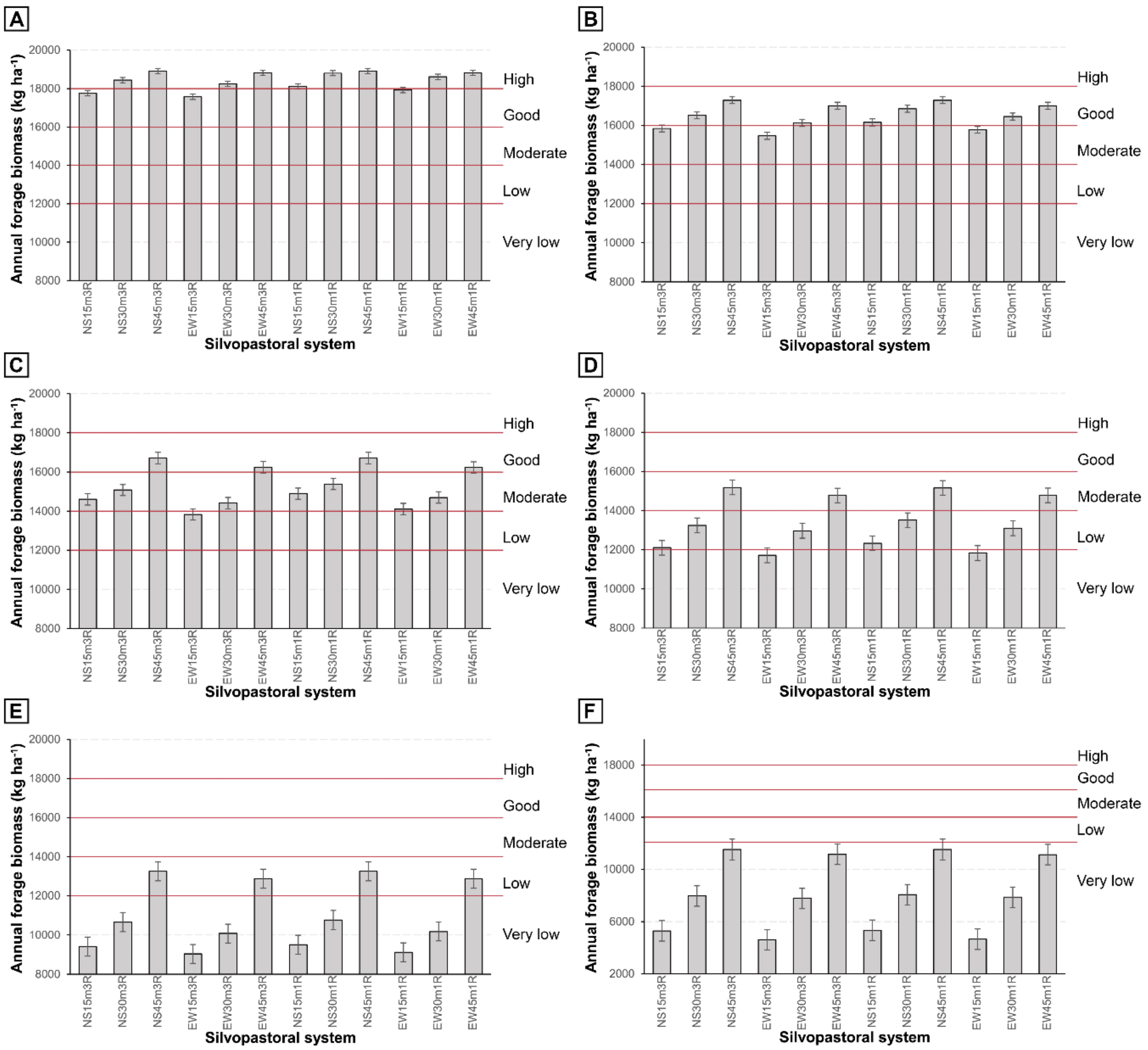


Fig. 9. Mean of annual forage biomass production (kg ha^{-1}) in different silvopastoral system arrangements and ages of the trees simulated (A – 2 years; B – 4 years; C – 6 years; D – 8 years; E – 10 years; F – 12 years) each in range in the period of 1984 to 2017. Production levels: High (> 18000 kg ha^{-1}); Good (16000 - 18000 kg ha^{-1}); Moderate (14000 - 16000 kg ha^{-1}); Low (12000 - 14000 kg ha^{-1}); Very Low (< 12000 kg ha^{-1}).

Based on levels of forage production in the silvopastoral systems, the best and worst arrangements were NS45m1R and EW15m3R respectively. We considered the production level for the agroclimatic zones at two important ages of the trees, i.e., at 6 years when the production level started to decrease and at 12 years, the last year of the simulations (Fig. 10). In NS45m1R the production of forage biomass at 6 years varied from 14000 to 18000 kg ha^{-1} in all regions, except in the northeast. Thus, the production level can be classified as Moderate in a large part of the country. In EW15m3R only 14000 kg ha^{-1} of forage biomass was produced in some agroclimatic zones in the southeast and south. In the 12th year, production was lower than 6000 kg ha^{-1} in EW15m3R in all Brazilian regions. In NS45m1R forage production ranged between 6000 and 10000 kg ha^{-1} in the northeast, and between 10000 and 14000 kg ha^{-1} in the other regions, which can be classified as Low or Moderate, depending on the agroclimatic zone.

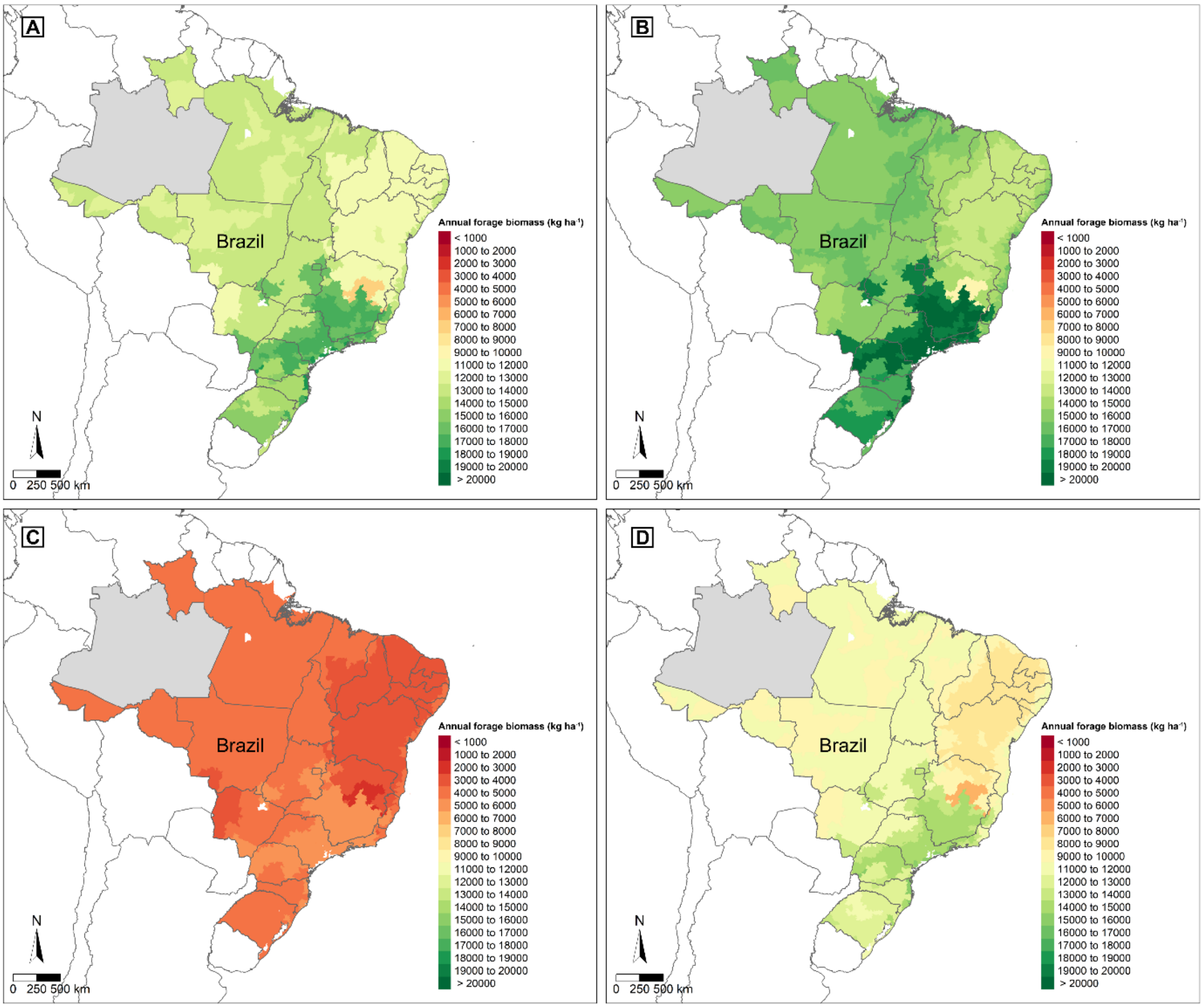


Fig. 10. Mean of annual forage biomass production (kg ha^{-1}) for the silvopastoral systems EW15m3R and NS45m1R with trees age of 6 and 12 years (A – EW15m3R / 6 years; B – NS45m1R / 6 years; C – EW15m3R / 12 years; D – NS45m1R / 12years) between 1984 to 2017.

The decline in forage biomass corroborated the production levels for each silvopastoral system (Fig. 11). In EW15m3R the decline varied from 5000 to 6000 kg ha^{-1} in the 6th year and between 8000 and 16000 ha^{-1} in the 12th year. This corresponds to a mean reduction of 28 and 76%, respectively, compared to the full sun system. In NS45m1R there was a lower decline in forage biomass, ranging between 1000 and 3000 kg ha^{-1} in the 6th year and from 5000 to 8000 kg ha^{-1} in the 12th year. This represents a mean reduction of between 13 and 40%, respectively. It is important to note the occurrence of failed simulation in several years between 1984 and 2017, when pasture death was caused by climatic conditions and excessive shading.

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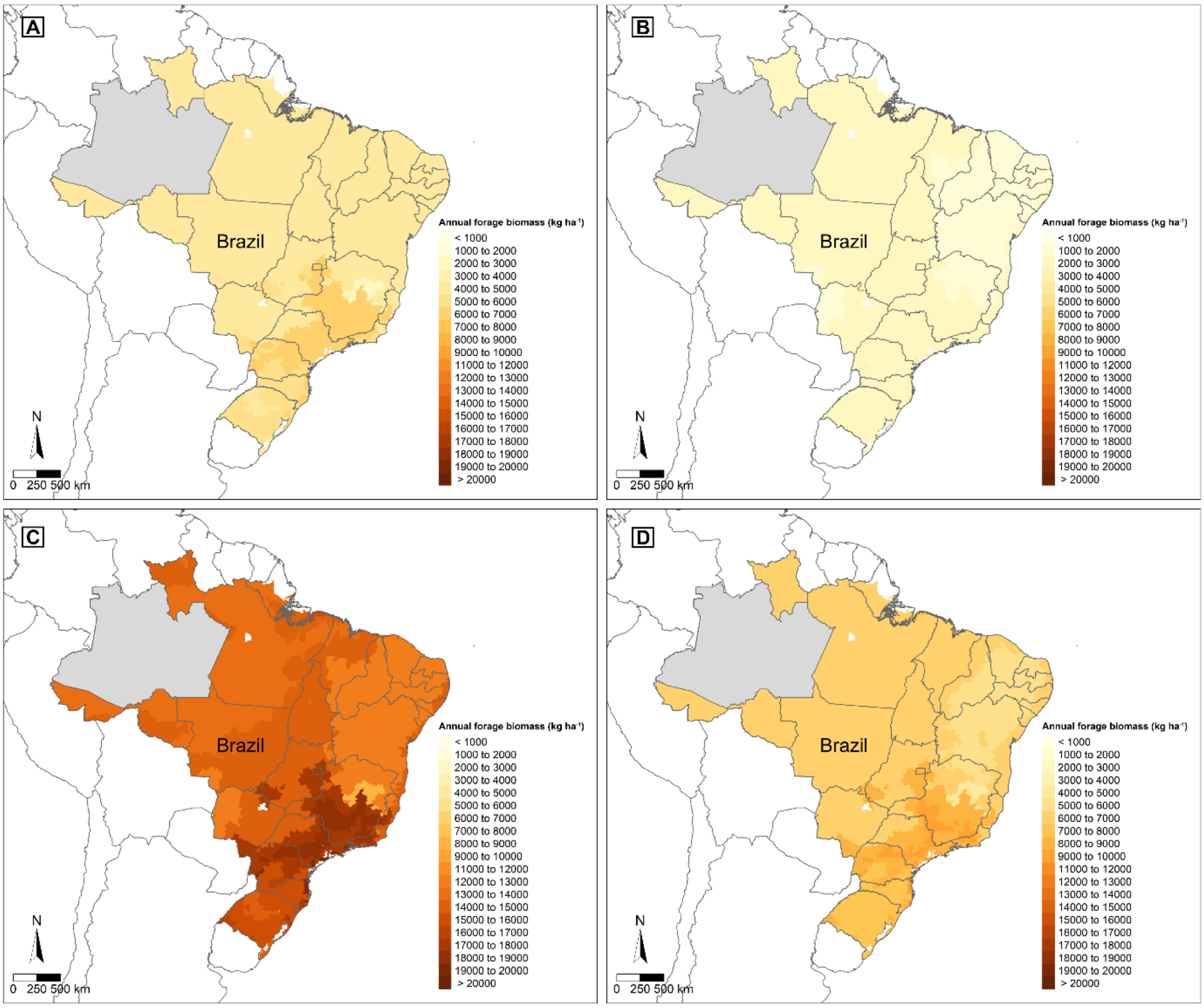

Fig. 11. Mean of annual biomass declines (kg ha^{-1}) for the silvopastoral systems EW15m3R and NS45m1R concerning to system full sun, with trees age of 6 and 12 years (A – EW15m3R / 6 years; B – NS45m1R / 6 years; C – EW15m3R / 12 years; D – NS45m1R / 12years) between 1984 to 2017.

3.4. DISCUSSION

The success of livestock production in silvopastoral systems is mainly determined by the availability of radiation within the system. Shading caused by trees has a huge impact on the equilibrium of the microclimate, and can result in benefits or damage to all system components (Geremia *et al*., 2018). The effect of incident radiation on the production of forage, in general, is conditioned by the management of four factors: (i) row spacing, through tree density and planting arrangement; (ii) selection of tree species with an open canopy: members of the genus Eucalyptus are the most cultivated in Brazil, followed by Pinus, Acacia, and Tectona (Andrade *et al*., 2012); (iii) thinning and pruning of trees; (iv) forage species tolerant to shading (Oliveira Neto and Paiva, 2010). According to the climatic conditions of each region, the interactions between these factors can result in different levels of pasture production. For this reason, the adoption of silvopastoral systems should be evaluated and planned specifically for each location (Soares *et al*., 2009). In agroclimatic zones in cluster 01 with row spacing of 30 and 45 m, the availability of radiation did not limit forage production, regardless of tree orientation or the number of rows. However, silvopastoral systems with 15 m of row spacing required more attention for their management (Fig. 8). The viability of the adoption of silvopastoral systems in regions in clusters 02 and 04 requires careful study. These agroclimatic zones are located mainly in the northeast of Brazil, where the climate is arid with high temperatures in several months of the year (Appendix C - Table 1). In this case, the shading caused by the tree component is one more limiting factor in pasture growth.

The sun's trajectory throughout the day and the tree row orientation directly affects the projection of shade and as a result the performance of system components. In the north-south orientation, the sun's trajectory is perpendicular to the tree rows, projecting shade oscillating between the east-west directions and in different amounts throughout the day (Vieira Junior *et al*., 2019). In contrast, in systems with the east - west row orientation the opposite occurs, with denser shade close to the tree rows (Gomes *et al*., 2019). We observed that forage production was lower in silvopastoral systems with a spacing of 15 m and east-west row orientation (Figs. 8 and 9). Triple rows can result in longer and denser shade close to the tree rows (Fig. 7), and can also affect pasture growth (Figs. 8 and 9). Nascimento *et al*. (2019) suggested that Marandu palisade grass can tolerate reductions in radiation in silvopastoral systems of up to ~20% without a negative impact on pasture production. Over 12 years, only systems with a row spacing of 45 m were able to guarantee radiation interception at levels adequate for the growth of Marandu palisade grass (Fig. 7).

Another important aspect to be considered for the success of the system is grazing management, with the aim of avoiding pasture depletion and allowing adequate regrowth. Grasses adapted to shading change their carbon translocation, prioritizing shoot growth to increase leaf area index and to improve radiation use efficiency (Gomes *et al*., 2019). If silvopastoral systems are arranged to guarantee sufficient radiation availability, shade tolerance mechanisms allow shaded pastures to sustain productivity at levels equivalent to those of pastures without shade (Gomes *et al*., 2020), resulting in similar livestock productivity (Carvalho *et al*., 2019). For example, in comparison with the full sun system, the annual reduction in forage biomass in NS45m1R in the midwest, southeast, and south of the country ranged between 2000 and 3000 kg ha^{-1}. This reduction was 16000 kg ha^{-1} in EW15m3R after 12 years (Fig. 11).

Tree row orientation is another determinant of shading availability in terms of providing an area large enough for the animals (Silva *et al*., 2014), reducing their cardiac frequency due to the lesser need for dissipation of corporal heat (Garcia *et al*., 2011) and, consequently, leading to higher animal productivity. Shade protects the animals from direct solar radiation, even if there are no changes in the temperature and relative humidity of the silvopastoral system (Karvatte Junior *et al*., 2016). A previous study reported that animals preferred to take refuge under the trees during the winter in the hottest hours of the day, whereas in summer, they stayed in the shade from the early hours of the morning, spending more than 70% of their time in the shade throughout the analyzed period, from 08:00 to 17:00 h (Vieira Junior *et al*., 2019). Thus, we considered a reduction of at least 10% in the radiation incidence within the system compared to the full sun system as an indicator of thermal comfort (Domiciano *et al*., 2018; Pezzopane *et al*., 2019). We observed that the average reduction in radiation interception over 12 years was higher than 10% in all arrangements (Fig. 7). In addition, it is important to consider that excessive shading can reduce the production of forage biomass. This highlights the need for adequate planning in the implementation of the system to maximize the benefits of shade projection for the animals while avoiding a reduction in pasture growth.

The proper management of trees is fundamental for capitalizing on existing synergies warranting forage growth and, consequently, livestock productivity (Carvalho *et al*., 2019). In this sense, pruning and thinning can be efficient ways to increase incident radiation within these systems and to provide favorable conditions for the pasture (Nicodemo *et al*., 2016). The arrangement adopted has a direct influence on the age of trees when these practices are required, and the percentage of canopy to be pruned or the number of trees to be thinned. To maintain forage production at a Moderate level in silvopastoral systems with a row spacing of 15 m, these kinds of practices are recommended from 6 years after establishment. For systems with a row spacing of 30 m, some management may be necessary from 8 years after establishment. For systems with 45 m of row spacing, shading starts affecting forage production 10 years after adoption of the system, so pruning or thinning is recommended at that point (Fig. 9). It is important to emphasize that pruning practices may also be necessary during the initial period of tree growth when the canopy is being formed to ensure good quality wood and to avoid excessive shading of the tree rows (Oliveira Neto and Paiva, 2010). In agroclimatic zones where forage production is lower (Fig. 6), the need for practices to increase incident radiation within the system should be monitored often regardless of the arrangement.

The methodology applied in this study was able to simulate different arrangements of silvopastoral systems throughout the years (Figs. 4, 5, and 6). Although the structural tree model showed small systematic biases, it also well captured the observed pattern of trees' architectural variables (Fig. 5). We believe these biases can be overcome by refining the parameterization described in Table 1 by either taking more field observations or via dynamic calibration procedures, a complex and time-consuming task in FSP models. Yet, our model evaluation results achieved satisfactory performance when compared with studies that simulated tree structures using functional structural plant models (Lu *et al*., 2011; Okoma *et al*., 2018; Tondjo *et al*.,

2018) and forage biomass production using *CROPGRO-Perennial* Forage (Bosi *et al*., 2020; Pequeno *et al*., 2014). Thus, this approach could be a valuable tool to aid informed decision making, define the optimal rows and arrangement of the trees, and help design a more efficient system. It could help to reduce uncertainties associated with deciding the arrangements of the trees (Santos *et al*., 2016) and make the livestock more productive and sustainable. Future improvements could be made to include the below-ground competition among species in this modeling framework. We believe this approach could also be adapted to other forage and tree species to optimize different arrangements for silvopastoral and other kinds of agrosilvopastoral systems.

3.5. CONCLUSION

The arrangement of trees in silvopastoral systems directly affects the incidence of radiation above the pasture and this results in different levels of forage production. Arrangements with a row spacing of 30 and 45 m can provide forage in satisfactory levels for several years. In contrast, treatments with a row spacing of 15 m or triple lines demand more careful planning and management, taking into account the soil and climatic characteristics of each region.

The production level declined after few years in silvopastoral systems with arrangements of 15 and 30 m. Pruning and thinning practices may be needed to increase the radiation incidence within the system. The FSP model could be employed to evaluate the effects of tree management on forage production.

The methodology employed in this study was capable of simulating the radiation intercepted by the trees and pasture growth, providing a valuable tool to aid the planning and management of this kind of system. Further studies should be carried out to investigate the effects of shading in other pasture species or kinds of agrosilvopastoral systems.

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4. PRUNING AND THINNING INFLUENCING RADIATION COMPETITION OF EUCALYPTUS-MARANDU PALISADE GRASS SILVOPASTORAL SYSTEMS IN BRAZIL

ABSTRACT

Silvopastoral systems can increase the sustainability and production of livestock, associating trees, forage species, and animals in the same area. The lack of knowledge about the correct management of trees can hold back the adoption of this kind of system. In this context, we simulated tree pruning and thinning impacts on the production of forage biomass in several arrangements of the Eucalyptus-Marandu palisadegrass silvopastoral system in different regions of Brazil. The approach was based on a coupled functional-structural plant model to the CROPGRO-Perennial process-based crop model to simulate the forage biomass production for different silvopastoral systems arrangements and under several tree managements. The models were calibrated with experimental data collected in a silvopastoral system site in Brazil. We simulated four scenarios of pruning and thinning based on more usual practices adopted by farmers. Our simulations showed that the effect of tree management affected the forage production according to the region of Brazil. The pruning technique alone may not be sufficient to provide enough radiation for pasture growth. The tree-row orientation East-West may demand pruning and thinning practices earlier than North-South orientation. In general, the pruning and thinning practices combined showed the efficient performance to maintain adequate levels of forage production over the years. The methodology proposed in this study is efficient to simulate the effects of pruning and thinning in silvopastoral systems and can help the farmers to adopt this kind of system, aiding the tree management strategies.

Keywords: Livestock-forest; Tree management; Functional-Structural Plant Modeling; Shading.

4.1. INTRODUCTION

Silvopastoral systems are defined as the association of trees, animals, and forage species in the same area (Paciullo *et al.*, 2017). The interaction between these components can provide benefits that become the livestock production more efficient and sustainable such as diversification of farming products (Costa *et al.*, 2016), improvement of physical and chemical soil characteristics (Lemaire *et al.*, 2014), resulting in the recovery of degraded areas (Silva *et al.*, 2017), ecosystem services (Sollenberger *et al.*, 2019), and animal welfare (Magalhães *et al*, 2020; Pezzopane *et* *al.*, 2019). Still, several studies had shown the potential of silvopastoral systems to mitigate greenhouse gases resulting from livestock production (Silva *et al.*, 2016; Pontes *et al.*, 2018), promoting the sustainability of livestock production in climate change scenarios (Pezzopane *et al.*, 2015).

The maintenance of forage biomass production forage production in enough quantity and quality to feed the animals is directly related to radiation incidence above the pasture. In general, it is conditioned by the management of the following factors: (i) row spacing, through tree density and planting arrangement (See section 3); (ii) adoption of tree species with an open canopy, i.e., the most cultivated in Brazil is the gender Eucalyptus, followed by Pinus, Acacia, and Tectona (Andrade *et al.*, 2012); (iii) managing of thinning and pruning of trees (Santos *et al.*, 2016; Pezzopane *et al.*, 2021); (iv) selection forage species shade-tolerant (Oliveira Neto and Paiva, 2010). Yet, even forages considered tolerant to shading show a decrease in dry matter production when exposed to intense shading (Faria *et al.,* 2018), which is associated with morphologic and physiologic responses of the forage to maximize radiation uptake (Gomes *et al.,* 2019; Nascimento *et al.,* 2019). In the most popular arrangements adopted for silvopastoral systems, from a certain tree age, is not viable to practice intercropping between the tree rows due to the limitation caused by shading (see section 3). Tree management practices can play an important role in providing adequate levels of solar radiation incidence for improving the productivity of system components over the years (Ergon *et al.*, 2018). Pruning trees in silvopastoral systems regulate the tree height, increasing the radiation incidence into the system and favoring the pasture growth (Martínez Pastur *et al.*, 2018). Thinning decreases the competition for solar radiation, water, and nutrients both intra- and interspecies (Nicodemo *et al.*, 2016). However, few studies were carried out aiming to assess the effects of tree management in silvopastoral systems.

If the silvopastoral system is not properly scaled and managed, the potential advantages and benefits provided for the addition of the tree may negatively affect the physiological responses of the pastures, decreasing herbage accumulation (Zhang *et al.*, 2018). To understand the dynamics and interactions between trees and pasture species it is necessary to apply tools encompassing responses caused by environment and management factors. In this sense, crop modeling shows an efficient approach to represent and describe the relationship among components (Lara and Rakocevic, 2014). In the previous section, we proposed a novel approach applying functional-structural plant modeling combined with a based-process model to determine the rows and arrangements to silvopastoral systems.

Managing trees by pruning and thinning is another efficient way to improve the solar radiation competition, ensuring enough radiant energy for pasture growth. To our knowledge, however, the effects of tree management on pasture growth have not been studied using a robust simulation framework. The lack of information about properly thinning and pruning interventions may limit livestock production and, consequently, become a limitation for farmers to adopt the system. Thus, we hypothesize that radiation incidence is differently affected depending on tree management, as well as by the environment, and interactions among these factors would result in different forage biomass production levels. To test this hypothesis, we simulated the pruning and thinning impacts on the forage biomass production in several arrangements of the *Eucalyptus*-Marandu palisadegrass silvopastoral system in different regions of Brazil.

4.2. MATERIAL AND METHODS

Approach employed to simulate the forage biomass in silvopastoral systems

Based on the approach developed (See section 3) that combines a 3D model of the arrangements of trees in a silvopastoral system and a process-based model, we simulated the radiation interception by trees and forage as well as the biomass in silvopastoral systems under tree managements (pruning and thinning) for different regions of Brazil (Fig. 1).

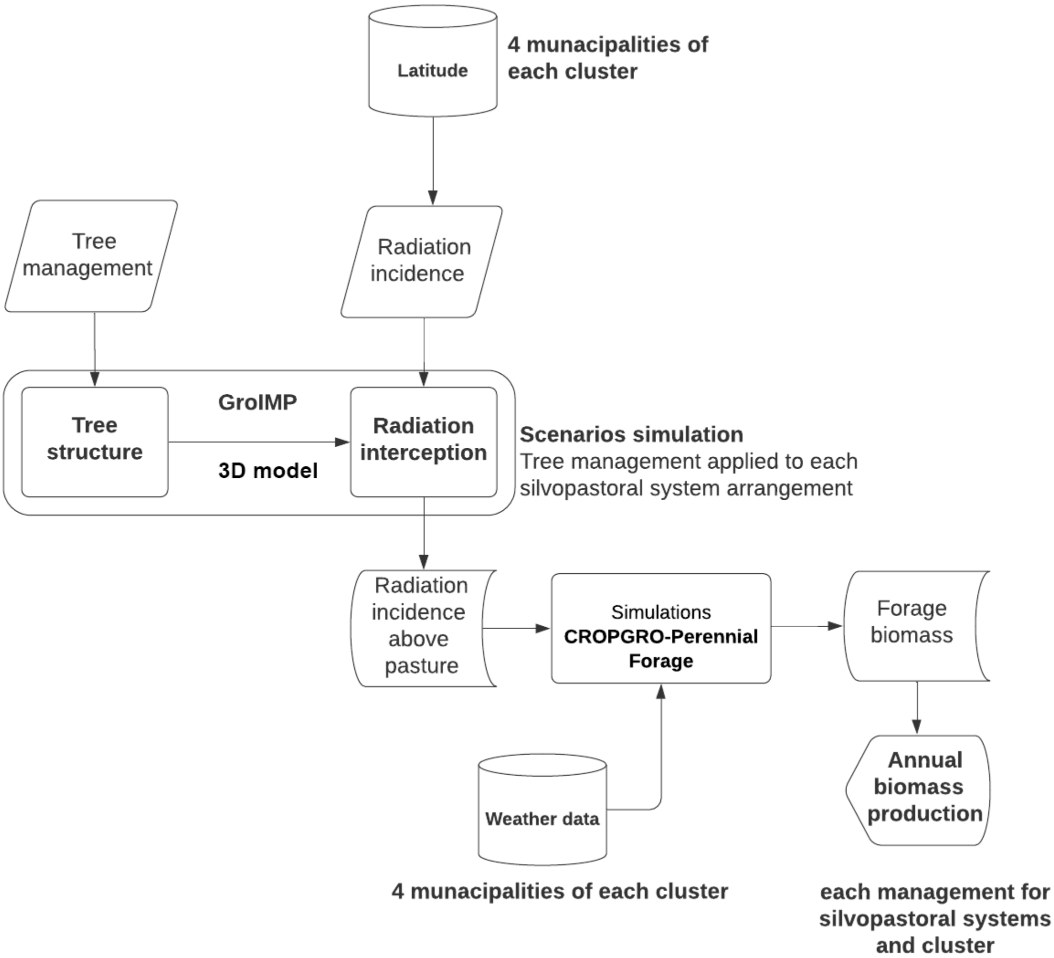

Fig. 1. Flowchart of the approach employed in the simulation of the forage biomass production under different tree managements and scenarios of silvopastoral systems.

The direct radiation was simulated using a matrix of 24 sources of light, representing the sun trajectory (Evers *et al.*, 2010; Buck-Sorlin *et al.*, 2011). The diffuse radiation model used 72 directional lights arranged in a hemisphere, composed of 6 concentric rings each consisting of 12 lights (Goudriaan and Van Laar, 1994). The time step of the radiation model was daily. The tree representation was expressed only in structural aspects. Aiming to recreate the trees in different ages were applied growth rules, determined by the degree-days accumulation. The growth of the trees was represented by the rate of trunk length increment, branch length increment, and leaves appearance. The Functional-Structural Plant (FSP) model was written in the programming language XL (eXtensible Language), rule-based, that all the routines were implemented in GroIMP v1.5 (Growth Grammar-related Interactive Modelling Platform), a 3D modeling platform (Hemmerling *et al.*, 2008).

The process-based crop model, CROPGRO-Perennial Forage (Rymph *et al.*, 2004) embedded in the DSSAT platform (Decision Support System for Agrotechnology Transfer, Jones *et al.*, 2003), was coupled to the solar radiation simulations composing the Functional-structural plant (FSP) model framework to simulate the forage biomass production. The forage biomass simulations were carried out using the DSSAT 4.7.5.0 version.

Calibration and evaluation of the functional-structural model

Both models were calibrated using a dataset collected in Sinop, Mato Grosso, Brazil (11°51' S, 55°35' W, 384 m elevation) between December 2015 to April 2018. Köppen classified the climate as Am, a tropical climate with dry winter (Alvares *et al.*, 2013). The soil was classified as Ferralsol. The silvopastoral system was composed by *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf. cv. Marandu (palisadegrass) with *Eucalyptus urograndis* (clone H13). The row spacing was 30 m, the arrangement was composed of a grove of triple rows spaced of 3.0 m between trees and 3.5 m between rows; 270 trees ha^{-1}. The rows were oriented in an east-west direction.

To calibrate the radiation model, we used daily data of photosynthetically active radiation (PAR) measured in five distances (0, 4, 7.5, 11, and 15 m) and for both sides (North and South) between the lines of trees. The structure of trees was calibrated with height (m), diameter at breast height (m), and leaf area index (LAI). Data of forage biomass accumulation in different distances (7.5 and 15 m) for or both the sides (North and South) between the tree rows was used to calibrate the CROPGRO-Perennial Forage. The performance of both structural (GroIMP) and functional (CROPGRO-Perennial Forage) models for simulating the radiation intercepted by the trees and the forage biomass production at different distances was evaluated by the root mean squared error (RMSE), determination index (r2) and Willmott index (d) (Willmott *et al.*, 2012).

Clustering the forage biomass production

Applying the protocol proposed by Van Wart *et al.* (2013), we defined 29 agroclimatic zones for representing the livestock production area in Brazil. Aiming to represent the climate and soil characteristics in each zone, we selected from the official statistical data on livestock production and area (IBGE, 2016), the municipality with the highest cattle population per agroclimatic zone to simulate the forage production in different layouts of silvopastoral systems, as full described in Viera Jr et. al (2021).

Based on the simulation of forage biomass production for each agroclimatic zone and classification level, we defined 03 main clusters to represent the livestock producing systems in Brazil. In each cluster, production levels were classified as (i) High (> 18000 kg ha^{-1}); (ii) Good (16000 - 18000 kg ha^{-1}); (iii) Moderate (14000 - 16000 kg ha^{-1}); (iv) Low (12000 - 14000 kg ha^{-1}); (v) Very Low (< 12000 kg ha^{-1}). Ward's hierarchical clustering (Murtagh and Legendre, 2011) was applied as the algorithm for the clustering of agroclimatic zones; the similarity was calculated by Euclidean distance and the separation between groups was determined by the Phenon line (Murtagh and Legendre, 2011). Aiming to represent the different regions (climatic and spatial variability) of clusters we selected 4 agroclimatic zones for each, represented by municipalities with the highest cattle population. Those representative points were defined based on the spatial distance between the municipalities and soil and climatic characteristics (Table 1).

Table 1. Weather station used from each municipality that represents the clusters, representative soil, long-term annual average temperature, and total annual rainfall.

Cluster	Location	Longitude	Latitude	Representative soil classification	Annual mean temperature and total rainfall (°C / mm)	
01	Patos De Minas - MG	-46.51	-18.59	Planosols	21.5	1344
01	Cascavel - PR	-53.45	-24.95	Ferralsols	21.0	1733
01	Mineiros - GO	-52.55	-17.56	Ferralsols	22.7	1536
01	Caraguatatuba - SP	-45.41	-23.62	Nitisols	22.3	1516
02	Rio Das Antas - SC	-51.07	-26.89	Acrisols	16.9	1847
02	Coronel Domingos Soares - PR	-52.03	-26.22	Cambisols	18.2	1905
02	Santo Antônio Do Tauá - PA	-48.13	-1.15	Ferralsols	27.0	2624
03	Itambé - BA	-40.62	-15.24	Cambisols	23.5	800
03	Marabá - PA	-49.14	-5.352	Arenosols	27.3	1751
03	Alta Floresta - MT	-56.09	-9.87	Luvisols	25.7	1412
03	Divisópolis - MG	-41.00	-15.72	Plinthosols	23.3	764

The weather dataset was obtained from the NASA POWER API Client (Sparks, 2018), for the period 1984 to 2017, containing daily data of solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), rainfall (mm), wind speed (m s^{-1}), and relative humidity (%). Defining the dominant soil type for each agroclimatic zone represented by municipalities was performed through regional soil analysis developed by Radam-Brazil Project (RADAMBRASIL, 1973). Based on the dominant soil, we selected the corresponding soil profile from the WISE (World Inventory of Soil Emission

Potentials) database available at International Soil Reference and Information Centre (ISRIC, http://www.isric.org).

Silvopastoral system arrangements

According to most adopted silvopastoral systems in Brazil (Porfírio-da-Silva *et al.*, 2009; Oliveira Neto and Paiva, 2010), we defined 12 tree arrangements aiming to evaluate the performance of Marandu palisadegrass for simulating the forage biomass production in each of these arrangements. These 12 silvopastoral systems resulted from the combinations of the following aspects: (i) tree rows spacing of 15, 30, and 45 m; (ii) row orientations (North-South and East-West); (iii) number of rows (single and triple rows) (Table 2).

Table 2. Description of the arrangements of the simulated silvopastoral systems.

Treatment	Abbreviation	Row orientation	Row spacing (m)	Number of rows
01	NS15m1R	North-South	15	1
02	NS30m1R	North-South	30	1
03	NS45m1R	North-South	45	1
04	NS15m3R	North-South	15	3
05	NS30m3R	North-South	30	3
06	NS45m3R	North-South	45	3
07	EW15m1R	East-West	15	1
08	EW30m1R	East-West	30	1
09	EW45m1R	East-West	45	1
10	EW15m3R	East-West	15	3
11	EW30m3R	East-West	30	3
12	EW45m3R	East-West	45	3

Pruning and thinning scenarios

The simulations started assuming the trees were 2 years old and the age of trees increased 2 years in each simulation (ranging from 2 to 12 years) until reaching the critical production level, which was defined as a trigger for pruning or thinning when forage biomass production was lower than 14000 kg ha^{-1}. For the cases when such a trigger was pulled, we then simulated four kinds of tree management, depending on the silvopastoral system arrangement (Table 3). For systems with single rows, it was simulated two managements: (i) pruning of 40% of the tree canopy and thinning alternately 50% of trees (M1) and (ii) pruning of 40% of the tree canopy (M2). For systems with triple rows, it was simulated the following managements: (i) pruning of 40% of the tree canopy and thinning alternately 50% of trees (M3) and (ii) pruning of 40% of the tree canopy and thinning trees of external rows (M4).

Table 3. Description of the tree management simulated for arrangements of silvopastoral systems.

Abbreviation	Number of rows	Pruning	Thinning
M1	1	40% of the tree canopy	50% of trees
M2	1	40% of the tree canopy	-
M3	3	40% of the tree canopy	50% of trees
M4	3	40% of the tree canopy	External rows

The next step was to continue simulating the radiation interception and the forage biomass production starting in the year that the system reached the critical production level until trees achieve 12 years old. We used weather data for municipalities that represent each cluster to simulate different scenarios for each arrangement and age of the trees. The simulations presented for each cluster were composed by the mean of the four municipalities over the years, between 1984 to 2017. The forage biomass simulations were taken for five equidistant points between the tree rows. We employed 3 calibrations of CROPGRO-Perennial Forage shown in the previous section (Fig. 6) and Appendix B (Table 1, 2, 3, and 4), which were matched to the average radiation incidence for each distance. The final production of forage biomass was obtained by calculating the average simulated production for the 5 distances.

4.3. RESULTS

The simulated managements affected the radiation intercepted by trees in the silvopastoral systems arrangements (Fig. 2). Comparing the amount of incident radiation for each arrangement with the availability in the full sun system, it was observed that the lack of management decreased the intercepted radiation by 48 to 75% after 12 years for the arrangements of 45 m (NS45m3R, EW45m3R, NS45m1R, and EW45m1R) and 15 m (NS15m3R, EW15m3R, NS15m1R, and EW15m1R), respectively (Fig. 2A). Silvopastoral systems with simple rows conducted with M1 radiation decreased to 39% for arrangements of 15 m (NS15m1R and EW15m1R) and 27% for 45 m (NS45m1R and EW45m1R) concerning the full sun (Fig. 2B). For triple rows systems managed with M4, the radiation interception was around 45% for arrangements of 15 m (NS15m3R and EW15m3R) and 33% for arrangements of 45 m (NS45m3R and EW45m3R) after 12 years (Fig. 2C). In addition, all tree management showed higher radiation interception in silvopastoral systems with row-orientation East-West than North-South (Fig. 2).

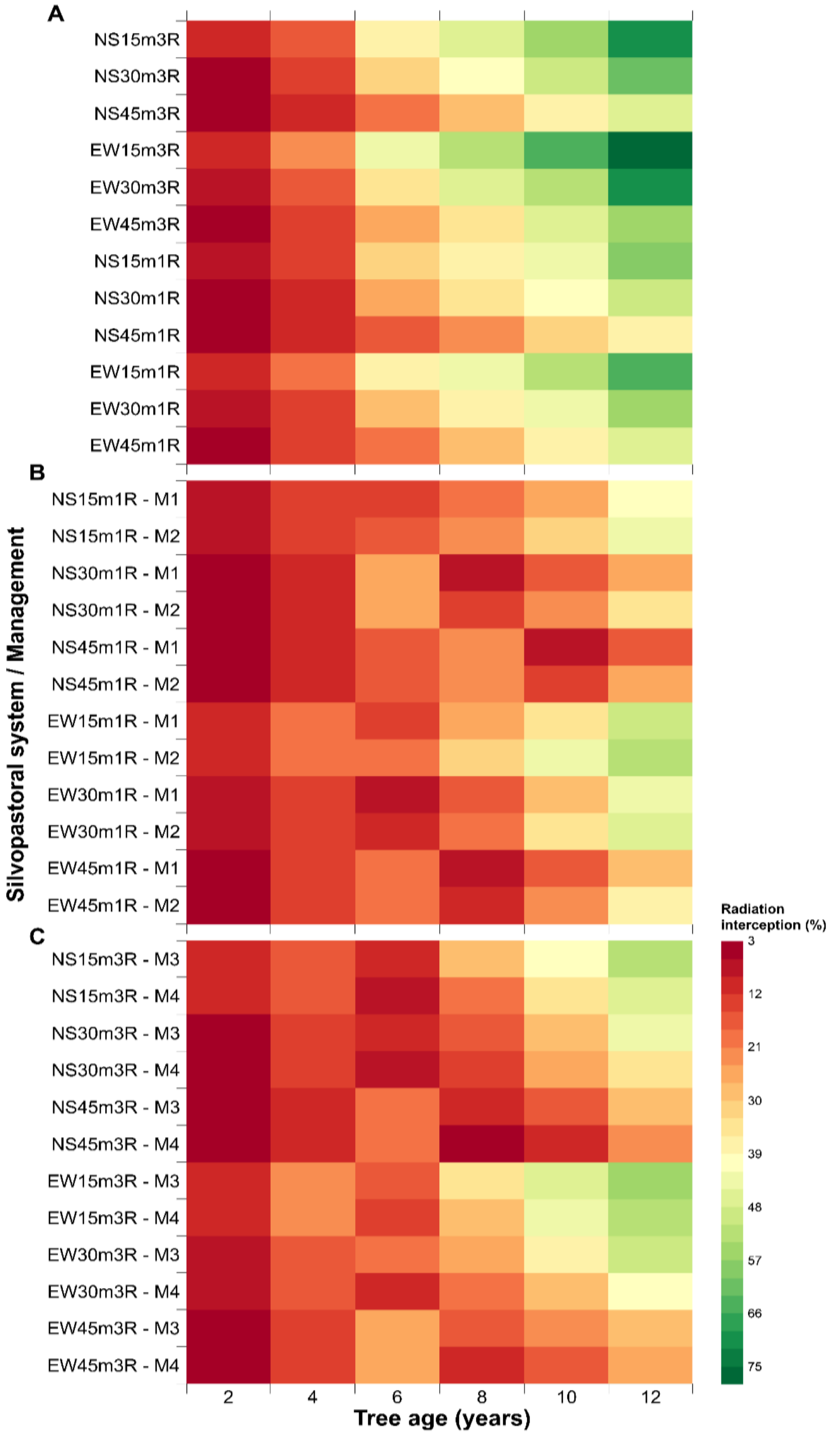

Fig. 2. Average radiation intercepted (%) for each silvopastoral system arrangement simulated without management (A), with managements for 1 row (B) and for 3 rows (C), for the agroclimatic zones between 1984 and 2017.

Increased incident radiation into the silvopastoral systems promoted by the pruning and thinning contributed to pasture growth. In systems with single rows, we verified that M1 performed better than M2 to provide enough solar radiation to pasture growth (Fig. 3). The M2 just presented satisfactory results in silvopastoral systems arrangement with row spacing of 45 m in regions of cluster 02. For all other simulated scenarios, this practice was not sufficient to maintain the forage biomass production higher than the Moderate level more than 2 years after the intervention. In contrast, the M1 guaranteed adequate levels of forage biomass production even in silvopastoral systems arrangements with row spacing of 15 m. Still, the need for pruning and thinning occurred later (2 years at least) in cluster 02, where one intervention was sufficient over the 12 years for all arrangements (Fig. 3). Moreover, in systems with row-orientation North-South, tree management was needed on average 2 years later than East-West (Fig. 3).

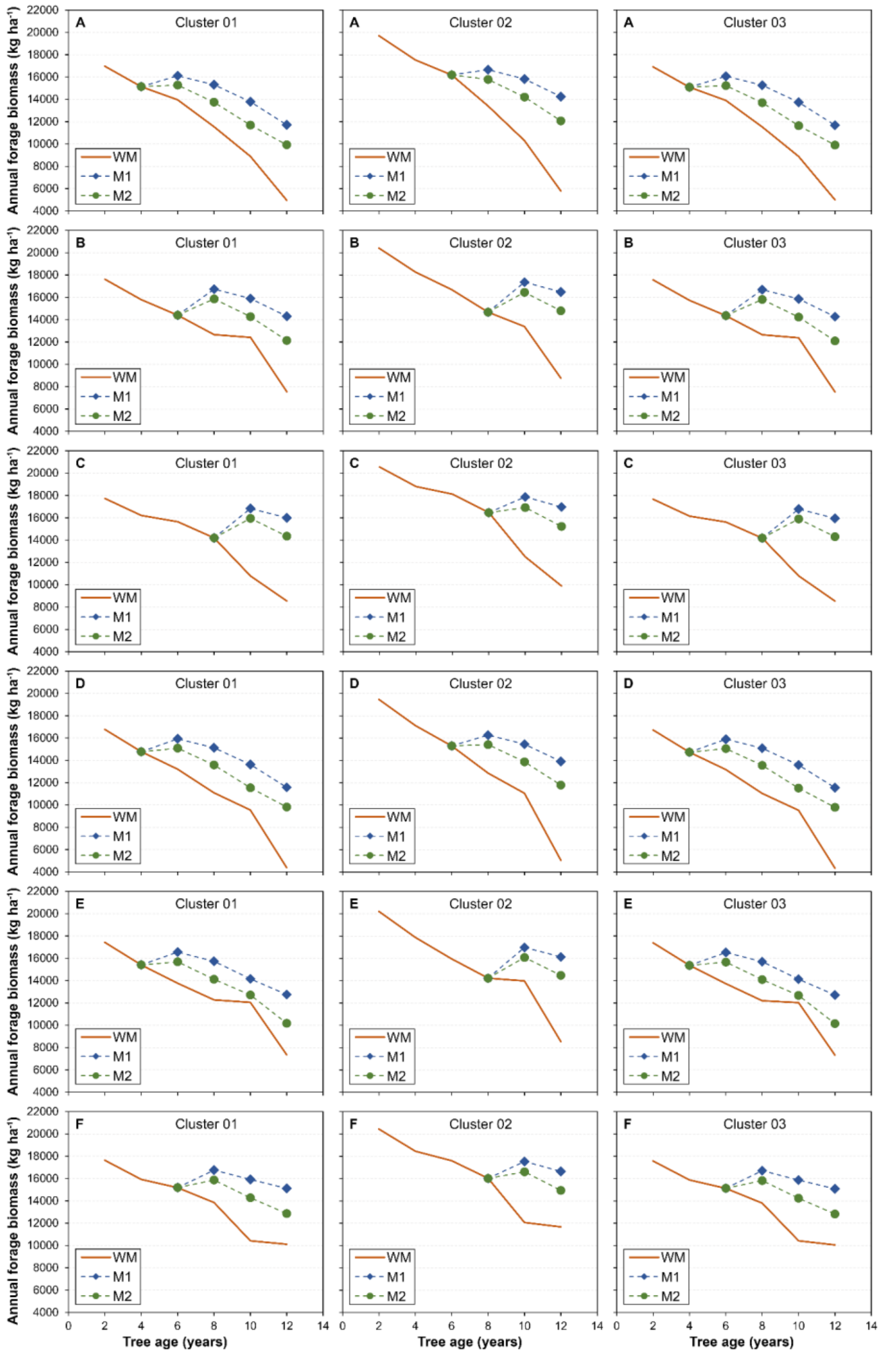

Fig. 3. Mean of annual (kg ha^{-1}) in silvopastoral system arrangements with single rows simulated (A – NS15m1R; B – NS30m1R; C – NS45m1R; D – EW15m1R; E – EW30m1R; F – EW45m1R, See Table 2) without management (WM), with pruning of 40% of the tree canopy and thinning alternately of 50% of trees (M3), and with pruning of 40% of the tree canopy and thinning of trees in the outside rows (M4) for each cluster in range in the period of 1984 to 2017.

Our simulations suggested that for silvopastoral systems with triple rows (NS15m3R, NS30m3R, NS45m3R, EW15m3R, EW30m3R, and EW45m3R), M4 was more efficient than M3 for providing solar radiation for pasture growth (Fig. 4). In cluster 02, only one intervention was requested for guaranteeing the forage biomass production higher than the Moderate level over the 12 years, for arrangements with row spacing of 30 and 45 m. In contrast, in clusters 01 and 03, at least two management practices could be necessary (Fig. 4B, C, E, and F). In silvopastoral systems with 15 m of row spacing, the M3 should be avoided because it did not achieve satisfactory performance, as forage biomass production was higher than 14000 kg ha^{-1} only after 2 years of management. Furthermore, the tree age at which the management interventions were required occurred on average 2 years earlier in arrangements East-West than North-South (Fig. 4).

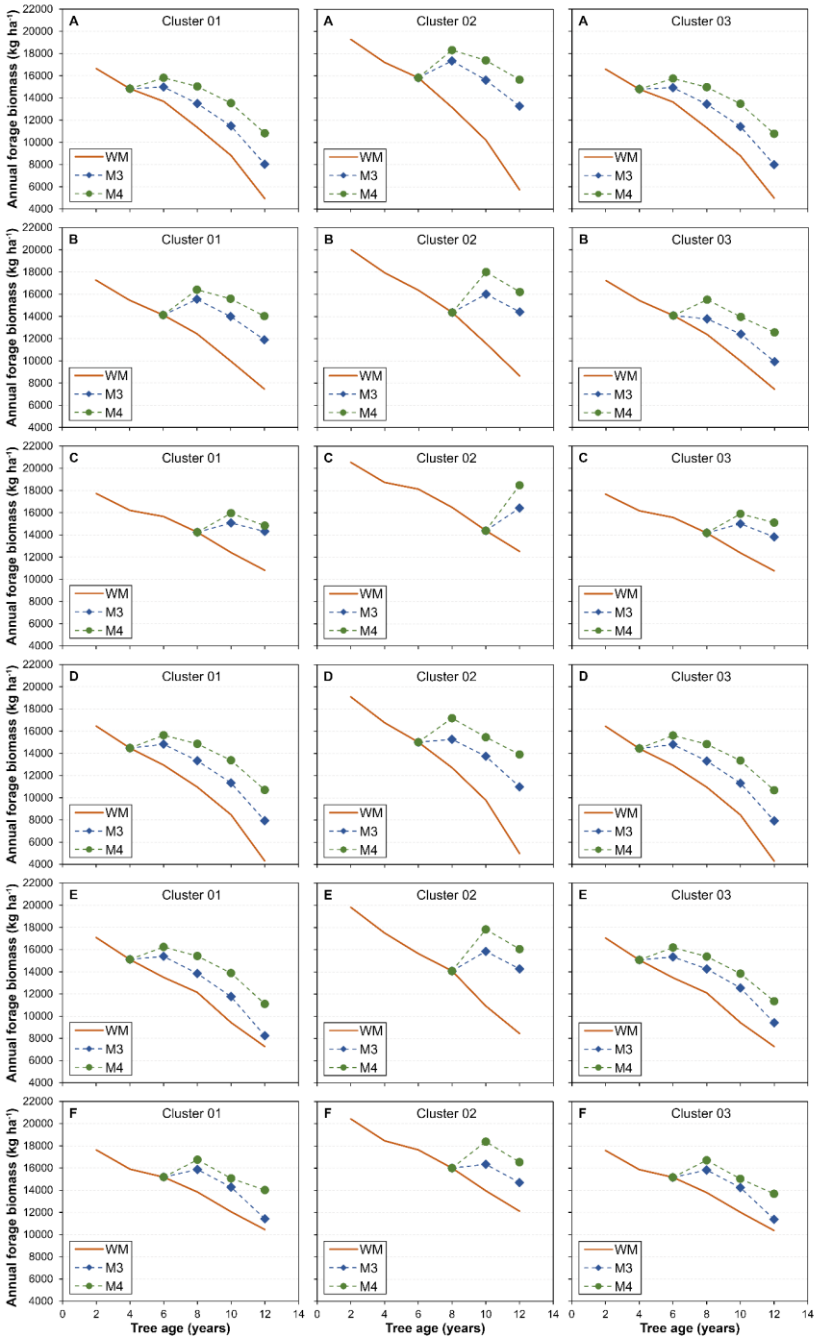

Fig. 4. Mean of annual forage biomass production (kg ha^{-1}) in silvopastoral system arrangements with triple rows simulated (A – NS15m3R; B – NS30m3R; C – NS45m3R; D – EW15m3R; E – EW30m3R; F – EW45m3R) without management (WM), with the pruning of 40% of the tree canopy and thinning alternately of 50% of trees (M1), and with the pruning of 40% of the tree canopy (M2) for each cluster in range in the period of 1984 to 2017.

The tree height when management was required varied with the arrangement, as closer row spacing reduced the PAR transmission and resulted in lower forage production even for smaller tree heights (Fig. 5). Arrangements with row spacing of 15 m (NS15m3R, EW15m3R, NS15m1R, and EW15m1R) the tree management was required with an average height of 19.5 m. This represents an average PAR transmission above the pasture of 60% when compared to the amount of PAR incident in a system conducted at full sun. Silvopastoral systems with row spacing of 30 m (NS30m3R, EW30m3R, NS30m1R, and EW30m1R) provided an average PAR transmission of 63% concerning the full sun system. It corresponded to intervention necessity for trees with a height between 25 to 27 m. Row spacing of 45 m (NS45m3R, EW45m3R, NS45m1R, and EW45m1R) between trees provided 66% of the PAR transmitted at the full sun above the pasture, and consequently the requirement for pruning or thinning occurred later, when trees reached height around 30 m (Fig. 5).

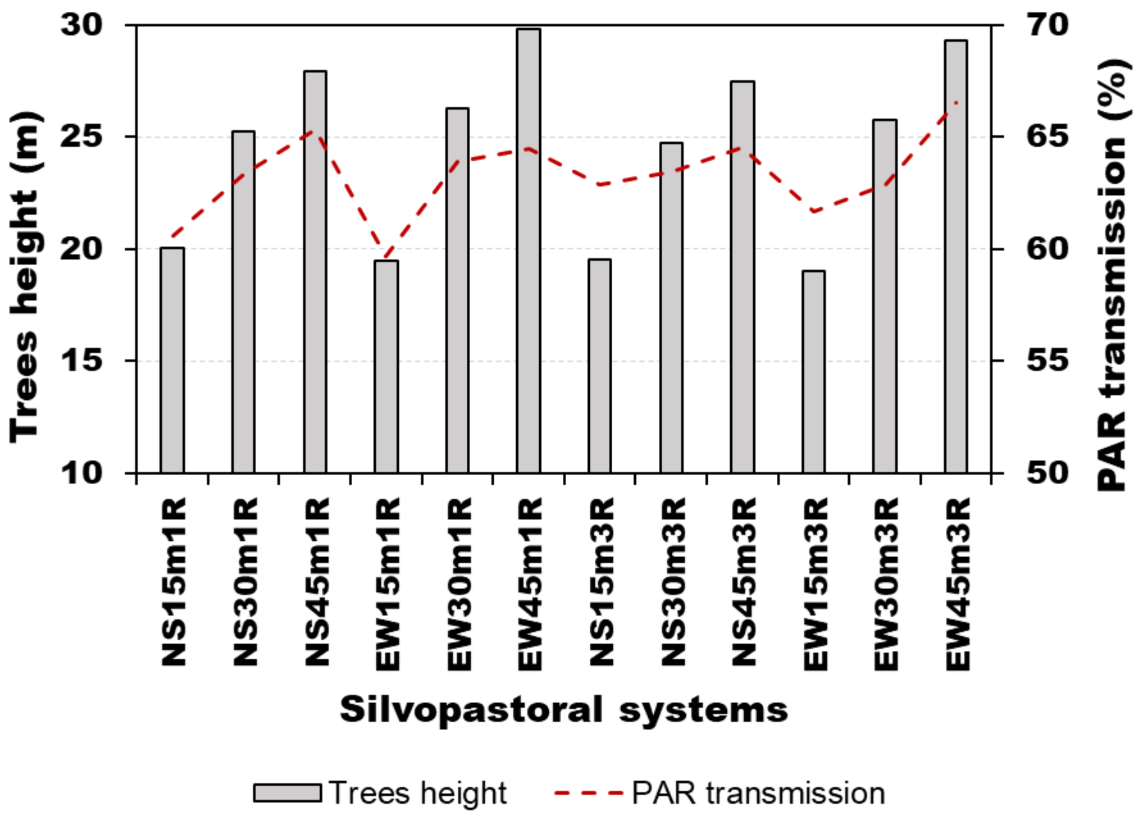

Fig. 5. Average of trees height (m) and photosynthetically active radiation (PAR) in the

year when tree management was necessary for each silvopastoral system arrangement simulated and for the clusters between 1984 and 2017.

4.4. DISCUSSION

The persistence of the forage species in silvopastoral systems depends on its adaptability to grow and develop under edaphoclimatic conditions altered by the presence of arboreal species (Geremia *et al.*, 2018), since the microclimate created in the system affects the quantity and quality of the forage produced (Gomes *et al.,* 2020). Light reduction and competition are among the main factors influencing the development of the plants (Fragoso *et al.,* 2016) and pruning and thinning may contribute to maintaining the equilibrium between the production of the components of the system (Pezzopane *et al.*, 2020). We concluded that solar radiation availability over the years was a key factor in maintaining pasture production in silvopastoral systems (Fig. 2 and 5). For example, for triple rows systems (NS15m3R, NS30m3R, NS45m3R, EW15m3R, EW30m3R, and EW45m3R), the management M4 was more efficient than M3 to provide enough radiation for the pasture growth due to the removal of the outside rows, which transforms the system in a simple row arrangement (Fig. 4). In this sense, pruning places a role to regulate the structure of trees and contribute to the growth of forage (Ortega-Vargas *et al.,* 2019), while thinning might reduce the light, water, and nutrient intraspecies competition, favoring the tree growth and avoiding depletion of the pasture production (Nicodemo *et al.*, 2016).

Marandu palisadegrass tolerates radiation decrease up to ~20% in silvopastoral systems without a negative impact on pasture production (Nascimento *et al.*, 2019). If any management practice was not conducted, values of radiation interception higher than this amount were verified for systems with an arrangement of 15 m (NS15m3R, EW15m3R, NS15m1R, and EW15m1R) for trees at 4 years old. For silvopastoral systems with 30 m (NS30m3R, EW30m3R, NS30m1R, and EW30m1R) and 45 m (NS45m3R, EW45m3R, NS45m1R, and EW45m1R) percentages of radiation interception higher than 20% were observed after 6 and 8 years of system implementation, respectively (Fig. 2). Yet, our simulations showed that pruning and thinning are efficient to provide radiation interception levels lower than 20% for trees 8 years old in silvopastoral systems with row spacing of 15 m (NS15m3R, EW15m3R, NS15m1R, and EW15m1R) (Fig. 2). For systems with arrangements of 30 m (NS30m3R, EW30m3R, NS30m1R, and EW30m1R) and 45 m (NS45m3R, EW45m3R, NS45m1R, and EW45m1R) adequate levels of radiation incidence can be achieved until trees were 12 years old (Fig. 2), consequently maintaining the annual forage biomass production at satisfactory levels (Fig. 3 and 4).

Beyond radiation availability, other environmental aspects influenced the pasture growth in silvopastoral systems, such as temperature, rainfall, and soil properties (Gomes *et al.*, 2020), which vary spatially across the country. In general, the climatic conditions were more favorable in regions of cluster 02, with higher rainfall and lower temperatures (Table 1) which resulted in a higher production level (Fig. 3 and 4). In this sense, the layout and arrangement of trees in silvopastoral systems affected the shading levels and, consequently, the forage biomass production The planning and implementation of silvopastoral systems must carry out more carefully in regions with higher temperatures and lower rainfall volumes, such in clusters 01 and 03 (Table 1), aims to minimize the radiation competition, avoiding that the addition of the trees become another limiting factor (See section 3). The pruning and thinning in systems properly designed according to edaphoclimatic conditions for each location can be more efficient and guarantee adequate levels of forage production over the years, reducing the number of the intervention (Fig. 3 and 4).

Morphological and physiological tree responses to pruning should be considered to guarantee favorable environmental conditions that permit the regrowth of removed branches (Ortega-Vargas *et al.,* 2019). When not properly planned, pruning may result in unsatisfactory results, such as those observed by Nicodemo *et al.* (2016) evaluating a system composed of native trees and black oats. They concluded that pruning of 50% of branches was not effective to reduce the radiation competition between species and increase the production of black oats to similar levels compared to the full sun treatment. Similar results were verified in our study for the M2 management in silvopastoral system arrangements of 15 m (NS15m1R and

EW15m1R) and 30 m (NS30m1R and EW30m1R) (Fig. 2), where the pruning alone was insufficient to increase the pasture production (Fig. 3). Then, it would be necessary a higher pruning frequency over the years to maintain adequate levels of forage production in the system. Yet, the proper planning of pruning must also consider the costs and complexity of the operation, as well as the interval between the interventions and the best season of the year to carry it out (Ghani *et al.*, 2021). Consequently, more labor, implements, and resources would be employed to maintain the solar radiation incidence into the system at reasonable levels for pasture growth. Finally, it is important to consider that pruning practices might be necessary during the initial period of tree growth, when the canopy is being formed, to ensure good quality of the wood (Oliveira Neto and Paiva, 2010), which was not considered in the management proposed in our simulations.

In silvicultural, the thinning objectives vary depending on forest species, environmental conditions (Martínez Pastur *et al.*, 2018), product for which the wood will be destined, and wood demand (Hintz *et al.*, 2021). For example, thinning may be applied to aim to favor the growth of trees and improve the quantity and quality of wood (Peri *et al.*, 2013). Still, thinning in silvopastoral systems requires more careful planning and must consider several objectives, as guaranteeing adequate conditions for tree development; at the same time, it is necessary to enhance pastures biomass production by increasing the radiation levels (Peri *et al.*, 2016; Martínez Pastur *et al.*, 2017). In this way, this management is directly related to tree height (Fig. 5), as systems with arrangements of 15 m (NS15m3R, EW15m3R, NS15m1R, and EW15m1R) could demand a thinning earlier than systems with arrangements of 30 m (NS30m3R, EW30m3R, NS30m1R, and EW30m1R) or 45 m (NS45m3R, EW45m3R, NS45m1R, and EW45m1R) (Fig. 3 and 4). This factor must be considered to adopt a management and planning of the wood commercialization. Early thinning of systems with dense tree stands is profitable when there would be market for the products, such as firewood and wooden bracing for construction (Nicodemo *et al.*, 2016). Otherwise, it may result in important expenses with thinning operations. Still, the thinning levels may change according to the region in which the system was implemented. Our simulations suggested that a lower percentage of trees could be removed in cluster 02 concerning clusters 01 and 03, without decreasing the annual forage biomass production (Fig. 3 and 4). On other hand, more intense thinning levels might be necessary for maintaining the radiation incidence levels adequate to the pasture growth (Martínez Pastur *et al.*, 2018).

4.5. CONCLUSION

This study employed an efficient approach for simulating the radiation interception by the trees and the pasture growth in different silvopastoral system arrangements and under several tree managements. It can help the farmers to adopt this kind of system and aid the tree management strategies.

Pruning alone may not be enough to provide radiation incidence for pasture growth and should be avoided mainly in the silvopastoral systems with row spacing of 15 and 30 m. The tree-row orientation East-West can demand pruning and thinning practices earlier than North-South.

In general, the combination of pruning and thinning was capable of maintaining the forage biomass production to adequate levels over the years.

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5. GENERAL CONCLUSIONS

Based on the results obtained in this study, we can conclude:

The addition of trees to a pasture system affected the incidence of the photosynthetically active radiation, which varied according to the solar inclination. Row orientation interfered with the radiation availability; rows need to be adequately arranged and managed to provide suitable conditions for pasture growth. Based on experimental data collected we verified that solar radiation interception caused by trees influenced the quality and quantity of pasture biomass. The excessive shading close to tree lines may result in lower biomass and higher fiber content.

A robust processed-based model (CROPGRO-Perennial Forage) was calibrated considering the different light conditions that tree components might cause in silvopastoral systems. The employment of different calibrations to represent the pasture growth in silvopastoral systems showed satisfactory performance.

A Functional-Structural Plant Model capable to simulate the light interception by trees of different ages and silvopastoral system arrangements was developed; Functional-Structural Plant Models are promising tools to represent the interactions that occur in intercropping systems, showing potential to aid in the planning to arrangement and management of this kind of systems.

The arrangement of trees in the silvopastoral systems affected the radiation incidence for pastures and this in turn affected the forage production level. The arrangements with a row spacing of 30 and 45 m can be efficient to provide forage and thermal comfort for the animals for several years. In contrast, treatments with a row spacing of 15 m or triple lines demand more careful planning and frequent management, considering the soil and climatic characteristics of each region.

Pruning alone may not be enough to provide radiation incidence for pasture growth and should be avoided mainly in the silvopastoral systems with row spacing of 15 and 30 m. The tree-row orientation East-West may demand pruning and thinning practices earlier than North-South. In general, the combination of pruning and thinning was capable of maintaining the forage biomass production to adequate levels over the years.

This study presented a novel approach that showed satisfactory performance in simulating forage biomass production in silvopastoral systems; to reduce the uncertain associates to this methodology, a higher level of complexity could be employed to represent the tree structure, by adding functional processes. Further studies can be proposed aiming to simulate and evaluate the water competition interspecies that occurs in silvopastoral systems and add soil processes in the routines of the approach.

APPENDIX

Appendix A - Schematic representation of the silvopastoral systems arrangements simulated.

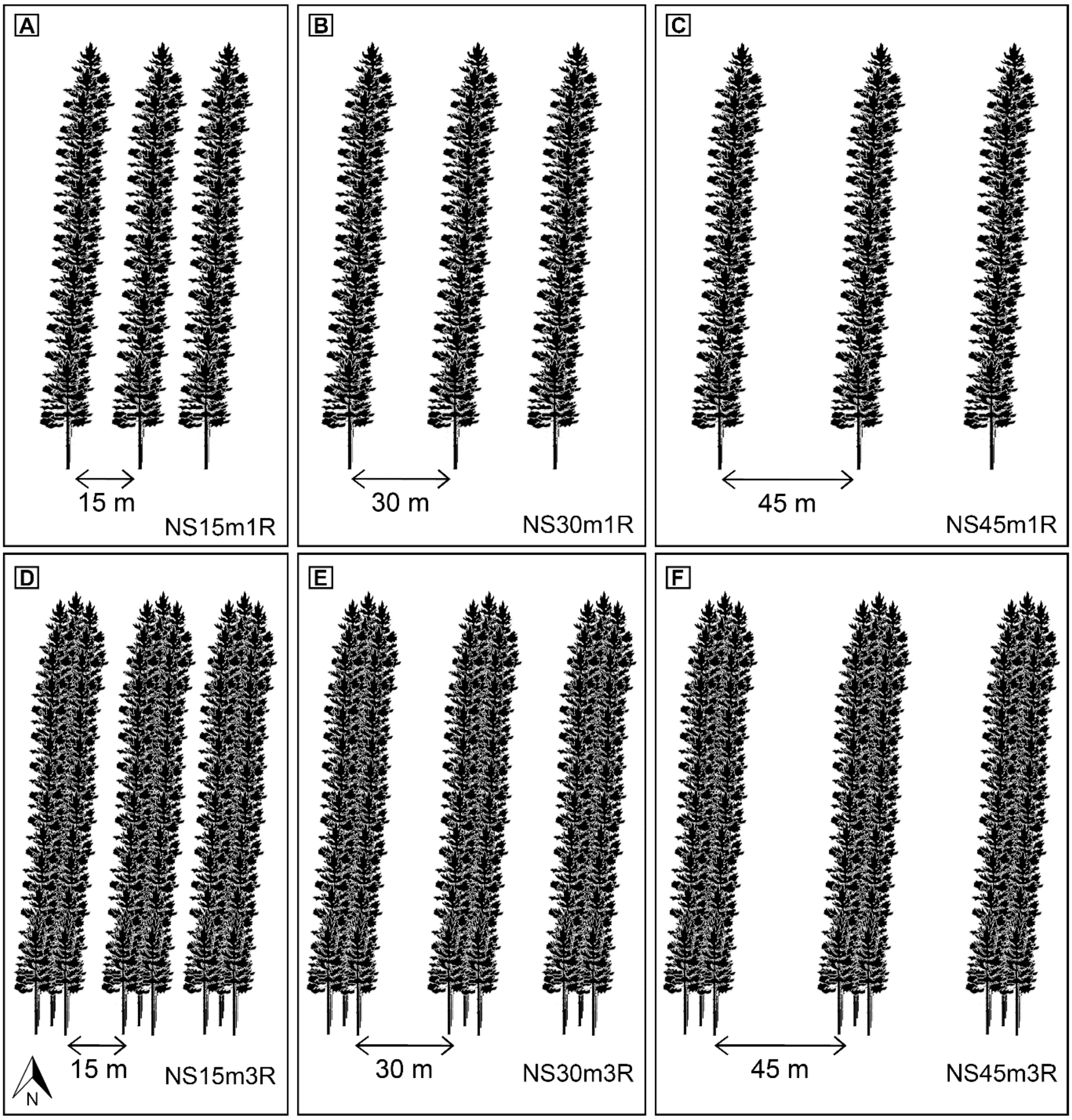

Fig. 1. Schematic representation of the silvopastoral systems arrangements simulated in the orientation North-South.

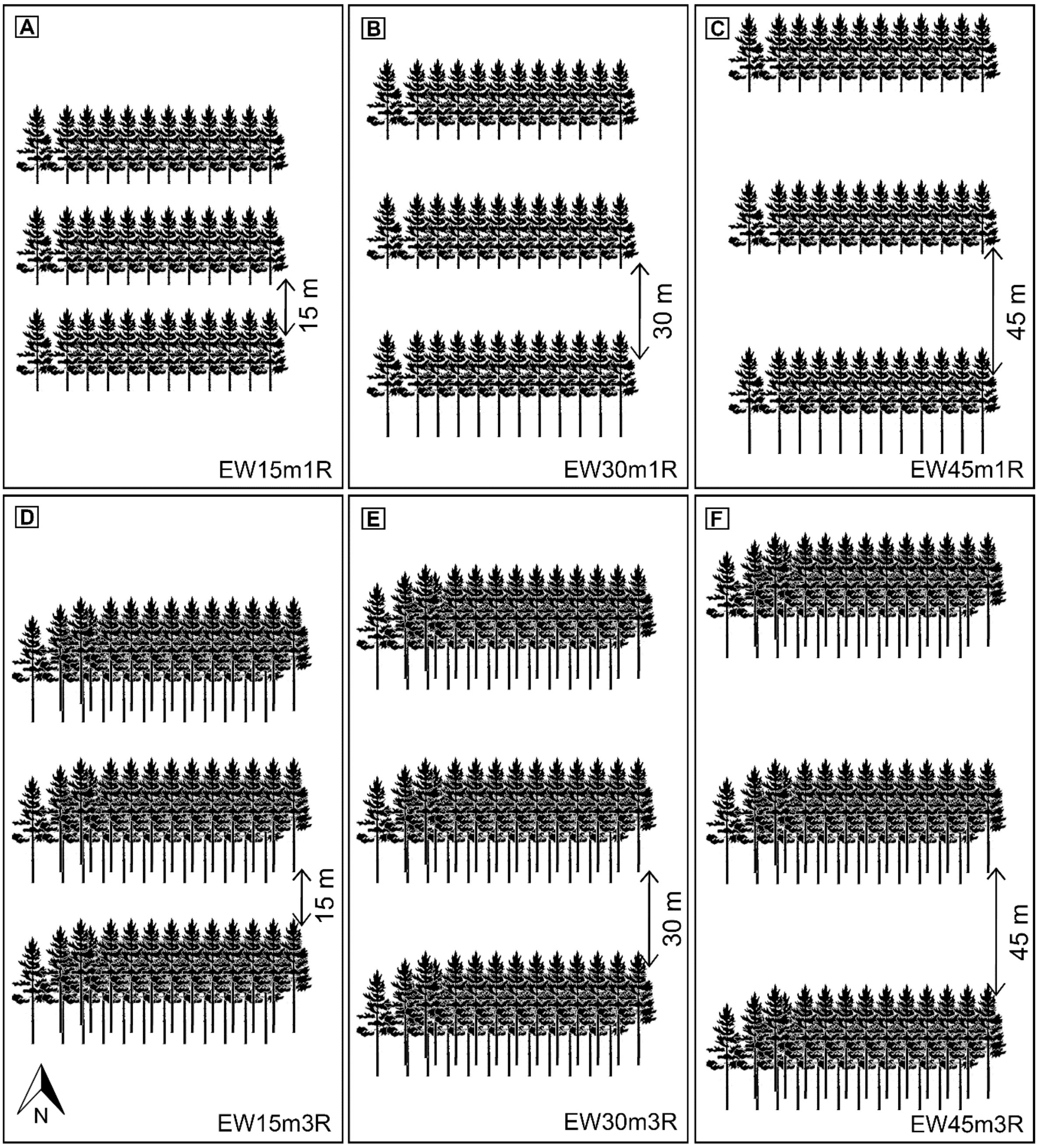

Fig. 2. Schematic representation of the silvopastoral systems arrangements simulated in the orientation East-West.

Appendix B – Calibration of CROPGRO-Perennial Forage model calibrated for Marandu palisade grass in 3 distances of silvopastoral systems and full sun.

Table 1. Model parameter names, definitions, initial values (Pequeno *et al.*, 2018) for Marandu palisade grass and calibrated values for plant composition, phenology, and productivity (photosynthesis and respiration) for different distances (15m, 7.5 North and South) for silvopastoral system and full sun (FS).

Name	**Definition**	**Pequeno *et al.*, 2018**	**FS**	**15m**	**7.5 North**	**7.5 South**
PRO_ _G	"Normal growth" protein conc. Fraction of tissue (leaf=LF, root=RT, stem=ST, storage organ=SR)	LF=0.160; RT=0.040; ST=0.080; SR=0.064	LF=0.160; RT=0.040; ST=0.080; SR=0.064	LF=0.160; RT=0.040; ST=0.080; SR=0.064	LF=0.160; RT=0.040; ST=0.080; SR=0.064	LF=0.160; RT=0.040; ST=0.080; SR=0.064
PRO_ _I	"Maximum" protein concentration of tissue	LF=0.240; RT=0.101; ST=0.120; SR=0.092	LF=0.250; RT=0.110; ST=0.130; SR=0.092	LF=0.250; RT=0.110; ST=0.130; SR=0.092	LF=0.250; RT=0.112; ST=0.130; SR=0.092	LF=0.250; RT=0.112; ST=0.130; SR=0.092
PRO_ _F	"Final" protein concentration of tissue (at senescence)	LF=0.035; RT=0.022; ST=0.025; SR=0.056	LF=0.035; RT=0.022; ST=0.025; SR=0.056	LF=0.035; RT=0.022; ST=0.025; SR=0.056	LF=0.035; RT=0.022; ST=0.025; SR=0.056	LF=0.035; RT=0.022; ST=0.025; SR=0.056

Tb	Base temperature for vegetative development (°C)	11.1	11.5	11.5	11.5	11.5
TO1	First optimum temperature for vegetative development (°C)	30.2	30.2	30.2	30.2	30.2
TO2	Second optimum temperature for vegetative development (°C)	40	40	40	40	40
TM	Maximum temperature for vegetative development (°C)	45	45	45	45	45
MRSWITCH	Respiration: M=mass based (original CROPGRO code) or P=protein based	M	M	M	M	M
RES30C	Constant describing maintenance respiration as a function of total crop dry weight (minus oil, protein, and starch in the seed) (g CH_2O (dry weight) $^{-1}$ hr^{-1})	3.0 x 10^{-4}	3.0 x 10^{-4}	3.0 x 10^{-4}	3.0 x 10^{-4}	3.0 x 10^{-4}
R30C2	Constant describing maintenance respiration as a function of canopy photosynthesis (g CH_2O/g photosynthate CH_2O/hr)	0.0024	0.0024	0.0024	0.0024	0.0024
LFMAX	Maximum leaf photosynthetic rate at 30 °C, 350 ppm CO_2, and high light (mg $CO_2 m^{-2}$ s^{-1})	1.80	1.80	1.80	1.80	1.80
FNPGN (1,2)	Leaf N concentration effect on photosynthesis or FNPGN (2), which is a two-sided quadratic curve describing leaf photosynthesis response to leaf N concentration: increases from zero at the minimum leaf N concentration to maximum leaf N concentration	0.80, 4.00	0.80, 4.00	0.80, 4.00	0.80, 4.00	0.80, 4.00

SLWREF	Specific leaf weight at which LFMAX is defined (g/m^2)	0.0071	0.0071	0.0071	0.0071	0.0071

Table 2. Model parameter names, definitions, initial values (Pequeno *et al.*, 2018) for Marandu palisade grass and calibrated values for temperature, solar radiation and photoperiod effects on vegetative partitioning, specific leaf area, and photosynthesis for different distances (15m, 7.5 North and South) for silvopastoral system and full sun (FS).

Name	**Definition**	**Pequeno *et al.*, 2018**	**FS**	**15m**	**7.5 North**	**7.5 South**
XLFEST	Leaf number or vegetative stage at which the partitioning is defined	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0, 40.0	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0, 40.0	0.0, 2.5, 4.0, 7.0, 10.0, 12.0, 30.0, 40.0	0.0, 2.0 4.0, 7.0, 10.0, 20.0, 30.0, 40.0	0.0, 2.0 4.0, 7.0, 10.0, 20.0, 30.0, 40.0
YLFEST	Describes dry-matter partitioning to leaf among vegetative tissue only, as a function of vegetative stage (fraction)	0.80, 0.80, 0.72, 0.63, 0.52, 0.51, 0.50, 0.50	0.80, 0.80, 0.74, 0.65, 0.62, 0.60, 0.60, 0.60	0.80, 0.80, 0.75, 0.64, 0.58, 0.60, 0.60, 0.60	0.80, 0.80, 0.70, 0.60, 0.55, 0.51, 0.50, 0.50	0.80, 0.80, 0.70, 0.60, 0.55, 0.51, 0.50, 0.50
YSTEST	Describes dry-matter partitioning to stem among vegetative tissue only, as a function of vegetative stage (fraction)	0.10, 0.10,	0.10, 0.10,	0.10, 0.10,	0.10, 0.10,	0.10, 0.10,

		0.14, 0.17, 0.32, 0.36, 0.35, 0.35	0.14, 0.15, 0.32, 0.25, 0.25, 0.25	0.13, 0.15, 0.30, 0.32, 0.35, 0.35	0.15, 0.18, 0.30, 0.30, 0.30, 0.30	0.18, 0.18, 0.30, 0.30, 0.30, 0.30
YSREST	Describes dry-matter partitioning to storage among vegetative tissue only, as a function of vegetative stage (fraction)	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2/g)	190	180	200	205	210
SLAMAX	Thinnest of leaves under low light (cm^2/g)	340	340	340	340	340
SLAMIN	Thickest of leaves under high light (cm^2/g)	139	139	139	139	139
FNPGL (1,2)	Relative effect of minimum night temperature on next day's leaf light-saturated photosynthesis rate. Quadratic shape, first value defines base (0.0) and second defines maximum (1.0) (°C)	5.1, 22.2	5.1, 22.2	5.1, 22.2	5.1, 22.2	5.1, 22.2
XLMAXT (2,3)	Relative rate of photosynthetic electron transport in response to temperature, linear from base (0.0) to maximum (1.0) (°C)	6.2, 40.2	6.2, 40.2	6.2, 40.2	6.2, 40.2	6.2, 40.2

XSLATM (3,4)	Relative temperature effect on specific leaf area of newly formed leaves (°C, x vs. y pair)	10.3, 24.2	10.3, 24.2	10.3, 24.2	10.3, 24.2	10.3, 24.2
YSLATM (3,4)	Relative temperature effect on specific leaf area of newly formed leaves, fraction reduction (x vs. y pair)	0.39, 1.00	0.39, 1.00	0.39, 1.00	0.39, 1.00	0.39, 1.00
FNPTD (2,3)	Daylength effect on partitioning (hr)	12.0, 16.0	12.0, 16.0	12.0, 16.0	12.0, 16.0	12.0, 16.0
FNPMD (1,3)	Daylength effect on mobilization (hr)	7.8, 12.0, 0.62	7.8, 12.0, 0.62	7.8, 12.0, 0.62	7.8, 12.0, 0.62	7.8, 12.0, 0.62
RDRMT	Relative dormancy sensitivity, daylength effect on partitioning	0.475	0.475	0.475	0.475	0.475
RDRMM	Relative dormancy sensitivity, daylength effect on mobilization	0.850	0.850	0.850	0.850	0.850

Table 3. Model parameter names, definitions, initial values (Pequeno *et al.*, 2018) for Marandu palisade grass and calibrated values for carbon and nitrogen mining parameters for different distances (15m, 7.5 North and South) for silvopastoral system and full sun (FS).

Name	Definition	Pequeno *et al.*, 2018	FS	15m	7.5 North	7.5 South
CMOBSRN	Minimum daily rate of CH_2O mobilization from storage (fraction)	0.020	0.020	0.020	0.020	0.020
CMOBSRX	Maximum daily rate of CH_2O mobilization from storage (fraction)	0.072	0.072	0.072	0.072	0.072
NMOBSRN	Minimum daily rate on N mobilization from storage (fraction)	0.010	0.010	0.010	0.010	0.010
NMOBSRX	Maximum daily rate of N mobilization from storage (fraction)	0.068	0.068	0.068	0.068	0.068
ALPHSR	Fraction of new storage tissue growth that is available CH_2O (fraction)	0.20	0.20	0.20	0.20	0.20
CADPV	Maximum fraction of photoassimilate available that can be allocated to CH_2O refill during non-stress conditions	0.356	0.356	0.356	0.356	0.356
LRMOB (3,4)	Leaf area index effect on mobilization (most rapid to least rapid)	0.41, 2.75	0.41, 2.75	0.41, 2.75	0.41, 2.75	0.41, 2.75
CRREF (2,3,4)	Carbohydrate status effect on refilling of storage tissue CH_2O pool	0.33, 0.81, 0.29	0.33, 0.81, 0.29	0.33, 0.81, 0.29	0.33, 0.81, 0.29	0.33, 0.81, 0.29
LRREF (1,2)	Leaf area index effect on refilling of storage tissue CH_2O pool (least to most rapid)	0.68, 2.58	0.68, 2.58	0.68, 2.58	0.68, 2.58	0.68, 2.58

PRREF (1,2)	Canopy photosynthesis effect on refilling of storage tissue CH_2O	0.12, 0.38	0.12, 0.38	0.12, 0.38	0.12, 0.38	0.12, 0.38
CMOBMX	Maximum mobilization of CH_2O from vegetative tissues, fraction of available CH_2O pool per day	0.50	0.50	0.50	0.50	0.50
NMOBMX	Maximum mobilization of protein from vegetative tissues, fraction of available protein pool per day	0.080	0.080	0.080	0.080	0.080
CADSRF	Fraction of carbohydrate reserves that are added to storage organs (remainder is allocated to stem and leaf)	0.439	0.439	0.439	0.439	0.439

Table 4. Model parameter names, definitions, initial values (Pequeno *et al.*, 2018) for Marandu palisade grass and calibrated values for for senescence parameters for different distances (15m, 7.5 North and South) for silvopastoral system and full sun (FS).

Name	**Definition**	**Pequeno *et al.*, 2018**	**FS**	**15m**	**7.5 North**	**7.5 South**
LFSEN	Natural leaf senescence rate/photothermal day (0.01 means 25-days of lifespan)	0.01	0.01	0.01	0.01	0.01
RTSEN	Root senescence (fraction per physiological day)	0.008	0.008	0.008	0.008	0.008
ICMP	Light compensation point (mol Photosynthetic photon flux density m^{-2} day^{-1}) for senescence of lower leaves because of excessive self-shading by the crop canopy	1.17	1.17	1.17	1.17	1.17
TCMP	Time constant (days) for senescence of lower leaves because of excessive self-shading by the crop canopy	13.1	13.1	13.1	13.1	13.1
PORPT	Stem senescence as a function of the senesced leaf mass (fraction)	0.27	0.27	0.27	0.27	0.27
SENSR	Senescence rate of storage organ tissue (proportion of cumulative storage mass lost per physiological day)	0.011	0.011	0.011	0.011	0.011

Appendix C - Characterization of weather stations (29 agroclimatic zones) applied to simulations of forage biomass in different arrangements of silvopastoral systems.

Table 1. Weather station used from each agroclimatic zone, representative soil, long-term annual average temperature and total annual rainfall.

CZ	Location	Longitude	Latitude	Representative soil classification	Average temperature and rainfall (°C / mm)	
6601	Bom Jesus - RS	-50.43	-28.67	Cambisols	16.4	1713
6701	Rio Das Antas - SC	-51.07	-26.89	Acrisols	16.9	1847
7401	Resende - RJ	-44.44	-22.47	Ferralsols	20.2	1503
7402	Uruguaiana - RS	-57.08	-29.75	Ferralsols	20.0	1484
7501	Ortigueira - PR	-50.92	-24.21	Ferralsols	19.9	1614
7502	Alegrete - RS	-55.79	-29.78	Ferralsols	19.7	1574
7601	São Francisco De Paula - RS	-50.58	-29.44	Nitisols	17.2	1667
7602	Santiago - RS	-54.86	-29.19	Nitisols	19.4	1765
7701	Coronel Domingos Soares - PR	-52.03	-26.22	Cambisols	18.2	1905
8301	Patos De Minas - MG	-46.51	-18.59	Planosols	21.5	1344
8401	Uberaba - MG	-47.98	-19.71	Ferralsols	22.1	1492
8501	Cascavel - PR	-53.45	-24.95	Ferralsols	21.0	1733
8502	Itaqui - RS	-56.55	-29.12	Acrisols	20.4	1576
8601	Cunha - SP	-44.95	-23.07	Planosols	21.6	1611
8602	Porto Xavier - RS	-55.13	-27.90	Podzols	20.7	1912
9001	Divisópolis - MG	-41.00	-15.72	Plinthosols	23.3	764
9201	Teófilo Otoni - MG	-41.51	-17.86	Leptsols	23.0	1035
9301	Prata - MG	-48.92	-19.30	Ferralsols	23.0	1358
9401	Mineiros - GO	-52.55	-17.56	Ferralsols	22.7	1536
9502	Marechal Cândido Rondon - PR	-54.06	-24.55	Acrisols	22.9	1690

9601	Caraguatatuba - SP	-45.41	-23.62	Nitisols	22.3	1516
10001	Itambé - BA	-40.62	-15.24	Cambisols	23.5	800
10201	Corumbá - MS	-57.65	-19.00	Acrisols	27.7	996
10301	Vila Bela Da Santíssima Trindade - MT	-59.95	-15.00	Ferralsols	26.5	12834
10401	Marabá - PA	-49.14	-5.352	Arenosols	27.3	1751
10501	São Félix Do Xingu - PA	-51.99	-6.64	Nitisols	25.9	1824
10601	Alta Floresta - MT	-56.09	-9.87	Luvisols	25.7	21412
10701	Viseu - PA	-46.13	-1.20	Gleysols	27.2	2333
10801	Santo Antônio Do Tauá - PA	-48.13	-1.15	Ferralsols	27.0	2624