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Soil Moisture Dynamics in Integrated Crop - Livestock - Forestry Systems in the Cerrado Biome in Central - West Brazil

Dissertation

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presented by

Sarah Glatzle
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Affidavit

pursuant to Sec. 8(2) of the University of Hohenheim's doctoral degree regulations for Dr.sc.agr.

1. I hereby declare that I independently completed the doctoral thesis submitted on the topic "Soil Moisture Dynamics in Integrated Crop - Livestock - Forestry Systems in the Cerrado Biome in Central - West Brazil"
2. I only used the sources and aids documented and only made use of permissible assistance by third parties. In particular, I properly documented any contents which I used - either by directly quoting or paraphrasing - from other works.
3. I did not accept any assistance from a commercial doctoral agency or consulting firm.
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Stuttgart, 2021

Sarah Glatzle

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Stuttgart, 28.04.2021 Sarah Glatzle

Place, Date Signature

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List of Abbreviations

ADF	Acid detergent fiber
ADG	Average daily body weight gain
AGBM	Aboveground biomass
AIC	Akaike information criterion
AU	Animal unite
AWG	Animal body weight gain per hectare
BM	Biomass
BW	Body weight
CER	Cerrado
CON	Control pasture in full sunlight
COP	Continuous pasture
CP	Crude protein
DM	Dry matter
DM	Dry weight
DS	Dry season
DW	Dry weight
ET	Evapotranspiration
FC	Field capacity
FDR	Frequency domain reflectometry
HAL	Herbage allowance
HAR	Herbage accumulation rate
HM	Herbage mass
ICL	Integrated-Crop-Livestock
ICLF	Integrated-Crop-Livestock-Forestry
IVDOM	Invitro digestibility of organic matter
LSD	Least significant differences
M	Month
NDF	Neutral detergent fiber

NIRS	Infrared reflectance spectrophotometry system
PAR	Photosynthetically active radiation
PWP	Permeant welting point
R	Replication
RS	Rainy season
S	Season
SM	Soil moisture
SP	Sample point
SPS	Silvopastoral system, SPS22: 227 tress ha^{-1}, SPS14: 357 trees ha^{-1}
SR	Stocking rate
Y	Year

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Summary

The Cerrado biome in Brazil covers about 200 million ha and is a global biodiversity hotspot with three of the largest watersheds of South America. Over the last decades, the Cerrado biome underwent and is still undergoing an excessive expansion in agriculture. Deforestation and replacement of the natural Savannah vegetation by cropland and pasture contributes to serious environmental problems, including soil degradation and altered water cycles.

The integrated crop-livestock-forestry (ICLF) system is currently promoted as a measure for sustainable intensification. It improves the use of cultivated areas, recovers previously degraded and unproductive land, and could be a strategy for adapting agriculture to climate change. A significant benefit of ICLF systems is soil conservation. They reduce erosion, maintain or increase soil organic matter, and improve soil structure and porosity, which results in increased water infiltration and water holding capacity.

Despite being considered a key indicator of how integrated systems affect ecological processes, soil moisture (SM) dynamics in literature have not been consistently analyzed, and continuous observation of seasonal SM dynamics are mostly unaddressed. Since SM of complex ecosystems is influenced by numerous factors, several additional parameters need to be considered to create a comprehensive understanding of the interlinked processes, such as radiation, rainfall, and biomass. This is further complicated by combining different components of crops, animals, and trees in diverse environments and under variable management. The objective of this cumulative PhD thesis was to investigate SM dynamics and aboveground grass biomass under different land use systems in the Cerrado biome of Central West Brazil, with a special focus on ICLF systems.

In the first study, photosynthetically active radiation (PAR) received at grass canopy level, SM, AGBM between the tree rows, and seasons in a mature ICLF system were investigated. Across the seasons, a distinct gradient was observed with SM being lower close to the tree rows than in the space between them. During winter, SM in the topsoil decreased to critical values, and dropped to the permanent wilting point next to the tree rows. During spring and summer, incident PAR was lower close to the trees than at the center point, while during autumn and winter, when PAR is generally lower, it was more evenly distributed between the tree rows. Aboveground grass biomass (AGBM) showed a distinct distribution within the ICLF system with maximum values in the center and about 50% of the biomass close to the tree rows. The results suggest that, restrictions in AGBM accumulation shifted among seasons between water limitations in winter and light limitations during summer.

In the second study, the seasonal and spatial variability of SM of Cerrado soils under four different land use systems was investigated under consideration of soil physical characteristics and grass biomass. The study presents first time results comparing measured soil moisture up to 100 cm depth for continuous pasture (COP), integrated crop-livestock (ICL) system, ICLF system, and natural Cerrado forest for almost two years on a long-term monitoring site with different land use plots and relict Cerrado vegetation. In rainy and dry season, SM in the upper 100 cm of the soil was highest in ICL, followed by COP, and lowest in the land use systems including trees, ICLF and Cerrado. Whereas in COP and in ICL, water was mainly taken up from the upper 30 cm, in ICLF, the strongest soil moisture depletion was observed between a soil depth of 40 and 100 cm. Although in the Cerrado SM in the topsoil was lower than in the other land use types, water was conserved below 60 cm depth. Both integrated systems improved soil properties, such as bulk density and soil organic carbon compared to COP, and increased biomass productivity was observed, demonstrating the benefits of the integrated systems over the traditional grazing system. The results suggest that ICLF systems show increased evapotranspiration compared to conventional pasture and other integrated systems without trees. Water pathways could therefore be managed towards increasing evapotranspiration and thus, potentially compensate for ecological functions of the deforested Cerrado biome.

In the third study, the effects of the presence of eucalyptus trees on the seasonal pasture and animal performance in ICLF systems 8 years after establishment were investigated. Forage morphology, production, and nutritive value plus performance of Nellore heifers in two ICLF systems with varying in trees density, ICLF22 (227 trees ha^{-1}) and ICLF14 (357 trees ha^{-1}), were evaluated and compared with a grass-only pasture. In both ICLF systems, the forage nutritive values, such as higher crude protein and digestibility and lower neutral and acid detergent fiber concentrations, were improved compared with a grass-only pasture. Nevertheless, grass biomass and accumulation rate were higher in the grass-only pasture. By the 8th year, the ICLF systems were unable to support both forage and animal production equivalent to a grass-only pasture, due to the high impact of the Eucalyptus trees on radiation received at the grass canopy and on soil moisture, especially during winter.

Improved soil characteristics and forage nutritive values compared to grass-only pastures, and the potential restoration of natural ecosystem functions with regard to water recycling into the atmosphere, demonstrated the benefits of ICLF systems and highlight their potential to contribute to sustainable agricultural intensification. However, high water consumption by trees poses a risk to grass productivity during the dry season and thus, the system may consequently not be used for grazing all year round. Therefore, research on management options mitigating the impact of drought on grass productivity is needed. As the impact of the trees on the system is highly dependent on their age, these studies should take into account the entire life cycle of the system.

Zusammenfassung

Das Cerrado Biom in Brasilen umfasst etwa 200 Millionen ha, umfasst drei der größten Wassereinzugsgebiete Südamerikas ein und gilt als globaler Biodiversitätshotspot. Seit einigen Jahrzehnten dehnt sich die Landwirtschaft innerhalb des Bioms exzessiv aus. Die Abholzung und Verdrängung der natürlichen Savannenvegetation durch Acker- und Weideland trägt zu schwerwiegenden Umweltproblemen, u.a. Bodendegradierung und veränderte Wasserkreisläufe bei.

Das ICLF (integrated crop-livestock-forestry) System, welches Pflanzenbau, Viehzucht und Forstwirtschaft integriert, wird derzeit als vielversprechende Maßnahme zur nachhaltigen Intensivierung vorangebracht. Es verbessert die Nutzung von Anbauflächen, rehabilitiert zuvor degradierte, unproduktive Flächen und könnte eine Strategie zur Anpassung der Landwirtschaft an den Klimawandel sein. Ein wesentlicher Vorteil von ICLF-Systemen wird der Bodenerhaltung zugeschrieben. Diese Bewirtschaftungsmethode verringert Erosion, erhält oder erhöht die organische Substanz des Bodens und verbessert die Bodenstruktur und Porosität, was zu einer erhöhten Wasserinfiltration und Wasserhaltekapazität führt.

Obwohl die Dynamik der Bodenfeuchte ein wichtiger Indikator dafür ist, wie integrierte Systeme ökologische Prozesse beeinflussen, wurde sie in der Literatur nicht konsequent analysiert. Des Weiteren wird die jahreszeitliche Bodenfeuchtedynamik meist nicht durch kontinuierliche Beobachtungen berücksichtigt. Da die Bodenfeuchte komplexer Ökosysteme von zahlreichen Faktoren beeinflusst wird, müssen mehrere zusätzliche Parameter wie z. B. Sonneneinstrahlung, Niederschlag und Biomasse einbezogen werden, um ein umfassendes Verständnis der verknüpften Prozesse zu schaffen. Kombinationen verschiedener Komponenten von Pflanzen, Tieren und Bäumen in unterschiedlichen Umgebungen und unter variablen Managementstrategien sind weitere Faktoren, die die Komplexität erhöhen. Das Ziel dieser kumulativen Dissertation war es, die Bodenfeuchtedynamik und die oberirdische Grasbiomasse unter verschiedenen Landnutzungssystemen im Cerrado Biom mit besonderem Fokus auf ICLF-Systeme zu untersuchen.

In der ersten Studie wurden die auf der Grasebene ankommende photosynthetisch aktive Strahlung (PAR), Bodenfeuchte und oberirdische Gras-Biomasse zwischen den Baumreihen zu verschiedenen Jahreszeiten in einem ICLF-System untersucht. Über die Jahreszeiten hinweg zeichnete sich ein deutlicher Gradient ab: die Bodenfeuchte nahe der Baumreihen war niedriger als im Bereich zwischen den Baumreihen. Während des Winters sank die Bodenfeuchte im

Oberboden auf kritische Werte und fiel in der Nähe der Baumreihen bis auf den permanenten Welkepunkt. Die Strahlung war im Frühjahr und Sommer in der Nähe der Bäume niedriger als im Bereich zwischen den Baumreihen, während sie im Herbst und Winter bei generell niedrigerer Strahlung gleichmäßiger zwischen den Baumreihen verteilt war. Die oberirdische Grasbiomasse zeigte eine deutlich unterschiedliche Verteilung innerhalb des ICLF-Systems mit Maximalwerten im Bereich zwischen den Baumreihen und etwa 50 % weniger Biomasse direkt neben den Baumreihen. Die Ergebnisse deuten darauf hin, dass sich die limitierenden Faktoren für die Akkumulation der oberirdischen Grasbiomasse zwischen den Jahreszeiten von Wassermangel im Winter zu Lichtmangel im Sommer verschoben.

In der zweiten Studie wurde die saisonale und räumliche Variabilität der Bodenfeuchte von Cerrado Böden unter vier verschiedenen Landnutzungssystemen und unter Berücksichtigung der bodenphysikalischen Eigenschaften und der oberirdischen Grasbiomasse untersucht. Die Studie präsentiert erstmalig Ergebnisse, die die gemessene Bodenfeuchte in bis zu 100 cm Tiefe für eine kontinuierlich Weide (COP), ein integriertes System ohne Bäume (ICL), ein integriertes System mit Bäumen (ICLF) und einen natürliche Cerrado-Wald über fast zwei Jahre vergleichen. Der Versuch befand sich auf einer Langzeituntersuchungsfläche mit verschiedenen Landnutzungssystemen und verbleibender Cerrado-Vegetation. In der Regen- und Trockenzeit war die Bodenfeuchte in den oberen 100 cm des Bodens im ICL am höchsten, gefolgt von COP, und am niedrigsten in den Landnutzungssystemen mit Bäumen, ICLF und Cerrado. Während in COP und in ICL das Wasser hauptsächlich aus den oberen 30 cm aufgenommen wurde, wurde in ICLF die stärkste Abnahme der Bodenfeuchte zwischen einer Bodentiefe von 40 und 100 cm beobachtet. Obwohl im Cerrado die Bodenfeuchte im Oberboden geringer war als in den anderen Landnutzungssystemen, blieb Wasser unterhalb von 60 cm Tiefe erhalten. Beide integrierten Systeme verbesserten die Bodeneigenschaften, wie z.B. die Lagerungsdichte und den Gehalt von organischem Kohlenstoff im Boden im Vergleich zu COP. Außerdem wurde eine erhöhte Biomasseproduktivität beobachtet, was die Vorteile der integrierten Systeme gegenüber dem traditionellen Weidesystem zeigt. Die Ergebnisse deuten darauf hin, dass ICLF-Systeme eine erhöhte Evapotranspiration im Vergleich zu herkömmlichen Weiden und anderen integrierten Systemen ohne Bäume aufweisen. Der Wasserhaushalt könnte daher so gesteuert werden, dass die Evapotranspiration erhöht und dadurch möglicherweise die verringerte ökologische Funktion des entwaldeten Cerrado Bioms kompensiert wird.

In der dritten Studie wurden die Auswirkungen von Eukalyptusbäumen auf die saisonale Produktion und Qualität von Grünfutter und die Nutztierleitung in ICLF-Systemen, 8 Jahre nach der Etablierung untersucht. Grünfuttermorphologie, -produktion und -nährwert sowie die Leistungsparameter von Färsen der Rasse Nellore in zwei ICLF-Systemen mit unterschiedlicher Baumdichte, ICLF22 (227 Bäume ha^{-1}) und ICLF14 (357 Bäume ha^{-1}), wurden bewertet und mit einer reinen Grasweide verglichen. In beiden ICLF-Systemen waren die Nährwerte des Futters (höheres Rohprotein und Verdaulichkeit) im Vergleich zu einer reinen Grasweide höher. Andererseits waren die Grasbiomasse und die Akkumulationsrate bei der reinen Grasweide höher. Im achten Jahr erzielten die ICLF-Systeme daher nicht mehr die gleiche Weidequalität und Nutztierleistung einer reinen Grasweide. Diese Leistungseinbußen waren auf den negativen Einfluss der Eukalyptusbäume auf die Beschattung der Grasschicht und Bodenfeuchte, insbesondere im Winter, zurückzuführen.

ICLF-Systeme zeigten verbesserte Bodeneigenschaften und Futternährwerte im Vergleich zu reinen Grasweiden, sowie die potenzielle Wiederherstellung natürlicher Ökosystemfunktionen im Hinblick auf die Rückführung von Wasser in die Atmosphäre. Sie zeigen ein hohes Potenzial, zu einer nachhaltigen landwirtschaftlichen Intensivierung beizutragen. Der hohe Wasserverbrauch der Bäume stellt jedoch ein Risiko für die Grasproduktivität während der Trockenzeit dar, so dass das System folglich nicht das ganze Jahr über beweidet werden kann. Daher ist die Untersuchung von Managementoptionen, die die Auswirkungen von Trockenheit auf die Grasproduktivität abmildern, notwendig. Da der Einfluss der Bäume auf das System stark von ihrem Alter abhängt, sollten diese Studien den gesamten Lebenszyklus des Systems berücksichtigen.

1 General Introduction

1.1 Cerrado and Land Cover and Land Use Changes

The Brazilian neotropical Savannah , known as Cerrado, covers about 200 million ha and is the second largest biome in South America (Sano et al., 2010). With over 4800 plant and vertebrate species found in this biome, the Cerrado is a global biodiversity hotspot with three of the largest watersheds of South America contributing 43% of Brazil's surface water outside of the Amazon (Klink and Machado, 2005; Strassburg et al., 2017). Despite its enormous importance for species conservation and the provision of ecosystem services, this biome underwent and is still undergoing excessive agriculture expansion since the 1970's (Sano et al., 2010; Strassburg et al., 2017; P.T.S. Oliveira et al., 2014a) (Figure 1.1).

Figure 1.1: Agricultural expansion (left side) compared to natural Cerrado vegetation (right side). Photograph by Marizilda Cruppe, Greenpeace (Dam View&VBID=27MDQYFLL9TKJ&FR_=1&W =1280&H=588).

This biome is highly heterogeneous not just in terms of biodiversity but also in terms of physiognomy (Figure 1.2) and is characterized by a strong seasonality with a rainy season from October to March and a dry season from April to September. Average annual temperatures range from 22 to 27 °C and average annual rainfall is 1500 mm, whereas about 70% of the mean annual rainfall fall within the rainy season and the remaining 30% within the dry season (Klink and Machado, 2005). Furthermore, dry spells (locally known as "veranicos") of up to 20 days during the peak of the rainy season between December and February are common (Klink et al., 2020). The natural Cerrado vegetation consists of a mixture of C4 grasses and C3 trees (shrubs) - with a wide range of physical appearance (physiognomy) ranging from open grasslands to almost closed tree canopy (P.S. Oliveira and Marquis, 2002). The strong seasonality in rainfall results in seasonal changes in the natural vegetation. The herbaceous vegetation becomes fully senescent until mid of the dry season and remains dormant until the following rainy season, whereas for the woody vegetation, the leaf expansion, flowering and fructification takes place during the dry season, indicating that the woody vegetation has access to soil moisture in the dry season probably from deeper soil layers (Quesada et al., 2008). The Cerrado vegetation has developed on old, highly weathered, deep, acidic, very nutrient poor soils that have a high concentration in aluminum and are characterized by a pseudo-sand structure (Goedert, 1983; Thomas et al., 1999).

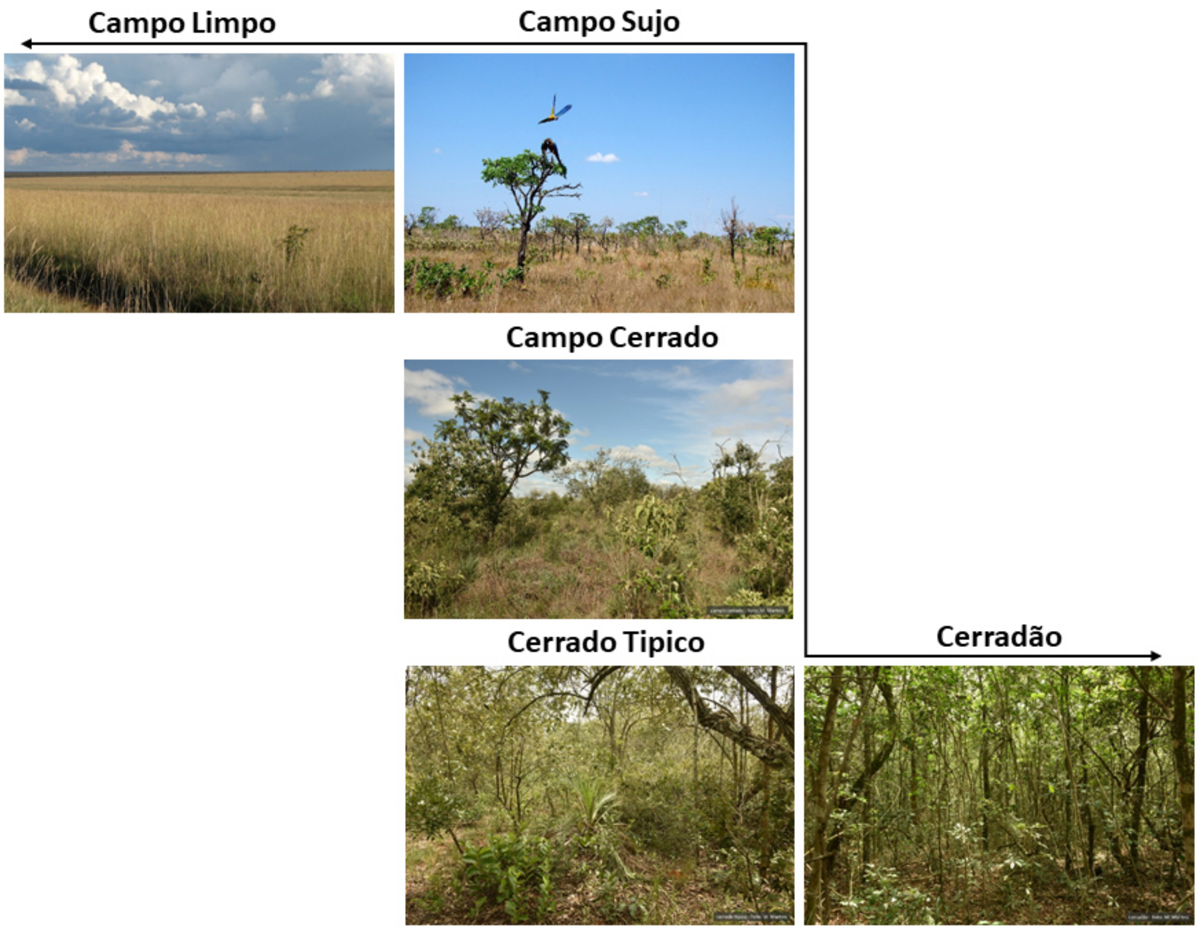

Figure 1.2: Sequence of Cerrado physiognomy ranging from open grasslands to almost closed tree canopy (http://eco.ib.usp.br/labvert/ASB-a-estacao-e-fisionomias.html)

About 46% of the natural Savannah vegetation has been replaced by monocultures of soybean, sugar cane, corn, coffee and cotton, as well as by energy plantations and pastures, and less than 20% remain undisturbed (Sano et al., 2010; Strassburg et al., 2017; Klink and Machado, 2005;

Marris, 2005). Between 2002 and 2011 the rate of deforestation in the Cerrado (1% per year) was 2.5 times higher than in the Amazon, being the largest biome in Brazil (Strassburg et al., 2017). Souza et al. (2020) reconstructed land cover and land use changes in the six Brazilian biomes between 1985 and 2017, showing the most obvious changes of pasture and agricultural expansion occurred in the Cerrado biome, but also in the Amazon and south of the Atlantic Forests biome (Figure 1.3).

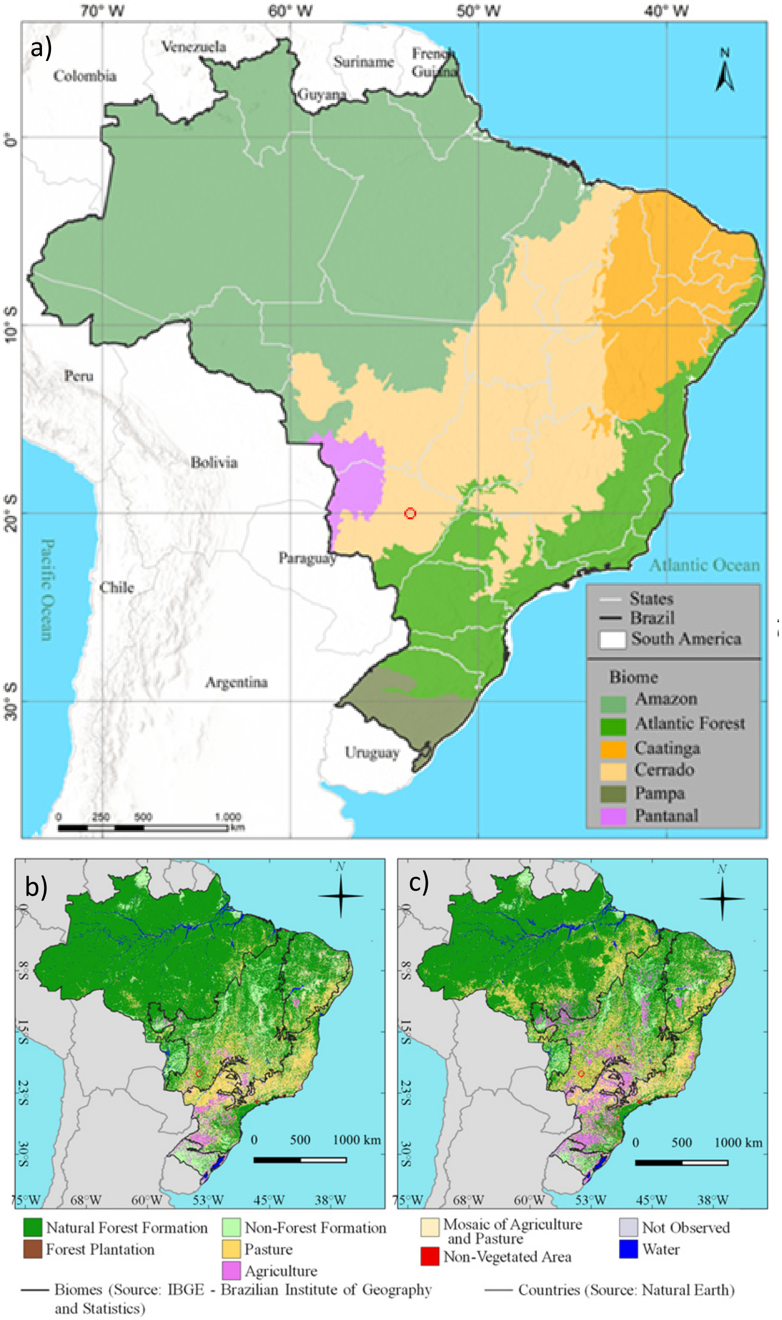

Figure 1.3: a) Map of the six biomes found in Brazil; Land cover and land use in b) 1985 and in c) 2017 in the six Brazilian biomes. Adapted from Souza et al. (2020). The red circle indicates the location of the study site within the Cerrado biome.

In the 1960s and 1970s, the Brazilian government started a national development policy aiming at integrating the vast spaces of the Cerrado into the Brazilian economy, creating favorable business opportunities for investments. Subsidies, developmental programs, and new technologies facilitated the agricultural expansion in the Cerrado. The rapid expansion of agriculture activities significantly increased crop production and economic wealth in the region, as soybean and soybean products are among the biggest export commodities of Brazil. Further, Brazil's largest cattle herds are located in the Cerrado. The negative aspects of this development are aggravated social inequality and serious environmental problems like landscape fragmentation, loss of biodiversity, biological invasion, soil erosion, water pollution, land degradation, heavy use of chemicals, changes in fire regime, and alterations of carbon and water cycling (Klink et al., 2020).

Because of overstocking with cattle and inadequate supply of nutrients to the soil, around 70% of the cultivated pastures in Brazil are at some stage of degradation or are fully degraded (Macedo et al., 2013). As soils are an essential factor for the sustainability of agricultural systems, improper management can compromise soil quality and sustainability. Traditional management systems, involving excessive use of tillage and overstocking are causing major ecological problems in the Brazilian Cerrado biome (Sousa Neto et al., 2014).

By 2050, the world population is predicted to increase to 9.1 billion, which will increase food demand by approximately 70 % (FAO, 2009). To satisfy this demand, expansion of agricultural land is discussed. It has been claimed that on a global scale the Savannahs and grasslands of Brazil, Argentina and Africa have the biggest potential for agricultural expansion, because most of these areas are non-forested, non-protected and have a low population density (Lambin and Meyfroidt, 2011). However, unless management is altered to increase yield potentials, additional land will be required to feed the increasing world population.

Especially in Brazil with its great biological biodiversity and the importance of the agricultural sector for the country's economy, expansion of agricultural area leads to serious conflicts with natural resource conservation. Thus, the growing food demand should be met by sustainable intensification of production. Furthermore, the challenge to increase food production, feedstock and raw materials will require ecologically, economically, and socially sound and efficient strategies in order to incorporate environmental benefits (Alves et al., 2017). Therefore, integrated systems are currently considered an efficient strategy for sustainable intensification, improving food security and environmental stability (Alves et al., 2017; de Moraes et al., 2014; Lemaire et al., 2014).

1.2 Integrated Systems in Brazil

Sustainable soil management and crop techniques have the potential to improve the use of cultivated areas and to recover previously degraded and unproductive areas in tropical and subtropical environments, as shown for integrated systems (IS) developed by EMBRAPA (Brazilian Corporation for Agricultural Research) (Costa et al., 2018). Integrated crop-livestock-forestry systems are sustainable production systems that involve components of crop, livestock and / or forestry production in the same cultivated area using intercropping, or sequential or rotational systems, aiming at synergies among the components in the agroecosystem (Balbino et al., 2011). There are four major groups of IS in Brazil: integrated crop-livestock (ICL), integrated crop-forestry (ICF), integrated forestry-livestock (IFL), and integrated crop-livestock-forestry (ICLF) (Figure 1.4), with the components within each system being integrated in space or time.

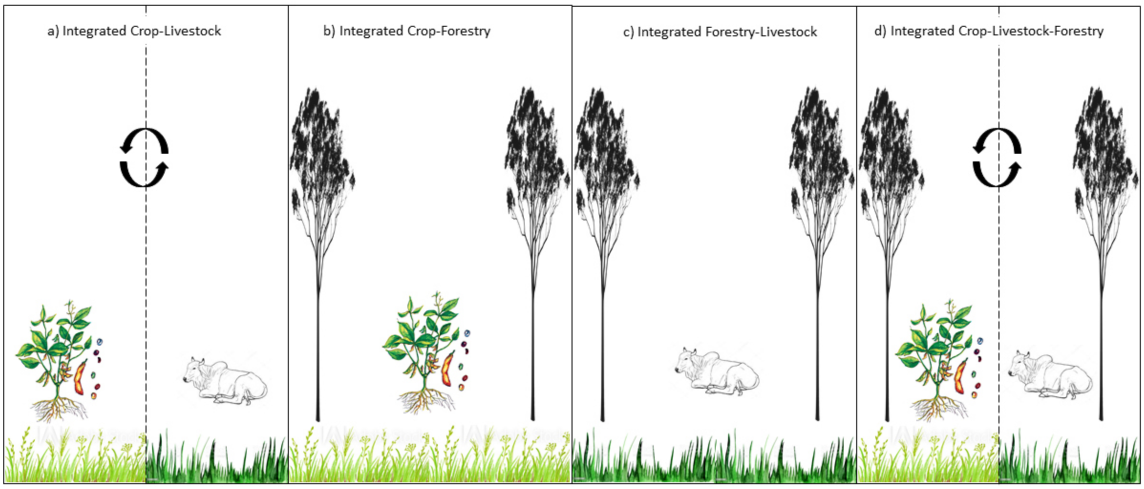

Figure 1.4: The four major integrated systems in Brazil according to Balbino et al. (2011).

The ICL system, for example, can integrate the two components crop and livestock, in the same area by intercropping (space) or rotational within the agricultural year (time). The ICLF system is similar to traditional agroforestry systems (Nair, 1993), however, IS in Brazil typically involve more use of heavy machinery and lower species diversity. These types of IS are a practical alternative in areas where large scale commercial agricultural production is already present, because in terms of low labor intensity and high output levels they are relatively similar to conventional production systems (Gil et al., 2015).

Several studies have shown the benefit of these types of IS with their large potential for sustainable agricultural intensification and for improving food security and environmental stability (Alves et al., 2017; de Moraes et al., 2014; Lemaire et al., 2014). Further, higher profitability of IS compared to traditional systems has been claimed, because of higher productivity, lower production costs, better input efficiency, lower need of pesticides and lower systematic risk related to the diversified sources of income (Kichel et al., 2014) and enhanced socio-eco-efficiency related to the contributions to the growing global demand for food and energy, while minimizing environmental impacts, recovering degraded pasture areas, conserving forestland, optimizing costs, and promoting positive effects in society (Costa et al., 2018).

Furthermore, these systems also provide ecosystem services, including carbon sequestration, biodiversity conservation, soil enrichment and air and water quality (Jose, 2009) and improve microclimatic conditions and animal well-being (C.C. Oliveira et al., 2019).

Moreover, a significant benefit of these systems is soil conservation, as they can reduce erosion, maintain or increase soil organic matter, and improve soil structure and porosity, resulting in increased infiltration and water holding capacity (Bono et al., 2012; Nair, 1993). Increased water infiltration and water storage in IS led to their promotion as a promising land use option to reduce drought impacts on agricultural production, which may be more frequent due to climate change (Bosi et al., 2019; IPCC, 2013).

1.3 Soil moisture dynamics

Soil moisture varies strongly in space and time and represents only a small part of all the water on earth but is nevertheless one of the most important. The soil plays a fundamental role in the terrestrial hydrological cycle by controlling the partitioning of rainfall in evapotranspiration, runoff and deep infiltration in a strongly nonlinear manner. Directly or indirectly soil moisture dynamics control meteorological processes, plant growth, soil biogeochemistry, groundwater dynamics and the exchange of nutrients and contaminants in the soil-plant-atmosphere continuum (Corradini, 2014; Daly and Porporato, 2005). Soil moisture dynamics are enormously complex due to the involvement: 1) of physical, chemical and biological processes; 2) of the large number of variables, including among others, the high intermittence of rainfall and the atmospheric turbulence, radiation, the heterogeneous soil structure and topography, vegetation, the presence of plant roots and organic matter; 3) of the wide range of spatial and temporal scales (Daly and Porporato, 2005). Nonetheless, the knowledge about seasonal variability in soil moisture dynamics can help to predict floods, to identify suitable periods for plant production in rain fed systems and to determine possible feedbacks between soil moisture and climate dynamics (Laio et al., 2002). According to Hunke et al. (2015b) several studies in the tropics have indicated that physical soil properties are impacted by land-use and vegetation cover. Physical soil properties like bulk density compaction, porosity, and soil aggregate stability control soil moisture flow, and therefore represent sensitive parameters for quantifying the effect of deforestation and land-use change.

1.4 Objectives

Despite being considered a key indicator of how IS affect ecological processes, soil moisture dynamics in literature have not been consistently analyzed, and continuous observation of seasonal soil moisture dynamics are mostly unaddressed. Since soil moisture of complex ecosystems is influenced by numerous factors, several additional parameters need to be considered to create a comprehensive understanding of the interlinked processes, such as radiation, rainfall, and biomass productivity. This is further complicated by combining different components of crops, animals, and trees in diverse environments and under variable management.

The main objective of this study was to investigate the soil moisture dynamics and aboveground grass biomass in the characteristic seasons of the Cerrado biome under different land use systems with the specific objectives:

- to investigate photosynthetically active radiation received at grass canopy level, soil moisture, and aboveground grass biomass between the tree rows and seasons in an ICLF system.
- to investigate the seasonal and spatial variability of soil moisture of Cerrado soils under four different land use systems under consideration of soil physical characteristics and plant biomass.
- to investigate the effect of the presence of trees on the seasonal pasture and animal performance in ICLF systems with different tree densities.

2 Seasonal Dynamics of Soil Moisture in an Integrated-Crop-Livestock-Forestry System in Central-West Brazil

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Keywords: agroforestry; grazing cattle; Brachiaria brizantha; eucalyptus; photosynthetically active radiation

Abstract: Integrated-crop-livestock-forestry (ICLF) systems are currently promoted as a measure for sustainable intensification of agricultural production. However, due to complex interactions among ICLF components, we are still lacking evidence about the system's resilience regarding water availability, especially for regions characterized by pronounced wet and dry seasons and frequent droughts. For a mature ICLF system in the Cerrado biome of central-west Brazil comprising rows of eucalyptus trees (*Eucalyptus grandis x Eucalyptus urophylla*, H13 clone) at a spacing of 22 m in combination with *Brachiaria brizantha* cv. BRS Piatã pasture we continuously measured soil moisture (SM) until 1 m depth and supported this data with measurements of photosynthetically active radiation (PAR) and aboveground green grass biomass (AGBM) across transects between the tree rows for almost two years. Across the seasons a distinct gradient was observed with SM being lower close to the tree rows than in the space between them. During winter SM decreased to critical values near the tree lines in the topsoil. During spring and summer, incident PAR was 72% and 86% lower close to the trees than at the center point. For autumn and winter PAR was more evenly distributed between the tree rows due to inclination with notably up to four times more radiation input near the tree lines compared to spring and summer. AGBM showed a clear distribution with maximum values in the center and about half of the biomass close to the tree rows. Our data suggest that, restrictions in AGBM accumulation shifted among seasons between water limitations in winter and light limitations during summer. Interestingly, SM changes during wetting and drying events were most pronounced in subsoils near the tree rows, while the topsoil showed much less fluctuations. The subsoil in central position showed the lowest SM dynamics in response to drought maintaining a relative high and constant SM content, therefore functioning as important water reservoirs likely improving the resilience of the system to drought stress. Results of this study could help to improve management and the design of ICLF systems in view of sustainability and resistance to (water) crises but should be further supported by in depth analysis of soil water dynamics as affected by climate gradients, soil types and different management practices.

2.1 Introduction

The Brazilian Savannah, also known as the Cerrado, covers an area of 204.7 million ha (about 22% of the Brazilian territory). In the last few decades, about 50% of the natural Cerrado vegetation has been replaced by agricultural crops and pastures (P.T.S. Oliveira et al., 2014a; Sano et al., 2010; Santos et al., 2016). According to Macedo (2005), the planted pasture area in the Cerrado amounts to 60 million ha, of which 85% (51 million ha) is planted with *Brachiaria* grasses. It is estimated that more than 70% of the cultivated pastures in Brazil are degraded, or are at some stage of degradation, especially in the Cerrado region (Macedo et al., 2013). The main causes for pasture degradation in Brazil are overstocking with cattle and insufficient replenishment of soil nutrients (Macedo et al., 2013). Integrated crop–livestock–forestry (ICLF) systems combine crop and livestock in succession, rotation or by intercropping with trees in the same area (Balbino et al., 2011), and are a reliable alternative to restore degraded pastures (Dias-Filho, 2011). For this reason, integrated systems are currently considered an option for sustainable intensification, improving food security and environmental stability (Alves et al., 2017; de Moraes et al., 2014; Lemaire et al., 2014). A significant benefit of ICLF systems is soil conservation, which reduces erosion, maintains or increases soil organic matter, and improves soil structure and porosity, resulting in increased infiltration and water holding capacity (Bono et al., 2012; Nair, 1993). Increased soil water infiltration and water storage in ICLF systems led to their promotion as a promising land use option to reduce drought impacts on agricultural production, which may be more frequent due to climate change (Stocker et al., 2013).

The presence of trees in ICLF systems affects the understory *Brachiaria* pasture by changing microclimatic conditions, like reducing photosynthetically active radiation (PAR), and wind speed (Pezzopane et al., 2015). These changes have an impact on evapotranspiration and biomass production of the pasture and, consequently, soil moisture content (Bosi et al., 2019; Lin, 2010; Santos et al., 2016). The effect of the trees on the understory microclimate depends on the distance to the tree rows, and there are significant differences in quality and amount of solar radiation due to the spatial arrangement and density of the trees (Bosi et al., 2019; Rodrigues et al., 2014; Santos et al., 2016). According to Bruner and Belesky (2008), the reduction of PAR is the main constraint for aboveground biomass production, provided sufficient soil moisture availability.

Despite being considered a key indicator of how ICLF systems affect ecological processes, soil water dynamics in literature have not been consistently analyzed, and continuous observation of seasonal soil water dynamics are mostly unaddressed. Since soil moisture of complex ecosystems is influenced by a number of factors, several additional parameters need to be taken into account to create a comprehensive understanding of the interlinked processes, such as light, rainfall interception, SM dynamics, and biomass productivity. This is further complicated by combining different components of crops, trees, and animals in diverse environments and under variable management. Using the example of a mature ICLF system in Campo Grande (in the state of Mato Grosso do Sul), this study aims to analyze system’s water dynamics in characteristic seasons of the Cerrado ecotone complemented by simultaneous analysis of (1) photosynthetically active radiation (PAR) received at grass canopy level, (2) soil moisture (SM), and (3) aboveground green grass biomass (AGBM) between the tree rows and seasons in an ICLF system. We hypothesize that the seasonal impact alters interdependencies among the measured parameters, allowing for improved understanding of resilience and adaptive capacity of ICLF systems relating to variable environments triggered by climate variability or change.

2.2 Material and Methods

2.2.1 Experimental Site

The study was carried out on the experimental sites of EMBRAPA Beef Cattle (Brazilian Agricultural Research Corporation), located in Campo Grande, state of Mato Grosso do Sul, Brazil (20°24’54.9”S,54°42’25.8”W, altitude 530 m). The climate of the area is a tropical savannah Aw climate (Kottek et al., 2006) with a mean annual temperature of 22.6 °C. The study area is characterized by four defined seasons: summer (Dec–Feb), autumn (Mar–May), winter (Jun–Aug), spring (Sept–Nov), with the peak of the rainy season during the summer months and the peak of the dry season during the winter months (Figure 2.1). About 70% of the mean annual rainfall, around 1560 mm, falls within the rainy season, and the remaining 30% within the dry season. Temperature, relative air humidity, solar radiation, wind speed, and precipitation were monitored by a nearby meteorological station operated by EMBRAPA Beef Cattle. Furthermore, rainfall was monitored at one sampling point (P6S) between the trees at the experimental site using a IM523 rain gauge by iMetos connected to an event/temp data logger (HOBO Pendant Data Logger Event and Temperature UA-003), as well as along a transect of five sampling points between the tree rows with commercial rain gauges.

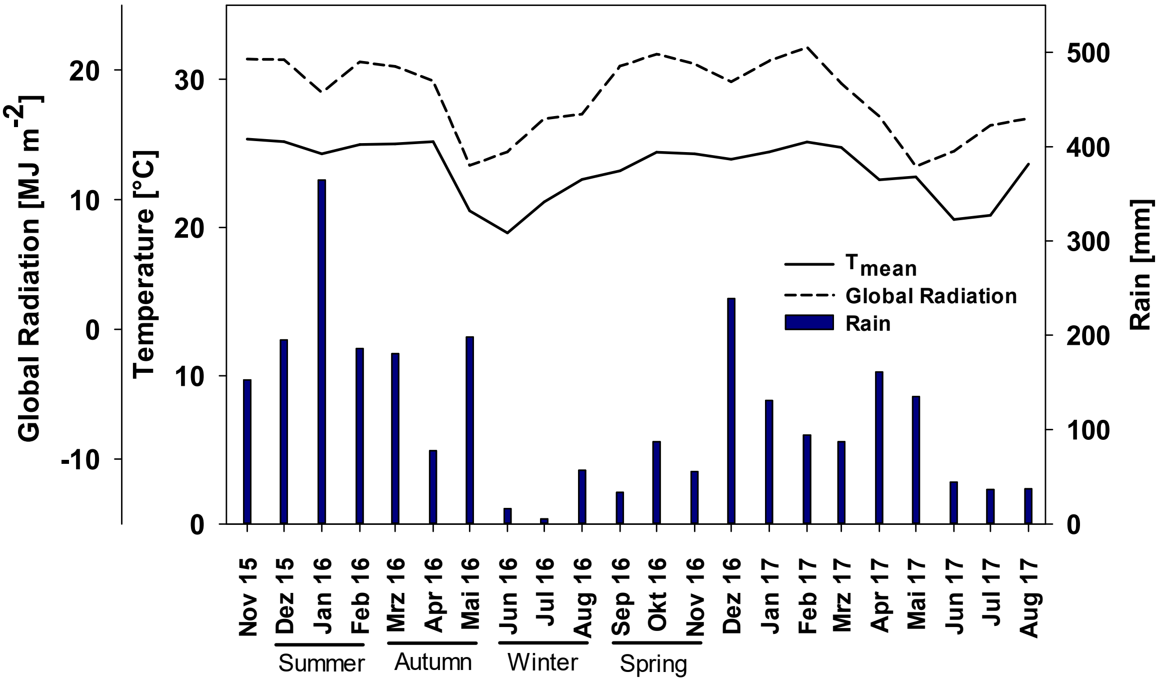

Figure 2.1: Monthly mean global radiation (MJ m-2), temperature (°C) and cumulative monthly rain (mm) from Nov 2015 until Aug 2017. Cumulative rain for year 1 (Nov 15–Oct 16) 1553 mm and for year 2 (Nov 16–Aug 17) 1020 mm.

According to the World Reference Base for Soil Resources (WRB, 2015), the soil of the study area is classified as a Ferralsol. Soil samples were taken in 10, 20, 30, 40, 60 and 100 cm depth with coring rings (10 cm^{-3}). The soil profile was created using an excavator in February 2017. The 1.2 m-deep and 1 m-wide hole was dug in Rep 2 (Figure 2.2). For each depth, soil samples were taken with a coring ring in three of the four soil profile walls, resulting in three replicates per depth. The soil had a sandy clay texture (55% sand, 6% silt, 39% clay), a bulk density of 1.15 g cm^{-3}, a usable field capacity between soil moisture values of 15.5 vol% (pF 4.2, permanent wilting point) and 42.5 vol% (pF 1.8, field capacity), a hydraulic conductivity of 59.2 cm day^{-1} and a pH value (measured in water) of 4.5.

2.2.2 ICLF Systems

The ICLF system was established in 2008. The area was prepared using light to heavy tillage and limestone/gypsum application (3 and 1 t ha^{-1}, respectively) to increase the pH and to improve P availability for the crops. In early November 2008, NPK fertilizer (5:25:15) was applied at a rate of 400 kg ha^{-1}, followed by levelling with a disk harrow. The amount of fertilizer was determined through chemical soil analysis and applied according to the experience and guidelines of EMBRAPA Beef cattle. In late November 2008, the crop component (*Glycine max* cv. BRS 255RR), and in January 2009, the tree component (*Eucalyptus grandis x Eucalyptus urophylla*, H13 clone), were planted. The eucalyptus seedlings were transplanted in east–west oriented rows. Each replicate had an area of 1.4 ha, and consisted of two single tree rows at a distance of 22 m and 2 m distance between the trees within each row, resulting in a tree density of 227 trees ha^{-1} (Figure 2.2). After the soybean harvest in April 2009, the pasture component (*Brachiaria brizantha* cv. BRS Piatã) was established and beef cattle (Nellore heifers) were introduced to the system as the trees reached a diameter at breast height, at least 60 mm. The cattle grazed at varying stocking rates depending on biomass production in order to keep the height of the pasture at approximately 35 cm (put and take method). The management of the ICLF system involved a crop rotation strategy every four years (i.e., cultivation of soybean as a crop for five months) followed by three and a half years of *Brachiaria brizantha* cv. BRS Piatã pasture. For this study, data was collected in the third year after pasture establishment during the second pasture cycle of the ICLF system from November 2015 until August 2017 at tree height of about 25 to 27 m. In January 2016, 50 kg N ha^{-1} (in the form of urea) and 300 kg NPK ha^{-1} (0:20:20) were applied to the pasture.

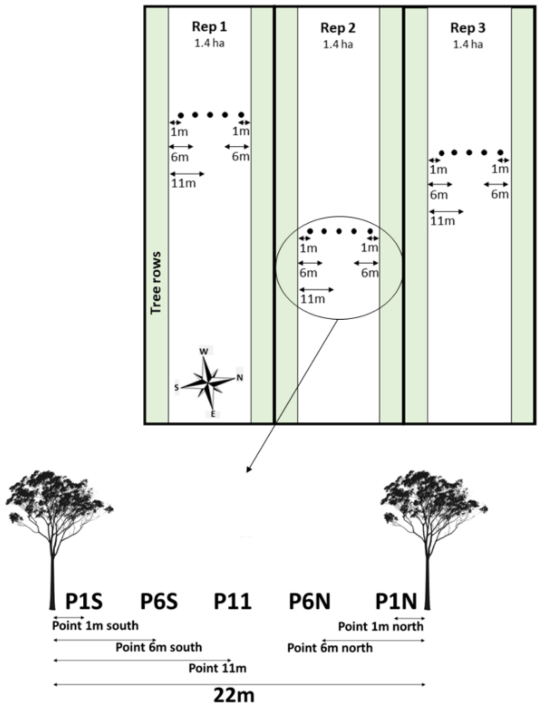

Figure 2.2: Schematic representation of the experimental plots indicating sampling and measurement points in each replicate. Green stripes represent the tree rows. Each replicate had two tree rows. Within the tree rows all data were sampled according to the distance to the trees. P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively.

2.2.3 PAR, SM and AGBM

Photosynthetically active radiation (PAR), soil moisture (SM) and aboveground green grass biomass (AGBM) were measured along a transect of five sampling points between tree rows to assess the shading and soil moisture gradient created by the trees. These five sampling points were: P1S: 1 m and P6S: 6 m from the southern row; P1N: 1 m and P6N: 6 m from the northern row; P11: 11 m from the southern and the northern row respectively (Figure 2.2).

PAR (µmol m^{-2} s^{-1}) was measured monthly with a Decagon AccuPAR LP-80 at clear sky, in the morning and in the afternoon directly above the grass canopy at each sample point between the tree rows, and on an open field (without any trees) beside the ICLF system. PAR values shown in this study represent means of measurements performed in the morning and afternoon.

At each sampling point in each replication, a fiberglass access tube (DeltaT Type: ALT1) of 1 m length was vertically installed for volumetric SM (vol%) measurements with a portable DeltaT FDR (frequency domain reflectometry) PR2/6 profile probe. FDR measurements were taken weekly in depths of 10, 20, 30, 40, 60 and 100 cm. The FDR soil moisture measurements were validated against gravimetrical soil moisture measurements. Samples for gravimetrical soil moisture measurements were taken with an auger right next to every FDR access tube at the same depths where the FDR probe measurements were taken.

AGBM (g DW m^{-2}) was quantified monthly. At each sampling point in each replication, 1 m^2 of grass biomass was harvested 5 cm from the ground. All harvested biomass samples were separated into green biomass and dead biomass, dried for 48 h at 70 °C and weighed to determine the dry weight biomass per area in g m^{-2}.

2.2.4 Data Analysis

Data was analyzed in a randomized complete block (three replicates) design using the generalized least squares model of R (Lenth, 2019; Pinheiro et al., 2018; R Core Team, 2019), with repeated measurements over time, and the seasons (spring, summer, autumn, winter) as a repeated factor. For the analysis of SM and AGBM sample points, season and block were considered as fixed effects. The most appropriate correlation structure for repeated measurements was chosen according to the Akaike Information Criterion (AIC). For AGBM the first order autoregressive (ar(1)) correlation structure was chosen. Fisher's LSD (least significant difference) test and significance at $p < 0.05$ were used for the comparison of mean values. The Pearson correlation coefficient (r) between PAR and AGBM and SM and AGBM was calculated also using R (Lenth, 2019; Pinheiro et al., 2018; R Core Team, 2019). To normalize data for the correlation analysis, relative values of PAR, SM and AGBM along the gradient between the tree rows were calculated.

2.3 Results

2.3.1 PAR between the Tree Rows during Different Seasons

PAR received by the grass canopy varied widely between the seasons, but also between the tree rows, especially in spring and summer (Figure 2.3). In comparison to open field measurements, P11 received 9% less PAR in spring and 21% less PAR in summer, respectively. Furthermore, in both seasons, the sample points closest to the tree rows (P1S and P1N) received with about 200 µmol m^{-2} s^{-1} even less PAR than all other sample points in winter. In winter, PAR was more evenly distributed between the sample points, with P1S receiving 43% and P6S 74% less PAR compared to the open field. In autumn, P1S and P6S received 33% less PAR compared to the open field, P11 and P1N about 50% less, and P6N 78% less. In contrast to spring and summer, in autumn and winter, the sample points P6S and P6N received even slightly more PAR than the center sample points.

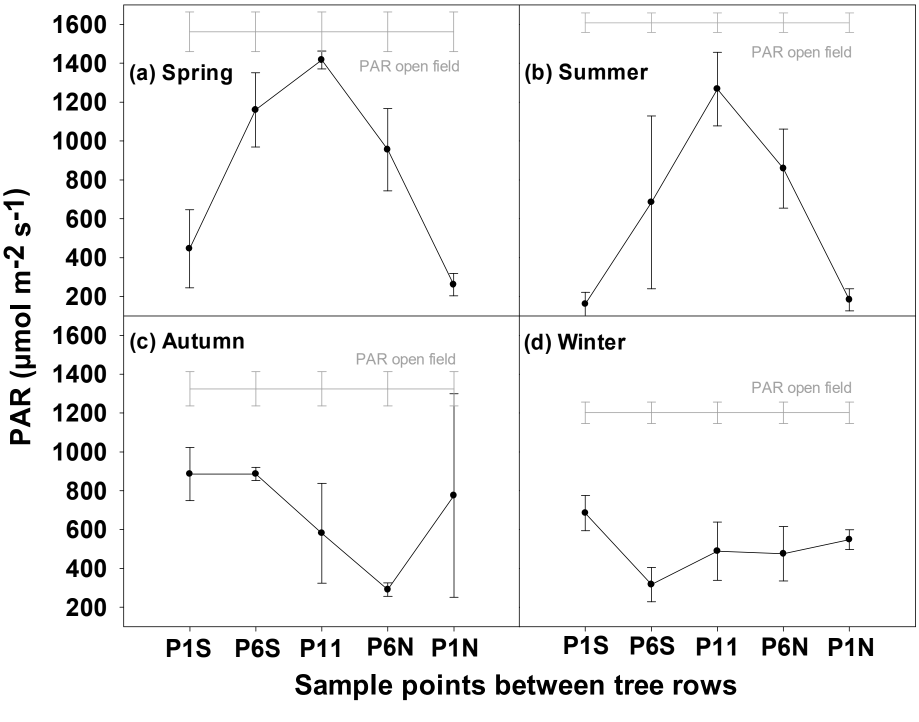

Figure 2.3: Mean photosynthetically active radiation (PAR; in µmol m^{-1} s^{-1}) for each sample point between the tree rows compared to PAR measured on an open field during (a) spring, (b) summer, (c) autumn and (d) winter. P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern.

2.3.2 SM in ICLF between the Tree Rows during Different Seasons

Throughout the measurement period, monthly mean SM in the top 1 m soil layer was highest in the rainy season (Nov–Apr), and up to 10 vol% lower in the dry season (May–Oct) for all sample points (Figure 2.4). On average over the sample points, SM was lowest in August 2016, with 21.1 vol%, and highest in May 2016, with 30.5 vol%. Between the sample points, SM was lowest at P1N, with 23.2 vol%, followed by P1S, with 25.0 vol%, and highest at P11, with 30.1 Vol%, on average over the measurement period. Little difference was found between P6S and P6N, which had 27.2 vol% and 27.9 vol% SM on average over the measurement period.

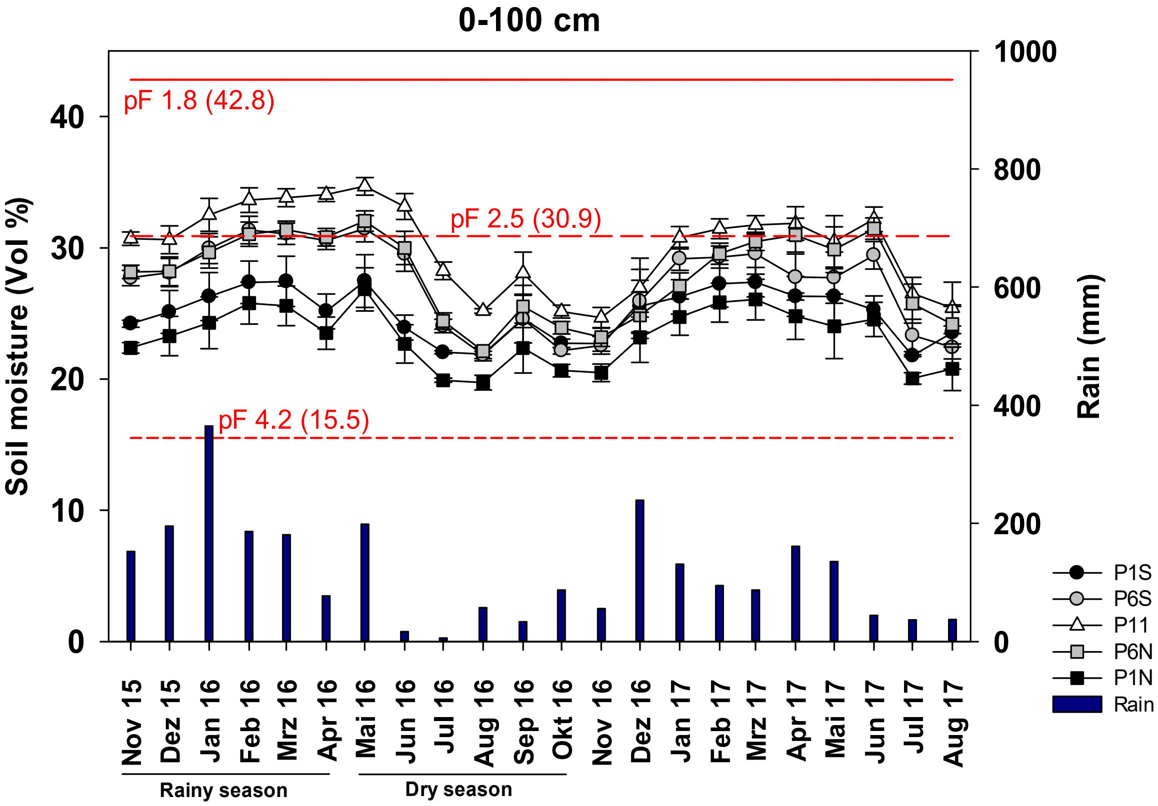

Figure 2.4: Monthly mean soil moisture (SM, in vol%) for each sample point between the tree rows over 0–1 m soil depth from Nov 2015 until Aug 2017. P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively. Bars represent standard errors. Cumulative monthly rain [mm] from Nov 2015 until Aug 2017. Cumulative rain for year 1 (Nov 15–Oct 16) 1553 mm and for year 2 (Nov 16–Aug 17) 1020 mm. Dotted horizontal lines mark usable field capacity from pF 1.8 (field capacity) to pF 4.2 (permanent wilting point).

Analysis of variance revealed highly significant differences ($p \leq 0.001$) between the months and between the sample points, but no significant difference between both years (Table 2.1).

Table 2.1: Analysis of variance for soil moisture 0–100 cm depth. ***, **, *: significant at p-value ≤ 0.001, ≤ 0.01, ≤ 0.05, respectively. Abbreviations: Df: degree of freedom; SS: sum of square; MS: mean square.

Soil Moisture (Vol%)		**SM = Y × M × SP + R**		
0–100 cm	**Df**	**SS**	**MS**	***p***
Year (Y)	1	5.0	5.0	0.39010
Month (M)	20	2329.7	116.5	< 0.001 ***
Sample point (SP)	4	1766.9	441.7	< 0.001 ***
Replication (R)	2	169.5	84.7	< 0.001 ***
Interaction (Y × SP)	4	35.2	8.8	0.26710
Interaction (M × SP)	80	273.0	3.4	0.99970
Residuals	218	1463.7	6.7	

During the first year and the second year, and at all SP, SM increased with depth, except at P6S, P11, and P6N in the first year and spring of the second year (Figure 2.5). At these sample points, SM decreased at depths between 40 m and 60 cm, but increased at greater depths. Throughout the profile, SM was lower during the second year compared to the first year. During both years and for all seasons, SM next to the trees (P1S and P1N) was lower compared to the center point P11, as well as P6S and P6N. Further, SM at P1S was always slightly lower than at P1N. Throughout the profile, SM was lowest during winter followed by spring, summer, and autumn during the first year, whereas during the second year, SM was lowest in spring followed by winter, summer and autumn. However, in the topsoil (10 cm to 30 cm depth), SM was lowest during winter in both years.

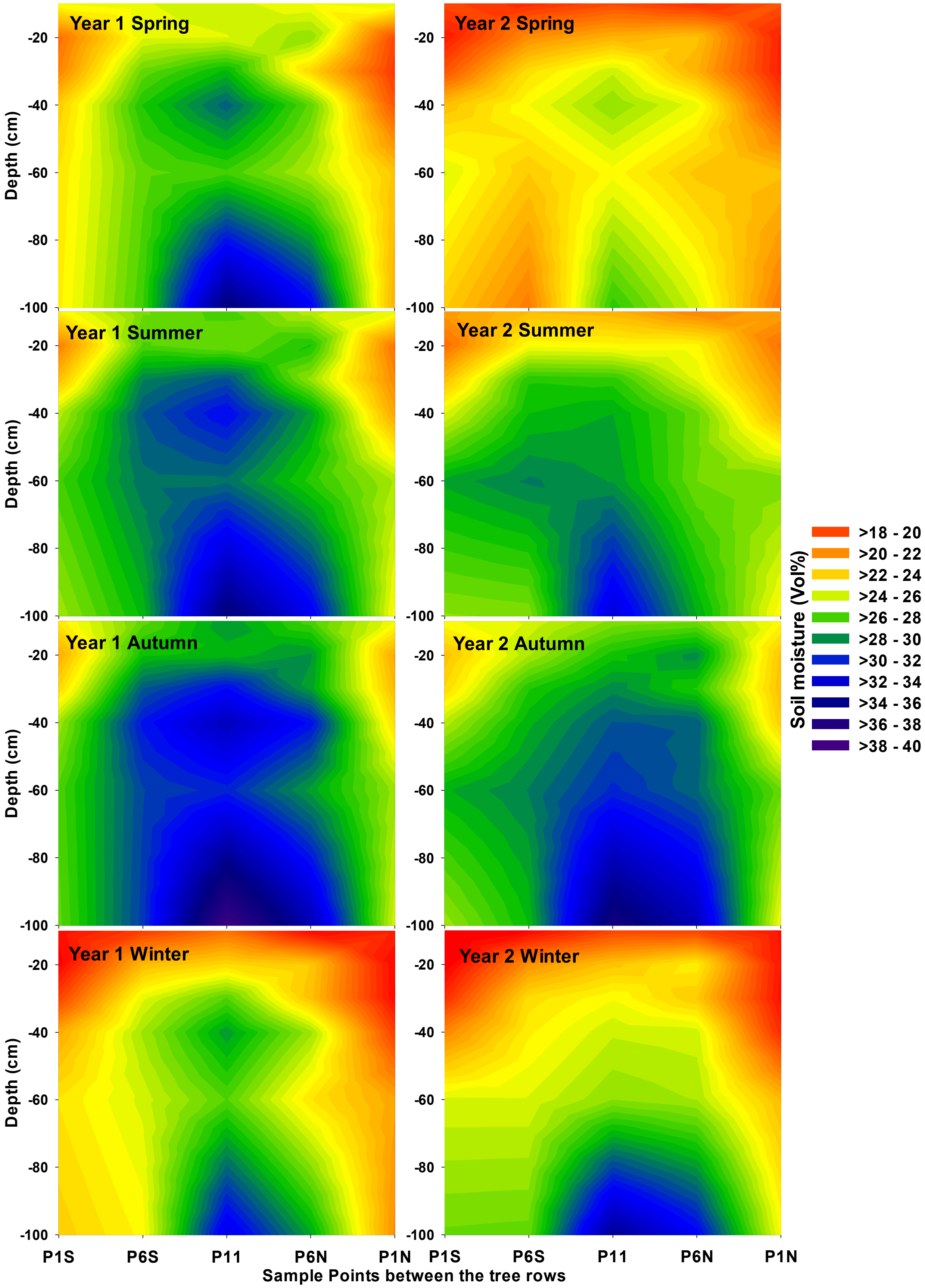

Figure 2.5: Mean soil moisture (SM, in vol%) for each sample point between the tree rows. Left panel shows SM for spring, summer, autumn and winter of year 1 and the right panel shows SM for spring, summer, autumn and winter of year 2. P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively.

Analysis of variance showed significant differences in SM between years (except for 60 cm depth), seasons and sample points at all measured depths (Table 2.2). Whereas in the topsoil at 10 cm depth, season had the largest effect on SM, the influence of the sample point became larger with increasing soil depth.

Table 2.2: Analysis of variance for soil moisture in depth (a) 10 cm (b) 20 cm (c) 30 cm (d) 40 cm (e) 60 cm and (f) 100 cm. ***, **, *: significant at p-value ≤ 0.001, ≤ 0.01, ≤ 0.05, respectively. Abbreviations: Df: degree of freedom; SS: sum of square; MS: mean square.

Soil Moisture (Vol%)			**SM = Y × S × SP + R**	
(a) Depth: 10 cm	Df	SS	MS	*p*
Year (Y)	1	552	552	< 0.001 ***
Season (S)	3	2965	988	< 0.001 ***
Sample point (SP)	4	184	46	< 0.001 ***
Replication (R)	2	4	2	0.8
Interaction (Y × S)	3	307	102	< 0.001 ***
Interaction (Y × SP)	4	53	13	0.2
Interaction (S × SP)	12	91	8	0.5
Interaction (Y × S × SP)	12	42	4	0.9
Residuals	288	2248	8	
(b) Depth: 20 cm	Df	SS	MS	*p*
Year (Y)	1	133	133	< 0.001 ***
Season (S)	3	1398	466	< 0.001 ***
Sample point (SP)	4	2296	574	< 0.001 ***
Replication (R)	2	39	19	0.9
Interaction (Y × S)	3	75	25	< 0.05 *
Interaction (Y × SP)	4	61	15	0.1
Interaction (S × SP)	12	32	3	1
Interaction (Y × S × SP)	12	36	3	1
Residuals	288	2275	8	
(c) Depth: 30 cm	Df	SS	MS	*p*
Year (Y)	1	172	172	< 0.001 ***
Season (S)	3	1390	463	< 0.001 ***
Sample point (SP)	4	3143	784	< 0.001 ***
Replication (R)	2	111	56	< 0.01 **
Interaction (Y × S)	3	9	3	0.8
Interaction (Y × SP)	4	84	21	0.07
Interaction (S × SP)	12	42	3	1
Interaction (Y × S × SP)	12	10	1	1
Residuals	288	2794	10	
(d) Depth: 40 cm	Df	SS	MS	*p*
Year (Y)	1	311	311	< 0.001 ***
Season (S)	3	1270	423	< 0.001 ***
Sample point (SP)	4	2984	746	< 0.001 ***
Replication (R)	2	351	176	< 0.001 ***
Interaction (Y × S)	3	2	1	1

Interaction (Y × SP)	4	116	29	< 0.05 *
Interaction (S × SP)	12	50	4	1
Interaction (Y × S × SP)	12	13	1	1
Residuals	288	3039	11	
(e) Depth: 60 cm	Df	SS	MS	*p*
Year (Y)	1	15	15	0.4
Season (S)	3	1405	468	< 0.001 ***
Sample point (SP)	4	541	135	< 0.001 ***
Replication (R)	2	145	72	< 0.05 *
Interaction (Y × S)	3	42	14	0.5
Interaction (Y × SP)	4	78	19	0.4
Interaction (S × SP)	12	79	7	1
Interaction (Y × S × SP)	12	39	3	1
Residuals	288	5386	19	
(f) Depth: 100 cm	Df	SS	MS	*p*
Year (Y)	1	138	138	< 0.001 ***
Season (S)	3	1165	388	< 0.001 ***
Sample point (SP)	4	5089	1272	< 0.001 ***
Replication (R)	2	438	219	< 0.001 ***
Interaction (Y × S)	3	531	177	< 0.001 ***
Interaction (Y × SP)	4	126	31	< 0.05 *
Interaction (S × SP)	12	137	11	0.8
Interaction (Y × S × SP)	12	82	7	1
Residuals	288	2886	10	

2.3.3 AGBM between the Tree Rows during Different Seasons

Grazing intensity differed largely between both years, with grazing activities from December until July, and the highest stocking rate (3.2 AU ha^{-1}) in February during the first year and grazing in December only during the second year (Figure 2.6). Consequently, in the first year, AGBM was with 114 g DW (dry weight) m^{-2} on average, substantially lower than in the second year, with 297 g DM m^{-2}.

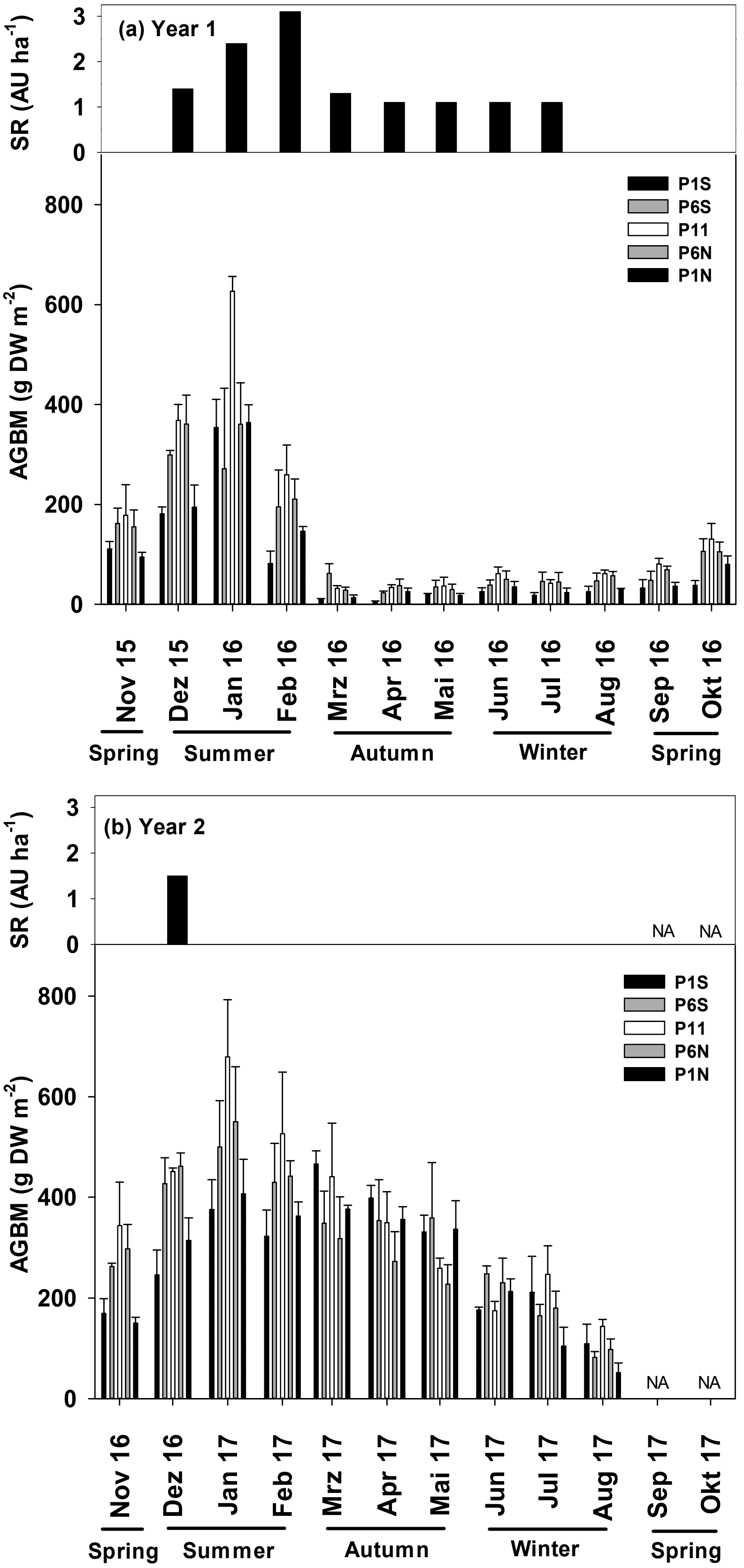

Figure 2.6: Monthly stocking rate (AU ha^{-1}; SR = stocking rate, AU = animal unit = 450 kg) and mean monthly aboveground green grass biomass (AGBM) (g DW m^{-2}) for each sample point between the tree rows for (a) year 1: Nov 2015–Oct 2016 and (b) year 2 Nov 2016–Aug 2017. P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively. Bars represent standard errors.

The ANOVA showed highly significant differences ($p \leq 0.001$) between both years, months and sample points (Table 2.3). In both years, the highest AGBM was measured in January, but in the first year, AGBM drastically decreased from February to March, whereas in the second year, AGBM decreased more slowly. The largest difference between both years was found between March and August. In both years, between most of October and February, AGBM was highest at P11, and lowest at P1S and P1N. However, between March and May in the second year, the highest AGBM was found at P1S and P6S.

Table 2.3: Analysis of variance for aboveground green grass biomass (AGBM). ***, **, *: significant at p-value ≤ 0.001, ≤ 0.01, ≤ 0.05, respectively. Abbreviations: Df: degree of freedom; SS: sum of square; MS: mean square.

AGBM [g DW m^{-2}]		**BM = Y × M × SP + R**		
	Df	**SS**	**MS**	***p***
Year (Y)	1	1,767,996	1,767,996	< 0.001 ***
Month (M)	20	5,914,719	295,736	< 0.001 ***
Sample point (SP)	4	298,911	74,728	< 0.001 ***
Replication	2	136,707	68,353	< 0.001 ***
Interaction (Y × SP)	4	6134	1533	0.882625
Interaction (M × SP)	80	653,342	8167	< 0.01 **
Residuals	218	1,142,667	5242	

Table 2.4: Aboveground green grass biomass (AGBM) [g DW m^{-2}] (mean ± standard error of the mean) for the seasons spring, summer, autumn, and winter in year 1 (Nov 15–Oct 16) and year 2 (Nov 16–Aug 17). Sample points between the tree rows are P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively.

AGBM (g DW m^{-2})	**Spring**	**Summer**	**Autumn**	**Winter**	
Sample Points		Year 1			Average
P1S	111.0 ± 14.9 aAB [1]	205.7 ± 43.7 bA	11.7 ± 2.3 cB	23.0 ± 4.3 cB	83.2 ± 20.2b
P6S	162.1 ± 30.5 aB	290.3 ± 43.0 bA	40.1 ± 8.9 aC	43.6 ± 7.8 bC	128.4 ± 24.5ab
P11	178.0 ± 61.7 aB	418.1 ± 58.6 aA	34.1 ± 5.5 aC	55.0 ± 5.8 aC	170.0 ± 35.8a
P6N	155.1± 33.9 aB	310.8 ± 40.1 abA	31.7 ± 5.4 abC	50.7 ± 7.9 abC	133.5 ± 25.6ab
P1N	94.6 ± 9.6 aB	234.8 ± 37.0 bA	18.7 ± 3.5 bcB	29.8 ± 4.3 cB	94.4 ± 20.6b
Average	140.1 ± 15.8B	291.9 ± 22.2A	27.3 ± 2.9C	40.4 ± 3.2C	
Sample Points		Year 2			Average
P1S	79.9 ± 24.6 bB	329.1 ± 34.6 cA	398.3 ± 24.2 aA	165.3 ± 28.1 abB	243.1 ± 25.3ab
P6S	138.8 ± 33.3 abB	452.3 ± 39.6 abA	353.8 ± 43.5 abA	165.1 ± 25.4 abB	277.5 ± 28.0ab
P11	185.1 ± 48.4 aC	552.2 ± 58.7 aA	349.8 ± 44.5 abB	188.4 ± 23.4 aC	318.9 ± 33.5a
P6N	157.6 ± 38.5 abC	484.6 ± 37.5 aA	272.4 ± 34.1 bB	169.3 ± 26.5 abBC	271.0 ± 27.6ab
P1N	88.9 ± 17.7 abB	361.3 ± 28.3 bcA	356.3 ± 19.0 abA	122.9 ± 27.6 bB	232.4 ± 24.3b
Average	130.0 ± 15.8C	433.0 ± 21.4A	346.1 ± 16.0B	162.2 ± 11.6C	

[1] Means followed by different lowercase letters within the same column indicate differences between the sample points; different uppercase letters within the same row indicate differences between the seasons; both at 5% probability.

AGBM was highest during summer at all sampling points in both years (Table 2.4). In the first year, AGBM was lowest in autumn and winter, while in the second year, it was lowest in spring and winter. In the first year, AGBM at P11 was significantly higher than at P1S and P1N during summer, autumn and winter. During spring, no significant differences between the sample points were found. In year 2, AGBM was only significantly higher at P11 than at both points close to the trees during summer, while during spring and winter, significant differences were only found between P11 and one of both measurement points close to the trees.

2.3.4 Correlations between PAR and AGBM and SM0-100 cm and AGBM between the Tree Rows

In spring and summer, AGBM was closely correlated with both, PAR and SM, with higher correlation coefficients with PAR (Table 2.5). In autumn and winter, the correlation between PAR and AGBM was negative and not significant, whereas the correlation between SM and AGBM was positive and in winter, also highly significant.

Table 2.5: Pearson correlation coefficient for correlations between PAR (µmol m^{-1} s^{-1}) and AGBM (g DW m^{-2}) and SM 0–1000 mm (vol%) and AG BM (g DW m^{-2}) in spring, summer, autumn, winter. ***, **, *: significant at p-value ≤0.001, ≤ 0.01, ≤ 0.05, respectively.

Pearson Correlation Coefficient r	**Spring**	**Summer**	**Autumn**	**Winter**
PAR vs. AGBM	0.90 ***	0.94 ***	−0.12	−0.44
SM $_{0–100\ cm}$ vs. AGBM	0.8 **	0.87 ***	0.49	0.87 **
				N = 10

2.4 Discussion

2.4.1 PAR, SM and AGBM Distribution throughout the Year

The trees in the ICLF system affected the amount of PAR received by the pasture, with a relative PAR reduction depending on the season and on the distance to the trees. The fact that in silvopastoral systems the pasture is shaded by the trees, is a well-known phenomenon with negative effects on both, light quantity and quality as red/far red ratio, received at the grass canopy (Feldhake, 2001; Rodrigues et al., 2014). The relative PAR reduction depends mostly on tree height, which was about 26 m at the beginning of our measurements and thus, led to a relatively large mean PAR reduction of 53% compared to above canopy PAR values (Table 2.6). Further, the magnitude of the effects depends on tree spacing, with spacing of more than 20 m between tree rows, as in our case, being beneficial for the relative light intensity in the median between tree rows (Rodrigues et al., 2014; Santos et al., 2016). In addition to tree height and spacing, time of day and time of year influence PAR reception at grass canopy level, related to the inclination of the sun. Light transmission at the center point between the tree rows was observed to be lower close to sunrise and sunset and during autumn and winter months (Pezzopane et al., 2015). In our experimental plots, PAR was reduced by more than 50% at the center point P11 during autumn and winter. Since PAR values represent means of measurements performed in the morning and afternoon, the sun did not rise above the tree canopy yet at the time of measurement during autumn and winter. However, a reduction in PAR near the trees was higher during spring and summer, whereas during autumn and winter, PAR was more evenly distributed between the tree rows. In absolute values, PAR received by the grass canopy close to the trees was up to 4 times higher in autumn and winter, than during spring and summer. Feldhake (2001) observed peak levels of solar radiation under the trees at 25% cloud cover because of increased diffuse radiation. In our experiment, PAR measurements were performed only under clear sky conditions. However, we hypothesized that a high ratio of diffuse radiation between the tree rows during autumn and winter led to both, a low relative PAR reduction close to the trees in comparison to the center point P11, and higher absolute PAR value close to the trees during autumn and winter compared to spring and summer. As seasons were defined meteorologically, and not by days of solstice and equinox, spring (September–November) and summer (December–February) resulted in relatively similar PAR values. Equally, PAR distribution during autumn (March–May) and winter (June–August) were very similar.

Table 2.6: PAR reduction (%) compared to open field measurements for spring, summer, autumn, and winter. Sample points between the tree rows are P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively.

PAR Reduction (%)	**Season**				
Sample Point	**Spring**	**Summer**	**Autumn**	**Winter**	**Average**
P1S	71	90	33	43	59
P6S	26	57	33	74	47
P11	9	21	56	59	36
P6N	39	47	78	60	56
P1N	83	89	42	54	67
Average	46	61	48	58	

SM over a soil depth of 0–100 cm showed a distinct seasonal dynamic closely related to rainfall pattern (Figure 2.4). SM was significantly lower in the second year, since precipitation was substantially lower than in the first year (1020 mm vs. 1553 mm). Further, SM in the topsoil (0–30 cm) was generally lower and more dynamic, which has also been found in a similar experimental setup by Bosi et al. (Bosi et al., 2019), who related this effect to water uptake by the pasture and evaporation from the soil, especially at the beginning of a drying period. Furthermore, in the topsoil, permanent wilting point was almost reached at some measurement points. For Brachiaria brizantha, more than 80% of the roots were found in the upper 30 cm of the soil, both under full irrigation and under water deficit (Guenni et al., 2002), and plant biomass was significantly decreased by water deficit, when soil water levels reached 25% of field capacity (Araujo et al., 2011). At our study site, a soil water content of 25% of field capacity equals a volumetric soil moisture of 19.4%. During winter, soil moisture at 0–30 cm was often below this threshold and, thus, negatively affected plant biomass.

Intra- and inter-annual AGBM values varied largely to intra- and inter-annual climate variability and development related senescence processes of the grass. Depending on temperature, daylength, solar radiation, and rainfall (Pedreira et al., 2011), canopy senescence is faster than canopy renewal during the cool and dry winter period. With regard to development, in Brazil, the cultivar Piatã starts flowering in January and February (Valle et al., 2007), influenced by changes in photoperiod that stimulates floral induction (Araujo et al., 2018). Flowering and seed development generally serve as a cue for tiller senescence in grasses (Sarath et al., 2014).

Despite the lower precipitation, more AGBM was observed in the second year, due to a significantly lower grazing intensity. In the first year, the pasture was grazed starting in December, which lead to a strong decline in AGBM until March, without recovery during autumn and winter. In the second year, grazing took place only during summer and a very low stocking rate was maintained. Under the conditions of the second year AGBM still peaked during January, but declined very slowly until August. The much higher AGBM in the second year could explain the lower topsoil soil moisture values. Greater grass leaf area lead to increased transpiration, combined with less rainfall.

2.4.2 PAR, SM and AGBM Gradients between the Tree Rows

During all seasons and in both years, the highest AGBM was found in the center point (P11), with a gradient of decreasing values towards the tree rows. According to Wilson and Wild (Wilson and Wild, 1991), most tropical grasses decrease AGBM under shading almost proportionally to the amount of shade, provided water and nutrients are not limiting. Lower grass biomass as a result of lower light intensity under and next to the trees in silvopastoral systems has been reported by several authors [3,29,30]. In our study, a PAR gradient between the tree rows was found during spring and summer, but with large PAR reductions under the trees relative to the center point P11 of 72% and 86% in spring and summer, respectively, whereas AGBM was reduced under the trees by 48% in spring and 42% in summer. Combining measurements from different seasons and at different tree densities, Santos et al. (Santos et al., 2016) found in a similar ICLF system under similar climatic conditions that for every 1% reduction of PAR there was a 1.35% decrease of forage dry mass. Since grass growth is subject to strong seasonal variations related to both weather and development, we suggest that the effect of PAR reduction on biomass should be analyzed for each season individually. In our case, every 1% reduction of PAR resulted in a 0.67% reduction in AGBM during spring, but only a 0.49% reduction during summer. However, during autumn and winter the pattern of PAR distribution between the tree rows was by far less pronounced, and the observed differences in AGBM could not be explained by PAR reductions under the trees. Pasture growth responses to shading also depend on N management. At high N doses, Brachiaria species showed a stronger response to light intensity in terms of tiller number(Paciullo et al., 2007) . In this study, 50 kg/ha N was applied at the beginning of the measurements. Therefore, we assume there was a medium response of biomass to light intensity.

Although potential water loss via transpiration from the grass canopy was highest at the center point, due to higher PAR (especially during spring and summer) and greater AGBM, SM was highest at P11. Soil water loss from the upper 1 m during a dry spell and soil water recharge during a rainy period was higher closer to the trees at points P1S and P1N (Figure 2.7). Soil drying and wetting cycles lead to the greatest SM variability occurring in the subsoil near the tree lines, rather than the topsoil, the interface to the atmosphere and the main rooting zone for grasses. Surprisingly, the center subsoil areas at 60–100 cm depth were the most conservative water holding areas of the ICLF. Topsoil SM variability showed an intermediate response to a drying and wetting cycle. Although Eucalyptus species are considered an intensive consumer of water (Bouillet et al., 2008), our results show that highest fluctuations of SM are initiated in subsoil horizons, which are often considered as buffers to fluctuations created by drying and wetting cycles (Frelih-Larsen et al., 2018; Rosenbaum et al., 2012). This buffer function was still visible in the center subsoil area between tree lines, where the lowest fluctuations of SM were observed throughout drying and wetting cycle (Figure 2.7).

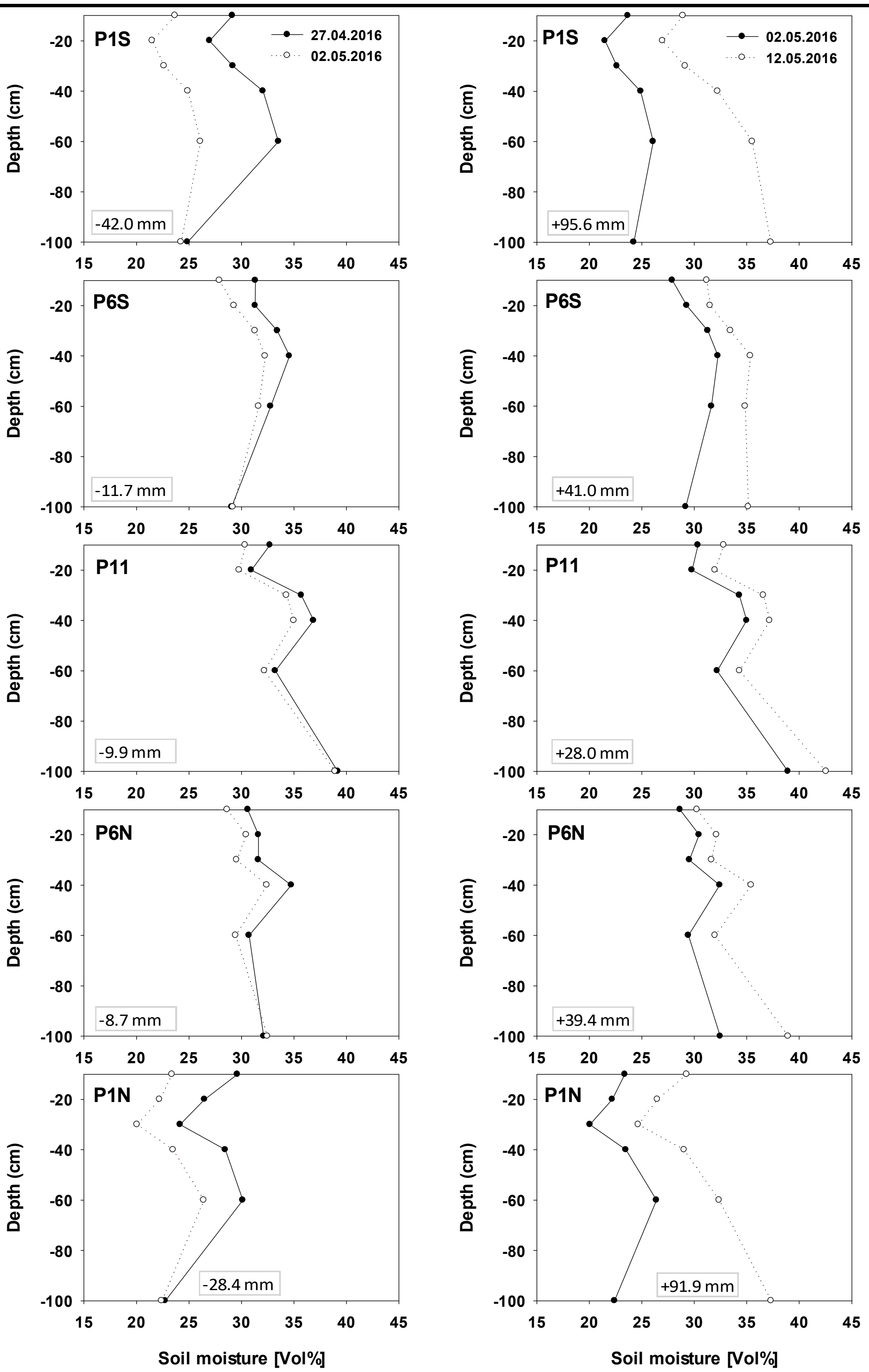

Figure 2.7: Soil moisture (vol%) at different depth for each sample points between the tree rows. Sample points between the tree rows are P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively. The left panel shows soil moisture change during a dry period between 27 April 2016 and 2 May 2016, when in total less than 1 mm of precipitation was recorded. In contrast to the right panel that shows, the subsequent rewetting period until 12.05.2016, when in total 123 mm of precipitation was recorded. Inserted numbers in each graph show the cumulative change in soil moisture over 0–100 cm.

Shaded forage grasses can increase specific leaf area, leaf elongation rate, and leaf length to increase light interception (Paciullo et al., 2011, 2008, 2007) , leading to a larger leaf area, despite a lower AGBM. However, it is unlikely that the higher soil water loss close to the trees is caused by higher transpiration of the grass next to the trees. Probably, the Eucalyptus trees depleted the soil water at P1S and P1N due to the large share of their fine roots found in the topsoil (Bouillet et al., 2002). Eucalyptus tree roots can grow deeper than 3 m within one year, but fine root density decreases sharply with depth (Laclau et al., 2001). Eucalyptus is a C3-species and thus, has a lower water use efficiency than the C4 species *Brachiaria* (Way et al., 2014) . Higher water uptake near the trees in silvopastoral systems was found by several authors for several species e.g., in ICLF systems with *Brachiaria brizanth*a and *Eucalyptus urograndis* (Bosi et al., 2019), or with *Brachiaria decumbens* and Brazilian native trees (Pezzopane et al., 2015), in an intercropping system with switchgrass and loblolly pine (Tian et al., 2017) and in a *Panicum maximum* pasture with *Eucalyptus argophloia* (Wilson, 1998).

However, not only water loss, but also soil water recharge during rainy periods was found to be higher closer to the trees. It has been argued that this effect is a result of large water interception by the trees and its subsequent deposition into the soil (Bosi et al., 2019). However, measurement of intercepted rainfall between the tree rows could not confirm this hypothesis as cumulative precipitation was roughly equal across the points of measurement between the tree rows (Figure 2.8).

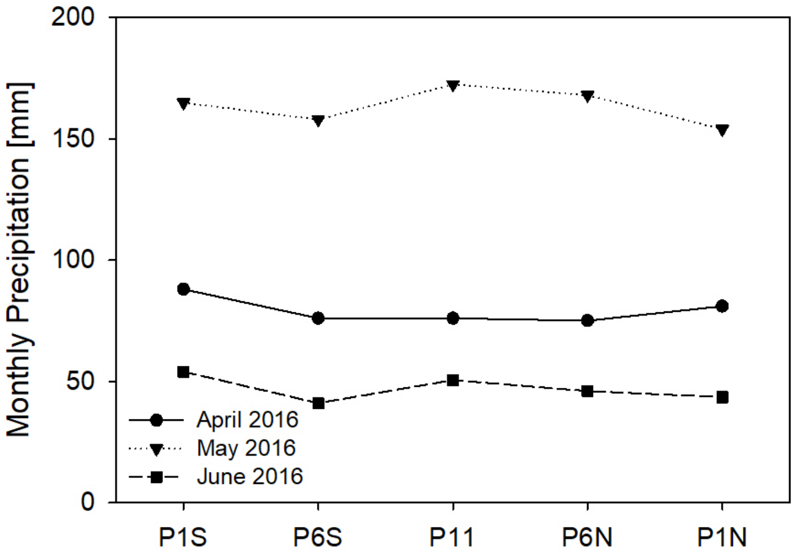

Figure 2.8: Cumulative monthly precipitation (mm) between April and June 2016 for the five different sample points between the tree rows. Sample points between the tree rows are P1S: 1 m and P6S: 6 m from southern row. P1N: 1 m and P6N: 6 m from northern row. P11: 11 m from southern and northern row, respectively.

Since soil water content and thus, soil water potential, was generally lower closer to the tree rows, we hypothesize that lateral subsurface water movements led to differences in soil water recharge. However, hydraulic conductivity of the soil at the experimental site was estimated to be 59.2 cm day^{-1}, which is probably too low to fully explain our observations. The experimental site has a slope of 2% in north–south direction, which makes it perpendicular to the tree rows, and means that lateral subsurface water movements could be facilitated by gravity, which could also explain the slightly higher soil moisture at P1S than at P1N.

During summer and spring, AGBM was strongly correlated with PAR, whereas the correlation between AGBM and SM was weaker, which indicates a stronger limitation of AGBM by radiation than by SM. Considering the relatively low SM during spring, a mainly radiation-driven growth of *Brachiaria brizantha* illustrates the good drought tolerance of this species (Fisher and Kerridge, 1996). A positive relationship between grass biomass and radiation in silvopastoral systems was also found by Santos et al. (2016) and Silva-Pando et al. (2002). However, we found that, during the winter, AGBM was solely correlated with SM, but not with PAR, indicating a water limitation. It has been suggested that in silvopastoral systems with a comparable climate to our site, a PAR limitation is the major constraint to production of dry matter when there are no limitations caused by soil water deficit (Burner and Belesky, 2008). As during winter, SM next to the trees was below 25% of the field capacity, which has been shown to be critical for *Brachiaria* growth (Araujo et al., 2011). The positive correlation between AGBM and SM between the tree rows supports the finding of a water limitation of the pasture next to the trees during the dry season of the year.

Trees provide shade for animals, which means that ICLF systems can also improve animal thermal comfort indices by reducing full sun exposure (C.C. Oliveira et al., 2019). Assuming animals are seeking comfort in the shade, they likely spend more time close to the trees during spring and summer. Therefore, we suggest that apart from lower light intensity and lower soil moisture, grass biomass next to the trees is also impaired by trampling and probable higher grazing intensity. However, a considerable accumulation of nutrients from dung and urine would also accumulate next to tree lines. Additionally, biomass inputs from foliage, including allelopathic substances depending on the species, could affect understory plant growth. During the second year, grazing intensity in summer was much lower than in the first year, while during autumn and winter no grazing took place. To support the idea of higher grazing and trampling intensity under the trees, in the second year, smaller differences in AGBM between the sampling points P11 and P1S/P1N were found from summer to winter. While during the first year, compared to P11, AGBM next to the trees was 47%, 55% and 52% lower during summer, autumn and winter, respectively, it was only 37%, 0% and 24% lower during summer, autumn and winter of the second year. As we can only compare two years of different grazing intensities, no valid conclusions can be drawn as to the impact of animal presence on the grass biomass gradient between the tree rows, including possible interactions with soil water dynamics.

ICLF systems offer a promising land use strategy to address the central challenges to future agricultural production systems (Alves et al., 2017). The available management options regarding combinations of different components and practices for ICLF systems are numerous, and indicators are highly requested to guide farmers towards a sustainable land use. While several studies show the beneficial effects and synergies created by integrated systems with attributes of reduced soil degradation (Lemaire et al., 2014), greenhouse gas emission (GHG) mitigation (Franzluebbers et al., 2017; Sato et al., 2017), and increased soil carbon sequestration (Sant'Anna et al., 2016), the effects on the water balance have yet to be explored. In view of a changing climate, water and its management will be seen as a critical aspect for integrated agricultural production systems. However, a sustainable management approach that takes into account water-related challenges requires a detailed knowledge base, including a comprehensive overview of how land use practices and environments are altering water pathways within ICLF systems.

Our results from a mature ICLF system in central-west Brazil suggest that the system's seasonality and resource cycles, such as those observed in episodic wetting and drying events, strongly interact with a management impact. Consequently, for plant water availability, temporary water stress may develop in deeper soil horizons near tree rows, where soil water content fluctuations were surprisingly more pronounced compared to topsoils across the analyzed gradient. These results stand in contrast to the generally held view that topsoils are usually subject to greater shifts in SM compared to the subsoil (Bosi et al., 2019; Rosenbaum et al., 2012). Deeper soil horizons in the center position between tree rows, however, showed a conservative response during a drying and wetting cycle, thus likely functioning as buffer zone for soil water resources. For the management of soil water reserves, improving the system's resilience to seasonal drought or periods of water stress, tree row distances and height, age (i.e., shading) as well as root architecture should be carefully considered and adapted to local conditions.

Management of water resources will certainly at the same time translate into processes triggering key-parameters affecting sustainability such as greenhouse gas emissions and C-sequestration of ICLF systems. The identification of tipping points, where stress and/or land use practices push systems towards a nonsustainable response is essential in the development of best practices for a responsive or regenerative management of ICLF systems. This would require monitoring of key parameters in high spatial and temporal resolution. Therefore, we advocate increased research on water-related functions and processes of ICLF systems to support and fully develop the promising land use potentials offered by these systems to improve sustainability of agricultural production.

2.5 Conclusions

Spatial and temporal water availability in mature ICLF systems is dynamic, affected by climate seasonality, management practices, and system design. Throughout the year soil moisture was lower closer to the tree rows, but critical values reaching the wilting point were only observed during winter (dry season) and in the topsoil. Seasonal soil moisture pattern and radiation input suggest that grass productivity is shifting from light limitation during summer to a water limitation during winter, especially near tree lines. Notably, soil drying and wetting cycles lead to highest SM variability in the subsoils near the tree lines, and not, as expected, in topsoils, which are considered the interface for evaporation to the atmosphere. Relatively wet subsoils in the center position between tree lines were most conservative regarding SM fluctuations, suggesting these areas function as important water reservoirs throughout the year, and during drought events. The system's resilience to resource fluctuations such as episodic wetting and drying events should therefore carefully be considered by taking soil water holding capacity into account for tree line spacing. Data from long-term monitoring across environmental gradients and including a variable tree planting design will improve our knowledge on water related functions and processes of ICLF systems in view of sustainable land use intensification and system resilience under climate change.

Author Contributions: Conceptualization, S.G., S.S. and M.G.; methodology, S.G., M.G. and R.G.d.A.; formal analysis, S.G.; investigation, S.G. and M.P.; resources, R.G.d.A., D.J.B. and M.C.M.M.; data curation, S.G.; writing—original draft preparation, S.G. and S.S.; writing—review and editing, S.G., S.S., M.G. and F.A.; visualization, S.G.; supervision, S.S. and M.G.; project administration, S.G.; funding acquisition, S.G. and M.G. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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3 Seasonal and Spatial Variability of Soil Moisture in Different Land Use Systems of the Brazilian Cerrado Biome

Glatzle, S., Stuerz, S., Giese, M., Pereira, M., de Almeida, R.G., Bungenstab, D.J., Macedo, M.C.M., Asch, F.; Seasonal and Spatial Variability of Soil Moisture in Different Land Use Systems of the Brazilian Cerrado Biome

Keywords: agroforestry, ICLF, ICL, soil water distribution, Savannah, pasture, conversion

Abstract: The Cerrado biome, constituting the native Brazilian semi-arid vegetation types, has been replaced to a large extent by crop and pastureland with pronounced effects on key agro-ecosystem functions including the water cycle, i.e. maintaining evapotranspiration (ET). As compared to conventional pasture or cropping systems, the introduction of trees via an integrated land-use raises the question if these systems hold potential to improve or maintain soil health and water related processes and thus function more akin natural Cerrado with regard to soil moisture dynamics and water cycles. Our study focus on soil moisture (SM) dynamics measured until 100 cm depth for natural Cerrado (CER) (*cerradão*), continuous pasture (COP), integrated crop livestock (ICL), and integrated crop livestock forestry (ICLF) systems for almost two years on a long term EMBRAPA monitoring site. In both dry and rainy season, mean SM was highest for ICL followed by COP and lowest in systems with trees (ICLF and CER). However, seasonal and spatial analysis of SM showed pronounced differences between soil layers and systems. While in COP and ICL water was mainly lost from topsoil, the strongest SM depletion for ICLF was observed between 40 -100 cm depth with values close to permanent wilting point during dry season. CER was driest in the upper 40 cm, but soil water storage was highest below 60 cm depth. As compared to conventional pasture and other integrated systems our results suggest that ICLF systems increase water recycling to the atmosphere via ET. Water pathways could therefore be managed towards increasing ET and thus potentially compensate for the loss of this water related ecological key-function of deforested Cerrado. However, spatial and seasonal soil water dynamics are strongly contrasting between both systems and, thus, other essential water dependent ecological processes might be affected with potential trade-offs for the overall system's sustainability.

3.1 Introduction

The Brazilian Cerrado biome, the second largest biome in south America, underwent and is still undergoing expansion of agriculture for the last five decades (Hunke et al. 2015; Sano et al. 2010). About 50% of the natural Savannah vegetation have been replaced by monocultures of soybean, sugar cane, corn, coffee, or cotton, as well as by energy plantations and pastures (Klink and Machado 2005; Marris 2005; Sano et al. 2010). On the one hand, rapid expansion of agricultural activities significantly increased crop yields and economic wealth in the region, on the other hand it contributes to serious environmental problems including soil degradation and altered water cycles (Spera et al., 2016).

Compared to undisturbed Cerrado vegetation, regions affected by deforestation and land use change were characterized by changed water pathways towards reduced evapotranspiration (ET) and relatively increased runoff and percolation (P.T.S. Oliveira et al., 2014a; Spera et al., 2016). Several studies reported potential feedback mechanism from land cover change which include reduced annual precipitation and increased rainfall variability (Butt et al., 2011, P.T.S. Oliveira et al., 2014a; Oliveira et al., 2005). The land use change, however, did not translate into increasing discharge due to the reduced ET, contrariwise, P.T.S. Oliveira et al. (2014a) reported decreasing discharge of the main river systems.

The strong seasonal variability of rain and temperature greatly influences soil moisture (SM) dynamics in this biome, resulting in low SM availability during the dry season. The natural savannah vegetation of the Cerrado biome is highly adapted to seasonal variability of SM, and has developed several coping strategies, such as deep rooting systems, dormancy of the herbaceous layer, stomata control, leaf abscission, and the ability to extract water from soil at different depths (Quesada et al., 2008). Integrated crop livestock systems (ICL) or integrated crop livestock forestry systems (ICLF), are management systems aiming at conserving soil resources while sustainably producing crops, livestock and / or timber integrated to the same area employing intercropping or rotations (Balbino et al., 2011). Compared to conventional continuously cropped or grazed systems, integrated systems conserve soil quality by reducing erosion, maintaining or increasing soil organic matter, and improving soil structure and porosity, resulting in increased infiltration and water retention capacity (Bono et al., 2012; Nair, 1993). Increased soil water infiltration and improved soil water storage of integrated systems potentially reduce drought impacts on agricultural production (Bosi et al., 2019). However, in comparison to a deep-rooting natural Cerrado vegetation, pastures as well as integrated systems take up water at shallower depth and represent a strong intervention in the spatial water distribution. Even on a transect within an ICLF system, large seasonal and spatial heterogeneity in SM has been found (Glatzle et al., 2021), and these effects are expected to be even more pronounced between systems. As the largest share of the roots of *Brachiaria brizantha* is found in the upper 30 cm of the soil (Guenni et al., 2002), SM of the topsoil can largely affect the productivity of the pasture and thus, spatial variability in SM needs to be considered in addition to the variability between seasons not only in respect of changes in the natural system, but also in respect of productivity.

Information on the impact of land use change from natural Cerrado to pasture or integrated systems on seasonal and spatial variability of the SM, soil quality and the physical characteristics affecting soil moisture (SM) remain scarce. Since SM is one of the key factors determining plant growth, land use change has not only long-term impact on soil physical characteristics and thus SM, but also on the land's productivity. Conversely, vegetation also directly affects SM through evapotranspiration and SM in different land use types cannot be compared without considering the transpiring biomass and the soil cover. Important agro-ecosystem functions are attributed to the interaction of soils, vegetation, and land use practices with regards to the water cycle. Therefore, the objective of this study was to elucidate the seasonal and spatial variability of SM of Cerrado soils as affected by different land use systems in the Brazilian Cerrado biome. The aim is to increase knowledge in order to assess land use systems in relation to soil water related functions originally provided by the natural Cerrado ecosystem.

3.2 Material and Methods

3.2.1 Experimental area

The study was conducted on the long-term experimental sites of EMBRAPA Beef Cattle situated in Campo Grande in the state of Mato Grosso do Sul, Brazil (20°24′54.9″ S, 54°42′25.8″, altitude 530m). The study area is characterised by a tropical savannah Aw climate (Kottek et al., 2006) with a mean annual temperature of 22.6°C and mean annual rainfall of 1560 mm. There is a distinct rainy season from November to April and a dry season from May to October (Figure 3.1). About 70% of the mean annual rainfall falls within the rainy season and the remaining 30% within the dry season. Temperature, relative air humidity, solar radiation, wind speed, and precipitation were monitored with a nearby meteorological station operated by EMBRAPA Beef Cattle.

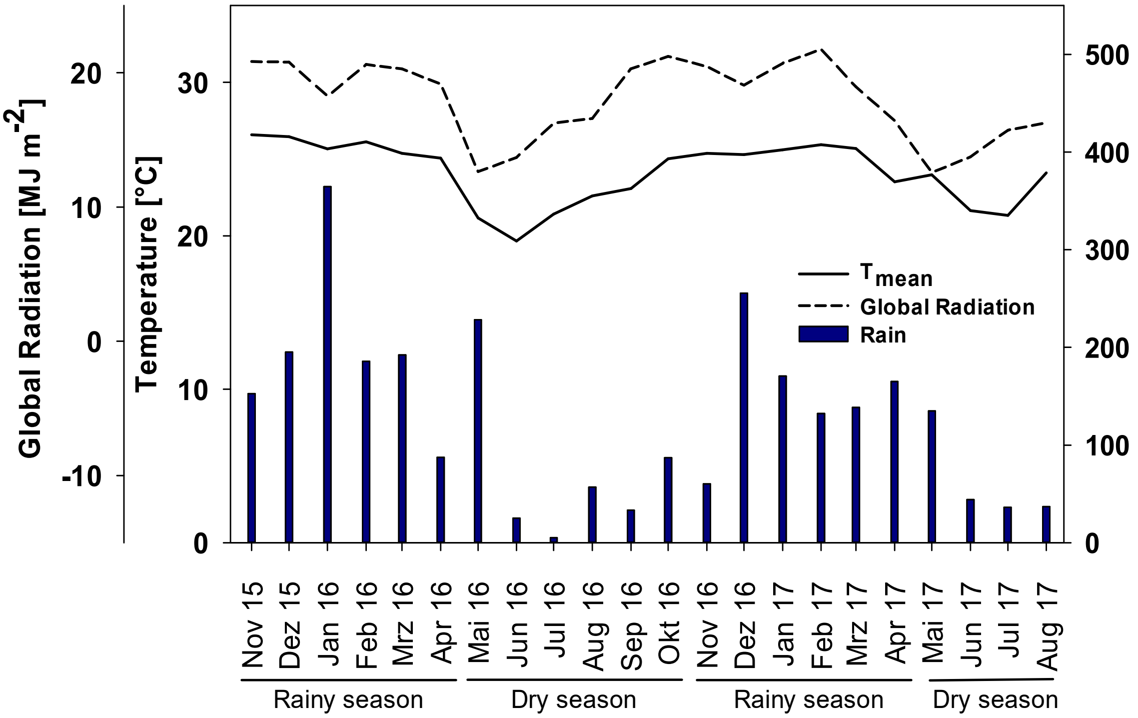

Figure 3.1: Monthly mean global radiation [MJ m^{-2}], temperature [°C] and cumulative monthly rain [mm] from Nov 2015 until Aug 2017.

3.2.2 Treatments

All measurements were performed in four land use systems, defined here as treatments, namely: continuous pastures (COP), integrated crop-livestock system (ICL), integrated-crop-livestock-forestry system (ICLF), and natural Savannah vegetation, Cerrado (CER). Plots of the four treatments were arranged on three replications and located in close proximity (Figure 3.2). For the CER treatment, measurement plots were established in a large continuous Cerrado area.

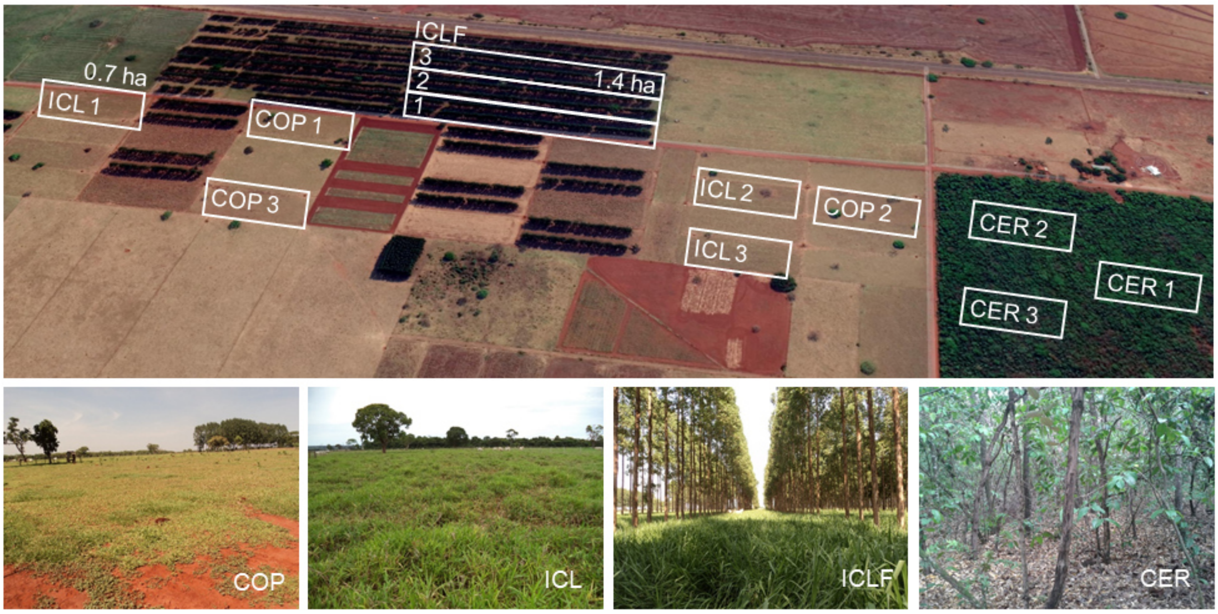

Figure 3.2: Top part: Map of the study area indicating the location of the four different treatments. COP: continuous pastures, ICL: integrated crop-livestock system, ICLF: integrated-crop-livestock-forestry system, CER: Cerrado (natural Savannah vegetation). Bottom part: Aspect of the respective treatment.

The plots of the treatments COP and ICL were part of a long-term management experiment that was established in 1995 and thus demonstrated management effects of more than 20 years. The COP treatment represented a typical degraded non-fertilized pasture often found in central west Brazil. The pasture consisted of *Brachiaria decumbens* cv. Basilisk under variable stocking rate with a minimum of two steers per plot and increasing stocking rate depending on forage availability. In ICL rotation strategy was established with a cycle of 4 years, rotating *Glycine max* under no-till for one year, followed by *Brachiaria brizantha* cv. BRS Piatã pasture under variable stocking rate with annual fertilizer application of 50 kg N ha^{-1} (in form of urea) and 300 kg NPK ha^{-1} (0:20:20) for three years. The ICLF was part of another long-term management experiment and were established in 2008. It consisted of an *Brachiaria brizantha* cv. BRS Piatã pasture lined with rows of 25 to 27 m high Eucalyptus (*Eucalyptus grandis x Eucalyptus urophylla*, H13 clone) trees with annual fertilizer application of 50 kg N ha^{-1} (in form of urea) and 300 kg NPK ha^{-1} (0:20:20). The Eucalyptus seedlings were transplanted in east -west oriented rows. Each replication consisted of two single tree rows at a distance of 22 m and 2 m distance between the trees within each row, resulting in a tree density of 227 trees ha^{-1}. The ICLF followed a 4-year rotation strategy with *Glycine max* for five months followed by 3.5 years of pasture. For this study, data were collected for the ICL and the ICLF treatment during the second and third year of the pasture cycle from November 2015 until August 2017. For the ICL and ICLF treatment the cattle (Nellore heifers) grazed at varying stocking rates depending on biomass production to keep the height of the pasture at approximately 35 cm (put and take method).

3.2.3 Soil characteristics

The soil of the study area is classified as a Ferralsol (WRB, 2014) a Typic Acrudox Oxisol (Sousa Neto et al., 2014). From soil pits, excavated in February 2017, undisturbed (coring rings 10 cm^3) and disturbed soil samples were taken for all four treatments plots in 10, 20, 30, 40, 60 and 100 cm depth, resulting in 3 replicates per depth. The undisturbed soil samples were used to determine soil bulk density (BD) and the disturbed soil samples to analyze pH measured in calcium chloride, soil organic carbon (SOC) using a C/N analyzer and soil texture using the pipette method (Table 3.1). Saturated hydraulic conductivity (K_{sat}), field capacity, and permeant wilting point were calculated using the computer program Rosetta Lite v. 1.1 within the software package HYDRUS 1D by PC Progress. Rosetta Lite v. 1.1 implements five hierarchical pedotransfer functions for the estimation of the van Genuchten water retention parameters (pF curve: field capacity and permeant wilting point) and the saturated hydraulic conductivity by using the measured soil texture and BD data (Schaap et al., 2001).

Table 3.1: Soil characteristics for the treatments COP: continuous pastures, ICL: integrated crop-livestock system, ICLF: integrated-crop-livestock-forestry system, CER: Cerrado (natural Savannah vegetation). SCL: sandy clay loam, SC: sandy clay.

	pH	**BD**	**SOC**	**Texture [%]**				**K_{sat}**
Depth [cm]	**($CaCl_2$)**	**[g cm^{-3}]**	**[%]**	**Sand**	**Silt**	**Clay**		**[cm d^{-1}]**
				COP				
10	4.9	1.34	1.75	64	5	31	SCL	49.1
20	4.8	1.24	1.51	60	6	34	SCL	57.5
30	4.7	1.28	1.29	61	4	35	SCL	52.1
40	4.6	1.24	1.05	59	4	37	SC	47.0
60	-	1.28	-	-	-	-	-	47.0
100	-	1.21	-	-	-	-	-	56.4
mean	*4.8*	*1.27*	*1.40*	*61*	*5*	*34*	*SCL*	*52.4*
				ICL				
10	5.2	1.25	2.39	53	7	40	SC	41.5
20	5.1	1.18	1.82	53	7	40	SC	51.8
30	5.0	1.21	1.50	53	8	39	SC	47.4
40	4.8	1.19	1.24	52	7	41	SC	49.1
60	-	1.18	-	-	-	-	-	50.6
100	-	1.10	-	-	-	-	-	64.1
mean	*5.0*	*1.18*	*1.74*	*61*	*5*	*34*	*SC*	*50.7*
				ICLF				
10	5.4	1.24	1.83	56	6	38	SC	46.9
20	5.0	1.17	1.60	55	6	39	SC	55.5
30	4.8	1.11	1.35	54	7	39	SC	65.0
40	4.8	1.14	1.18	55	6	39	SC	60.3
60	-	1.14	-	-	-	-	-	60.3
100	-	1.10	-	-	-	-	-	67.2
mean	*5.0*	*1.15*	*1.49*	*55*	*6*	*39*	*SC*	*59.2*
				CER				
10	4.3	0.91	3.13	56	7	37	SC	107.1
20	4.3	0.94	2.08	53	8	39	SC	99.8
30	4.4	1.00	1.68	52	7	41	SC	83.4
40	4.6	1.05	1.59	51	7	42	SC	71.9
60	-	0.99	-	-	-	-	-	83.6
100	-	1.01	-	-	-	-	-	79.7
mean	*4.4*	*0.98*	*2.12*	*53*	*7*	*40*	*SC*	*87.6*

3.2.4 Soil moisture and aboveground biomass measurements

For all treatments in each replication, five fiberglass access tube (DeltaT Type: ALT1) of 1 m length were vertically installed for volumetric SM [vol%] measurements with a portable DeltaT FDR (frequency domain reflectometry) PR2/6 profile probe. In the replications of the ICLF treatment, the fiberglass access tubes were installed along a transect of five sampling points between the tree rows to account for the shading and SM gradient caused by the trees. FDR measurements were taken weekly in depths of 10, 20, 30, 40, 60 and 100 cm. The FDR SM measurements were validated against gravimetrical SM measurements. Samples for gravimetrical SM measurements were taken with an auger right next to every FDR access tube at the same depths where the FDR probe measurements were taken.

In all four treatments, aboveground biomass (AGBM) [g DW m^{-2}] was quantified monthly at in total 22 sampling dates (Dec 2015 – Sept 2017). At each sampling date, biomass was collected at five sampling points in each replication (for ICLF along a transect between the tree rows). The grass layer was harvested on 1 m^2 and cut 5 cm above the ground. Furthermore, for COP and ICL all dead material laying on the ground within the 1m^2 was collected and for ICLF all dead material + litter from the Eucalyptus trees laying on the ground within the 1m^2 was collected. Due to the non-existing grass layer, only litter was collected from 1 m^2 sampling points in CER. All harvested biomass samples were separated into green biomass, standing dead biomass, and litter, dried for 48h at 70 °C and weighed to determine biomass as dry weight per area in g m^{-2}.

3.2.5 Data analysis

Data were analyzed in a randomized block (3 replicates) design, using the generalized least squares model of R (R Core Team, 2019). For the analysis of SM treatment, month and depth were considered as fixed effects. For the analysis of green AGBM and dead AGBM + litter, treatment, and month were considered as fixed effects. As SM was only measured at 10, 20, 30, 40, 60 and 100 cm depth, SM values at 50, 70, 80 and 90 cm depth were obtained by linear interpolation of the measured data points.

3.3 Results

3.3.1 Seasonal soil moisture

Soil moisture (SM) showed a clear seasonal pattern. Monthly mean SM (0-100 cm depth) was on average 10 to 15 vol% higher during the rainy season (Nov - Apr) compared to the dry season (May - Oct) for all treatments (Figure 3.3). Pooled over the rainy season, CER had with

27.5 vol% the lowest SM, closely followed by ICLF with 27.7 vol%, followed by COP with 30.0 vol%, while ICL had with 32.3 vol% the highest SM. The different treatments follow the same sequence pooled over the dry season just on a lower SM level. In the dry season, CER had with 25.0 vol% the lowest SM, closely followed by ICLF with 25.7 vol%, followed by COP with 27.5 vol% while ICL had with 29.3 vol% the highest SM.

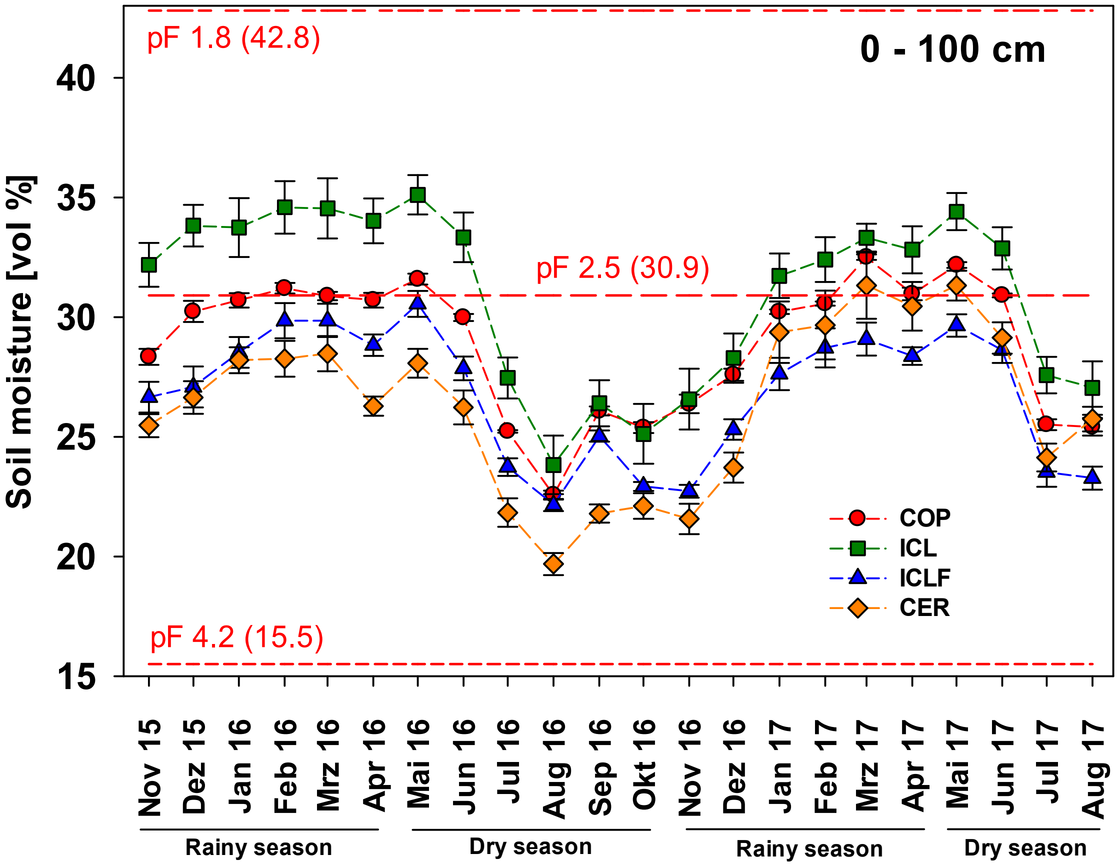

Figure 3.3: Monthly mean soil moisture [vol%] for COP: continuous pasture, ICL: integrated crop-livestock, ICLF: integrated crop-livestock-forestry, CER: Cerrado over 0 - 100 cm soil depth from Nov 2015 until Aug 2017. Bars represent standard errors. Dotted horizontal lines mark usable field capacity from pF 1.8 (field capacity) to pF 4.2 (permanent wilting point).

Analysis of variance revealed highly significant differences ($P \leq 0.001$) between the treatments, between the months and between the interaction of treatments and months (Table 3.2).

Table 3.2: Analysis of variance for SM 0-100 m. ***, **, *: significant at P-value ≤ 0.001, ≤ 0.01, ≤ 0.05, respectively. Abbreviations: Df: degree of freedom; SS: sum of square; MS: mean square

SM [vol%]		**SM = T x M + R**		
0 – 100 cm	**Df**	**SS**	**MS**	***P***
Treatment (T)	3	888	296	< 0.001***
Month (M)	21	2340	111	< 0.001***
Replication (R)	2	32	16	< 0.001***
Interaction (TxM)	63	199	3	< 0.001***
Residuals	174	226	1	

During the entire measuring period in all treatments, in general SM increased with depth (Figure 3.4). In all treatments and in all depths, SM was lower in the dry season (especially June to November) and higher in the rainy season. The topsoil (10 to 30 cm) of COP, ICL and ICLF, dried to values close to PWP only in the dry season. However, in CER, the topsoil was closer to the PWP almost throughout the measurement period. In contrast to the other treatments, SM values in CER decreased below 20 vol% also in deeper soil layers (up to 80 cm depth) during the dry season. Between 10 cm and 20 cm depth, ICL had the highest SM, followed by ICLF, COP and CER, whereas between 20 cm and 80 cm depth, highest SM in ICL was followed by COP, ICLF and CER. Between 80 cm and 100 cm depth, CER had the highest SM, followed by ICL, COP and ICLF.

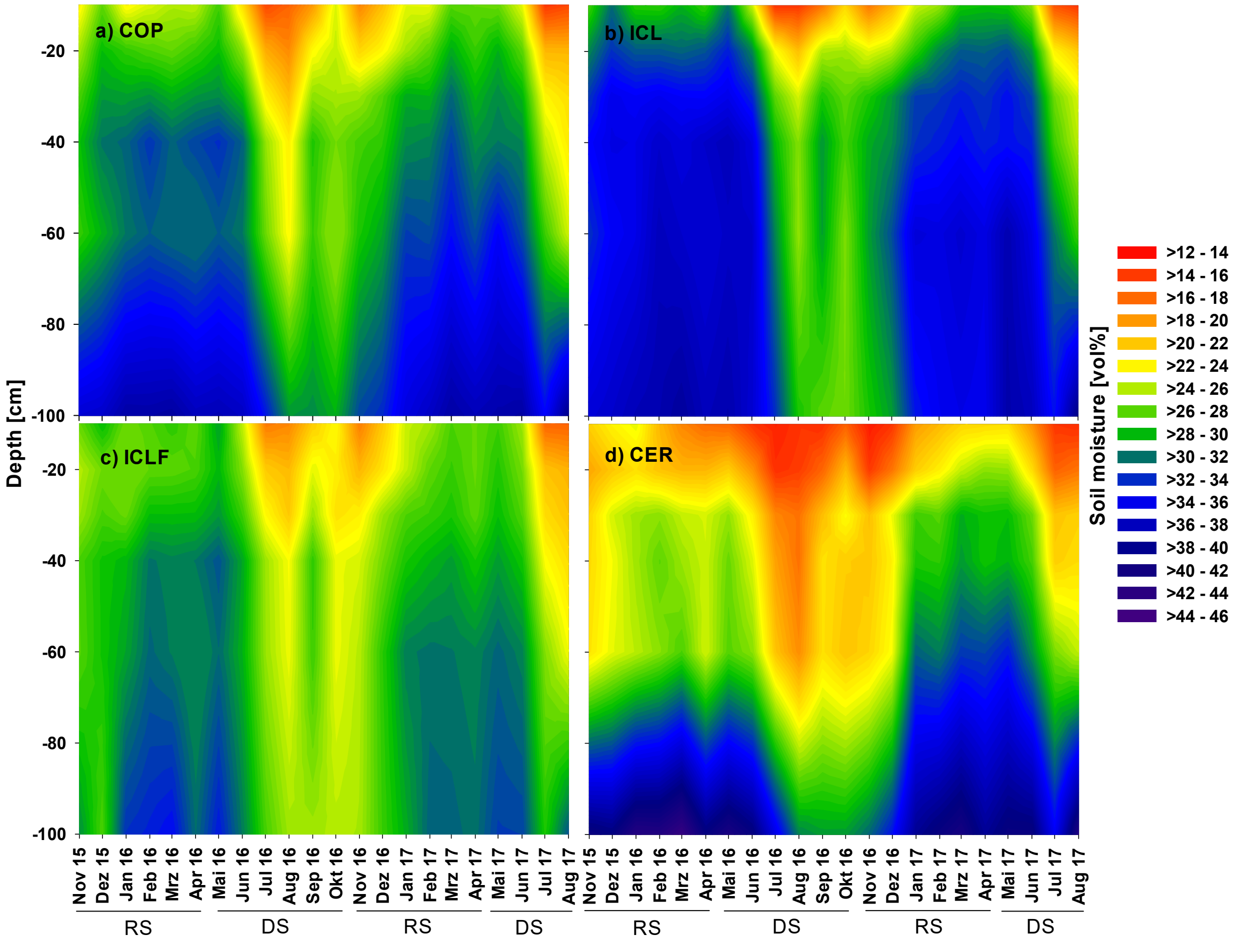

Figure 3.4: Soil moisture [vol%] between 10 and 100 cm depth shown as monthly means for a) COP: continuous pasture, b) ICL: integrated crop livestock, c) ICLF: integrated crop livestock forestry, d) CER: Cerrado from November 2015 until August 2017; RS: rainy season, DS: dry season

Analysis of variance showed significant effects on SM for treatments, months, and depths (Table 3.3), with depth having the largest effect on SM. The interaction between treatment and month, treatment and depth, and month and depth were highly significant, whereas the interaction between treatment, month, and depth was not significant.

Table 3.3: Analysis of variance for SM. ***, **, *: significant at P-value ≤ 0.001, ≤ 0.01, ≤ 0.05, respectively. Abbreviations: Df: degree of freedom; SS: sum of square; MS: mean square

SM	**SM = T*M*D+R**			
[vol%]	**Df**	**SS**	**MS**	***P***
Treatment (T)	3	6498	2166	< 0.001***
Month (M)	21	14657	698	< 0.001***
Depth (D)	5	23817	4763	< 0.001***
Replication (R)	2	117	58	< 0.001***
Interaction (TxM)	63	1261	20	< 0.001***
Interaction (TxD)	15	5623	375	< 0.001***
Interaction (MxD)	105	2701	26	< 0.001***
Interaction (TxMxD)	315	893	3	0.2
Residuals	1054	2738	3	

3.3.2 Soil moisture during drought events

During a drying period at the end of the rainy season, the largest volume of water between 10 cm and 100 cm depth was lost in CER with 64 mm, whereas in the other treatments, almost equal amounts of water were lost (Figure 3.5a, left panel). During this period, SM decreased stronger in the upper 40 cm in COP, ICL and CER, while in ICLF, SM decreased stronger between 60 and 100 cm. During a drying period during the early dry season (Figure 3.5b, mid panel), COP, ICLF and CER lost the same amount of water (61 mm) and ICL had a higher water loss (67 mm). Except for CER, SM decrease during this period was largest in the first 10 cm. However, in CER more water was lost in 20, 30, 40 and 60 cm than in 10 and 100 cm depth. During a drying period at the end of the dry season (Figure 3.5c, right panel), COP and ICL lost about the same amount of water (51 mm and 49 mm respectively), followed by ICLF (40 mm) and CER (34 mm). As in the drying period before, strongest decrease in SM was observed in COP, ICL and ICLF in the upper soil layer, while in CER, largest SM decrease was observed in between 20 and 60 cm depth. During this period, hardly any water was lost in 100 cm depth in all treatments. On average across the drying periods, largest variation in SM was observed between 30 and 40 cm at CER, whereas in the other treatments, water was mainly lost from the topsoil.

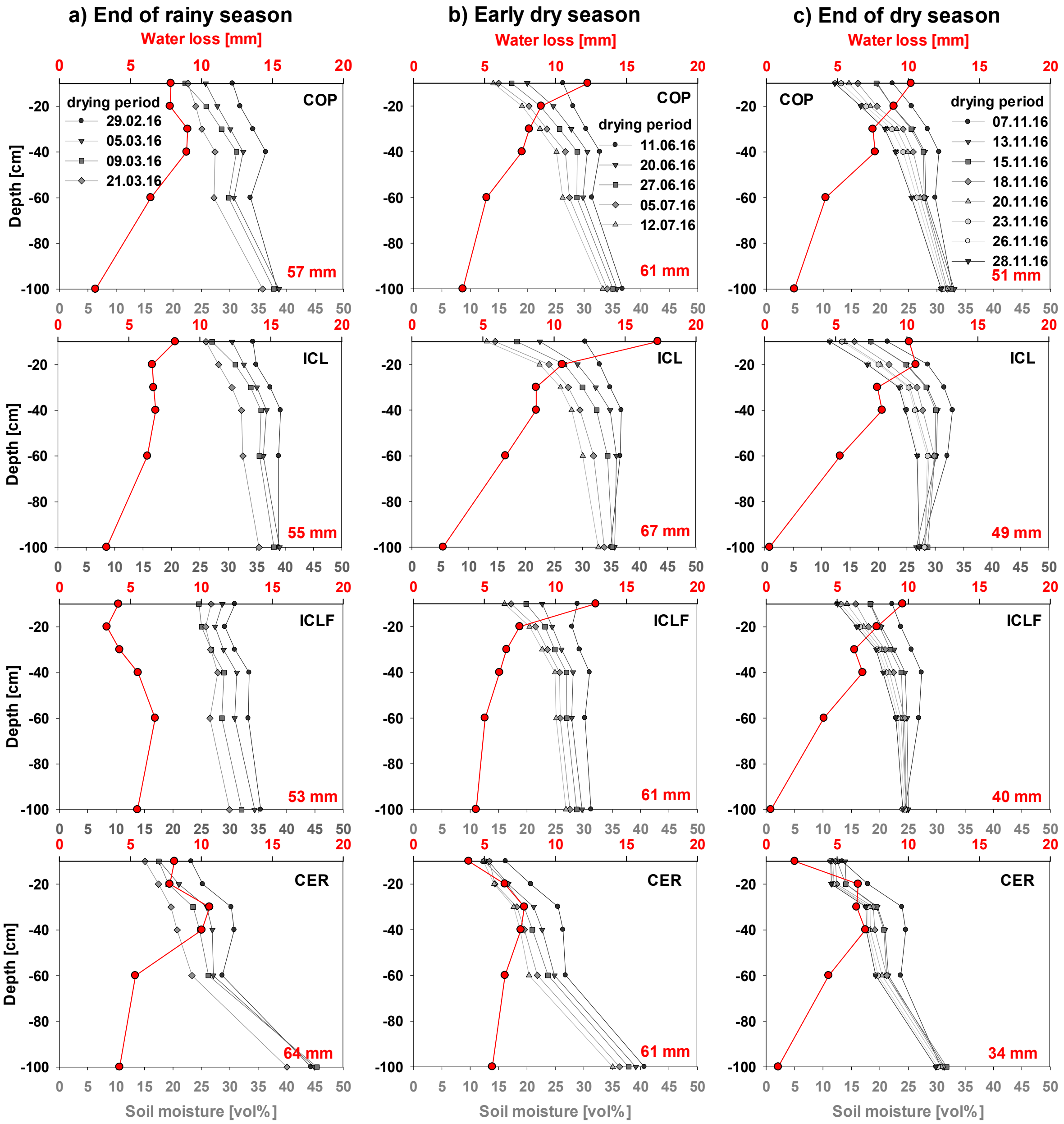

Figure 3.5: Soil moisture [vol%] in gray and water loss [mm] in red for COP: continuous pasture, ICL: integrated crop livestock, ICLF: integrated crop livestock forestry, CER: Cerrado. The left a), mid b) and right c) panels show SM change and water loss for the different treatments during drying periods at a) end of rainy season between 29.02.2016 and 21.03.2016, b) early dry season between 11.06.2016 and 12.07.2016, and c) end of dry season between 07.11.2016 and 28.11.2016, respectively. Inserted numbers in the right bottom corner of each graph show the cumulative water loss over 0-100 cm.

3.3.3 Aboveground Biomass

Throughout the measurement period, the total AGBM (green + dead +litter) was higher during the rainy season than during the dry season in all treatments (Figure 3.6). Comparing the treatments on average over the measurement period COP had with 206 g DW m^{-2} by far the lowest total AGBM, followed by ICLF with 607 g DW m^{-2}, and ICL with 760 g DW m^{-2}. Comparing green AGBM on average over the measurement period, COP had with 60 g DW m^{-2} the lowest green AGBM, followed by ICLF with 168 g DW m^{-2} and ICL with 262 g DW m^{-2}.

Comparing the dead + litter AGBM pool, COP (146 g DW m^{-2}) was lowest, followed by ICLF and ICL (439 and 497 g DW m^{-2}, respectively), while CER had with 899 g DW m^{-2} the highest amount of litter.

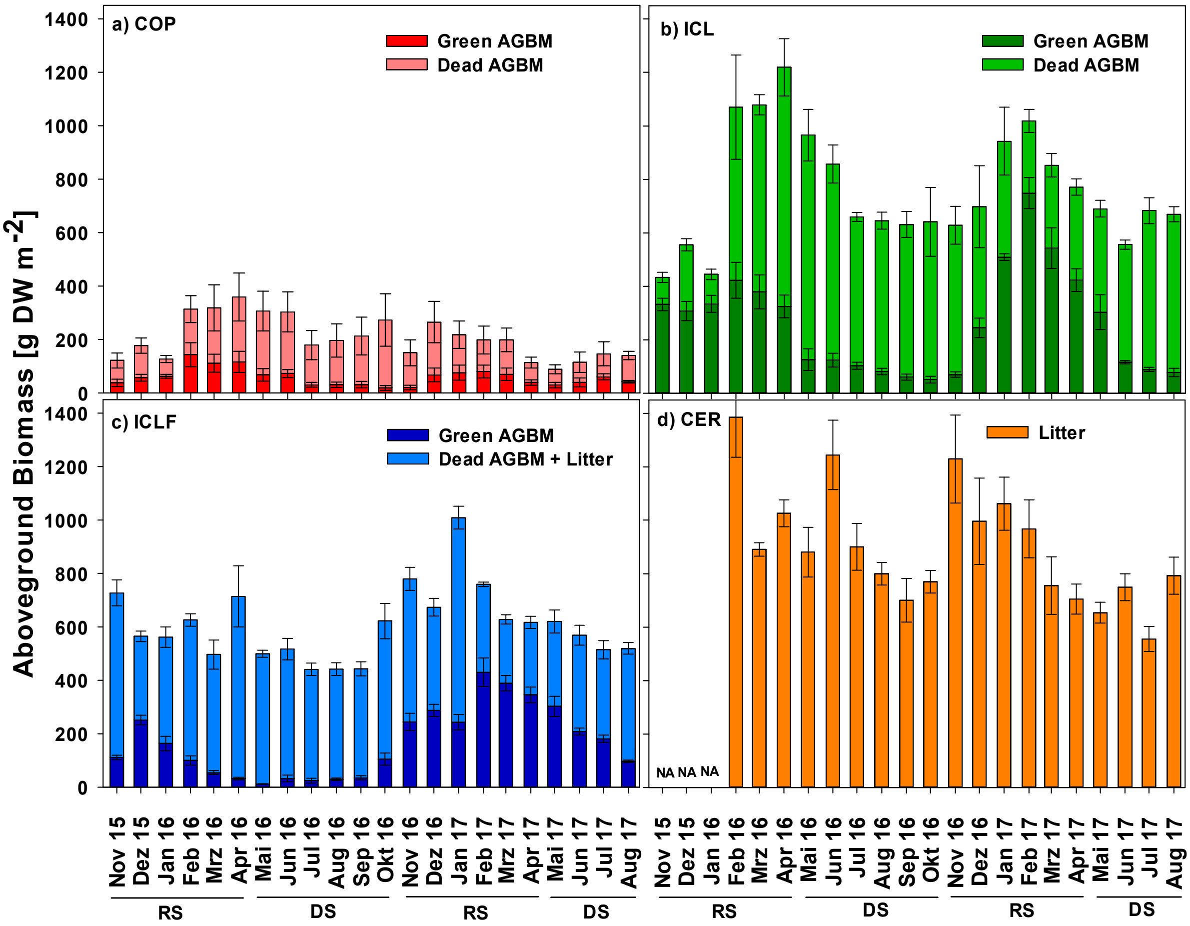

Figure 3.6: Monthly aboveground biomass [g DW m^{-2}] for a) COP: continuous pasture, separated into green AGBM and dead AGBM, b) ICL: integrated-crop-livestock, separated into green AGBM and dead AGBM, c) ICLF: integrated crop-livestock forestry, separated into green AGBM and dead AGBM + litter, d) CER: Cerrado, only litter from November 2015 until August 2017. RS: rainy season, DS: dry season. Error bars represent standard errors.

Analysis of variance showed significant differences in green AGBM and dead AGBM + litter between treatments and months (Table 3.4). For both AGBM pools treatment had the strongest effect. Furthermore, for both pools the interaction between treatment and month also showed highly significant differences.

Table 3.4: Analysis of variance for a) Green AGBM and b) Dead AGBM + Litter. ***, **, *: significant at P-value ≤ 0.001, ≤ 0.01, ≤ 0.05, respectively. Abbreviations: Df: degree of freedom; SS: sum of square; MS: mean square

a) Green AGBM		**BM = T*M+R**		
[g DW m^{-2}]	**Df**	**SS**	**MS**	***P***
Treatment (T)	2	1846	923	< 0.001***
Month (M)	21	2434	116	< 0.001***
Replication (R)	2	137	69	< 0.001***
Interaction (TxM)	2	42	48	< 0.001***
Residuals	130	332	3	
b) Dead AGBM + Litter		**BM = T*M+R**		
[g DW m^{-2}]	**Df**	**SS**	**MS**	***P***
Treatment (T)	3	9738	3246	< 0.001***
Month (M)	21	1888	90	< 0.001***
Replication (R)	2	284	142	< 0.001***
Interaction (TxM)	60	2192	37	< 0.001***
Residuals	168	1230	7	

3.4 Discussion

3.4.1 Soil moisture dynamics in the different land use systems

Monthly precipitation (Figure 3.1) and associated changes in SM to a depth of 100 cm for all 4 treatments were continuously measured for 22 months. SM changes in all treatments were strongly seasonal with high SM in the rainy season and lower SM in the dry season in response to the rainfall regime. Intra-annual changes in SM were similar for the different treatments but on different levels. For both seasons, pooled over 1 m depth, SM was always lower in the treatments with trees, ICLF and CER, as compared to treatments without trees, COP and ICL. It is well known that due to the different rooting patterns, trees and shrubs often access deeper soil layers resulting in increased water uptake and transpiration. It was shown for the ICLF system that soil water content especially in deeper layers was decreased close to tree lines as compared to the central areas between the tree lines (Glatzle et al., 2021).

Comparing Cerrado (*cerrado denso*) and a natural grassland (*cerrado sujo*), R.S. Oliveira et al. (2005) found higher evapotranspiration rates in the Cerrado, which was related to differences in tree densities and leaf area, but also to differences in root distribution. Similar results of lower SM at a higher tree density were found by Quesada et al. (2008) comparing a densely wooded Cerrado compared to a burned Cerrado with a high grass density in central Brazil and by Herrera et al. (2012) comparing an Eucalyptus plantation with a Savanah vegetation in Venezuela. SM in CER was on average over the measuring period even slightly lower than in ICLF, which was probably related to the higher density of woody vegetation and higher leaf area of the CER, resulting in higher transpiration rates.

However, despite threefold green AGBM and thus higher transpiration, SM was higher in ICL than in COP. This could be due to the higher SOC content in ICL, as an increase in SOC increases available soil water capacity (Minasny and McBratney, 2018) or could have been caused by the large quantity of dead AGBM in ICL that served as mulch and thus prevented evaporation (Iqbal et al., 2020). Furthermore, unlike ICL, COP did not form a closed grass cover, which increased SM loss through bare soil evaporation (Anache et al., 2019).

At saturation (pF 0), COP had the lowest SM value (49.0 vol%) followed by ICL (51.8 vol%) and ICLF (52.8 vol%) and CER (58.0 vol%) (Figure 3.7).

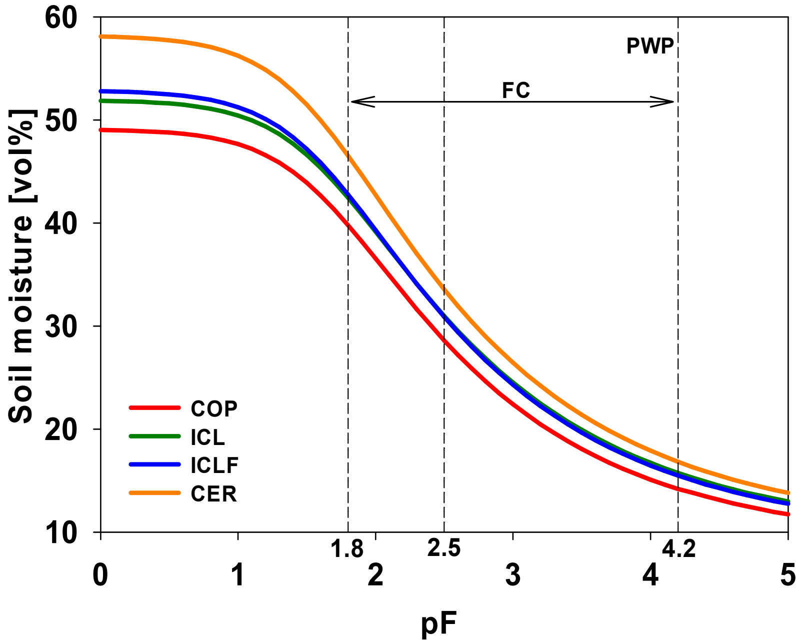

Figure 3.7: Water retention curves for COP: continuous pasture, ICL: integrated crop livestock, ICLF: integrated crop livestock forestry and CER: Cerrado, PWP: permeant wilting point, FC: field capacity

The water retention curve of COP in combination with the higher BD and lower K_{sat} (Table 3.1) indicates soil compaction and degradation resulting from deforestation, intensive cattle grazing, and machinery use (de Oliveira et al., 2004; Drewry et al., 2008; Greenwood and McKenzie, 2001; Nóbrega et al., 2017). Soil compaction is related to stunted aboveground BM growth coupled with reduced root growth (Shah et al., 2017), which could be a reason for the much lower green AGBM in COP compared to ICL and ICLF. However, as in contrast to COP, mineral fertilizer was applied in ICL and ICLF, comparisons of BM between the systems are difficult and must be considered with caution. The water retention curves showed higher SM at the same water potentials in the ICL and ICLF systems compared to COP indicating the potential of integrated systems (ICL and ICLF) and other conservation systems (e.g. No-Till systems) to mitigate the effect of soil compaction in pasture systems and thus, to restore degraded sites due to lower soil movement, the formation of biopores and input of SOC (He et al. 2011; Strudley et al. 2008). The potential of ICLF systems to improve the soil physical quality was also described by Moreira et al. (2018) and Assis et al. (2015), who found improved soil physical quality in ICLF and ICL systems compared to degraded pastures in the Cerrado biome. In line with these findings, Nóbrega et al. (2017) also found significantly greater bulk densities and smaller K_{sat} and total porosity in the topsoil of a pasture that was converted from a Cerrado. However, Feitosa et al. (2020), found higher water retention at field capacity of soils under pasture in the Cerrado biome of north Brazil, indicating potentially site specific responses. Due to the fact that our core experimental sites were established more than 25 years ago and were continuously maintained under the same management, we were able to capture a certain level of long term processes reflected in parameters of soil texture, carbon content and K_{sat} which could be clearly attributed to land-use management. In our experiment, we can in general confirm that tree components reduce average SM content independently from seasons, however, regarding seasonal dynamics in different soil depths differences in water extraction pattern were found between systems.

3.4.2 Seasonal and spatial soil moisture variations

In general SM was lowest in the topsoil and increased with depth. The moisture profile changed in the dry season, where relatively low SM values were found in greater depth. However, SM in the observed profile varied largely between treatments. While the topsoil was driest in CER throughout the seasons, it showed only little variation between the other treatments, with COP having the lowest SM during the peak of dry season and ICL having a higher SM during the rainy season (Figure 3.8). With regard to the subsoil, moisture was on average lowest in ICLF. However, differences in sub SM between ICLF and CER were strongly seasonal, with a large difference during the rainy season and similar values during the dry season. COP and ICL had on average a similar sub SM as CER, but during the dry season, SM was slightly higher in COP and ICL than in CER.

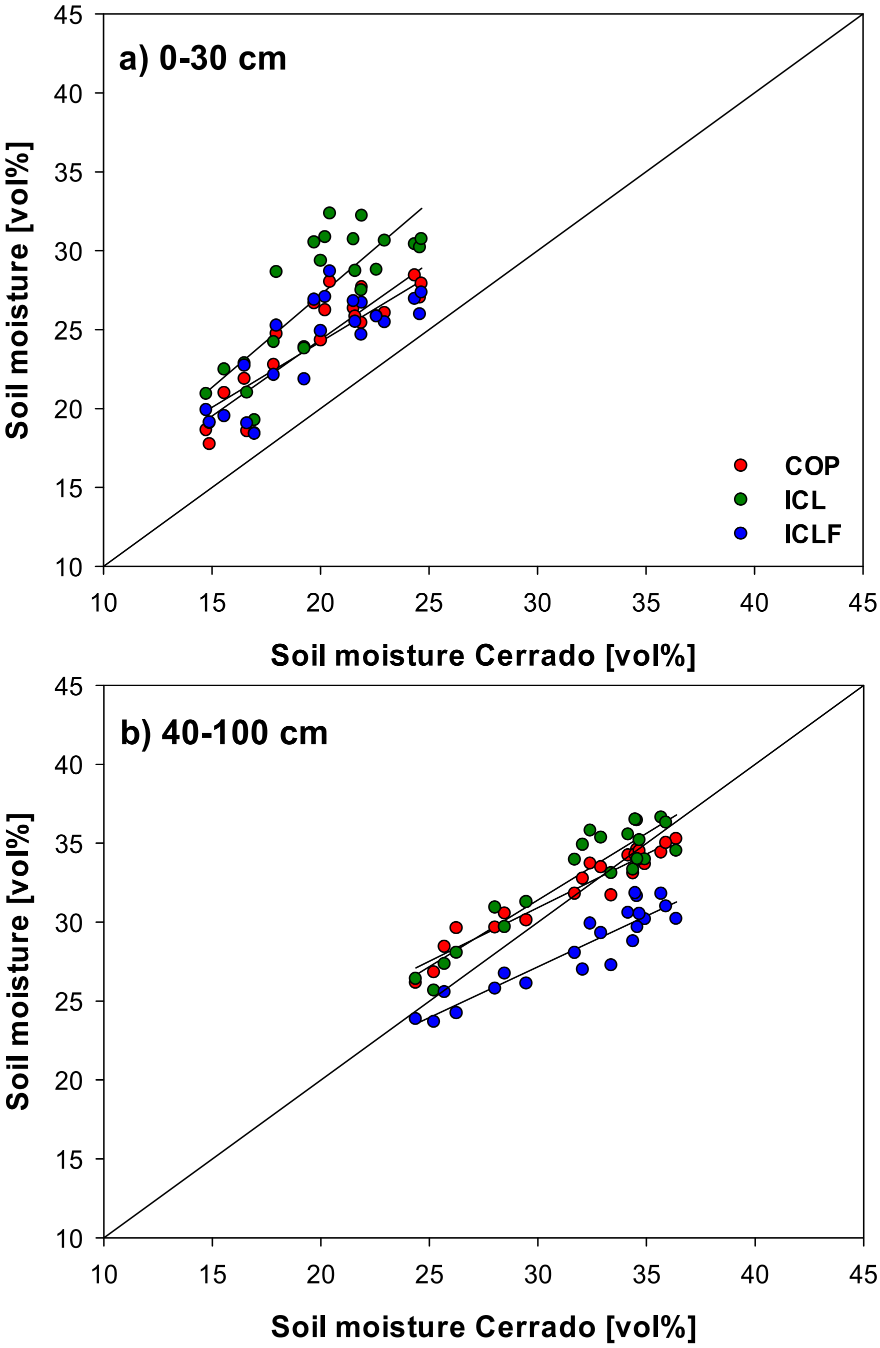

Figure 3.8: Mean monthly soil moisture of a) the topsoil (0-30 cm) and b) the subsoil (40-100 cm) of COP: continuous pasture, ICL: integrated crop livestock and ICLF: integrated crop livestock forestry regressed versus mean monthly SM of Cerrado between November 2015 and August 2017.

The upper layers of the soil in the Cerrado have been described as relatively dry, with values below the permanent wilting point during the dry season (Eiten, 1972) and a study comparing the hydrology of catchments predominated by either Cerrado or pasture found significantly higher streamflow values in the pasture catchment indicating higher evapotranspiration of the forest (Nóbrega et al., 2017). Similar results were found by Dias et al. (2015). Despite the extensive land conversion from Cerrado to pasture in recent years, studies directly comparing the SM between both land use types are scarce. With a lower bulk density and a higher share of organic matter, the topsoil of CER should have a higher water retention than the other land use systems. Further, evaporation from the topsoil has been found to be lower in the forest than in an open pasture (Magliano et al., 2017), as the tree canopy strongly limits the radiation reaching the ground and the soil is covered with a layer of litter. A layer of litter, which was present in CER year-round, not only strongly limits evaporation (Magliano et al., 2017), but also intercepts a substantial share of rain in the Cerrado (Rosalem et al., 2018). Interception from Cerrado canopy was estimated to around 20 % of total precipitation (P.T.S. Oliveira et al., 2014b) which in turn is directly contributing to higher ET of Cerrado systems compared to other land-use types.

We are aware that litter can also lead to errors during SM measurement with permittivity sensors (Schunk et al., 2015) such as the one used in our study. As the access tube needs to be in close contact with the surrounding soil for a precise FDR measurement (Delta-T Devices Ltd., 2016), and in CER, the upper 2-3 cm of the access tube were in contact with a layer of litter in a stage of decomposition, which impeded the required close contact, the precision of the upper SM measurement at 10 cm depth can be questioned. However, SM at 20 cm depth in CER was also lower than in the other land use types and its measurement can hardly be affected by the litter. As evaporation and litter-related measurement errors can be excluded as cause for the lower SM values in CER, one possible explanation could be the soil specific characteristics found in Ferralsols under native Savannah vegetation. Natural Ferralsols have a granular macrostructure due to the gibbsitic (Aluminum hydroxide) mineralogy (Ferreira et al., 1999a) resulting in a high amount of macropores, but also micropores (Ferreira et al., 1999b). The stable soil structure is based on the bonds between negatively charged clay minerals and positively charged Aluminum hydroxide. Juhász et al. (2007) found in the topsoil under native Cerrado vegetation (cerradão) low soil BD and low water retention caused by high organic matter content and high total macroporosity. According to this study the water infiltration, conductivity and retention depend on the shape of the pores and, consequently, on soil structure. The pore shapes found in the topsoil of these natural Ferralsols, favor water infiltration and conductivity in disadvantage to retention. Furthermore, natural Ferralsols were found to have more macropores under native perennial vegetation due to the formation of biopores (Salako and Kirchhof, 2003). The high total macroporosity, low water retention and higher saturated hydraulic conductivity (Table 3.1) in the topsoil of CER could explain low SM values in this treatment. Moreover, the slope of the CER retention curve (Figure 3.7) is steeper compared to the other treatments, indicating that the SM is less retained. In the pasture systems without tress COP and ICL, water was mainly lost from the upper 40 cm of the soil, while in CER the largest share of water lost, in the upper 1 m of the soil was depleted between 20 and 40 cm depth (Figure 3.5). In ICLF, most of the water was extracted below 40 cm at the end of the wet season, but with increasing water deficit, a larger share of water was lost from the upper part of the soil. In the pasture, it can be expected that the largest share of water is lost from the upper part of the soil, as more than 80% of the roots of Brachiaria brizantha can be found in the upper 30 cm of the soil (Guenni et al., 2002). For the ICLF system, SM values presented are mean values from measurements taken along a transect between the tree rows to account for variability in SM depending on the distance from the trees (Glatzle et al., 2021). Bosi et al. (2019) found the largest fluctuation in SM in the upper 30 cm of the soil in an ICLF system. However, they also described a fast soil water withdraw closer to the trees, indicating a higher water uptake by the trees than by the pasture. Even Eucalyptus has a large share of its roots in the surface layer of the soil, its roots grow far beyond the depth of 1 m (Bouillet et al., 2002). The varying depth of the zone of the largest water extraction found in our study (Figure 3.5), indicates a shift in water uptake to greater depth during the dry season. As with decreasing SM from the end of the wet season to the end of the dry season water extraction at 1 m depth in ICLF diminished, probably a larger share of water was extracted from greater depth. In a study from south-eastern Brazil, deep water uptake by Eucalyptus roots accounted for a relatively small proportion of the total water uptake, but during the dry season, trees increased the share of the water taken up near the water-table at 12 m depth (Christina et al., 2017). Similar effects were reported for the Cerrado. Even with the highest root density being found in the topsoil in a Cerrado forest and more than 90% of the fine roots in the upper 1 m of the soil, deep water uptake accounted for 83% of the total water use during the dry season (R.S. Oliveira et al., 2005). However, as SM was much lower in ICLF than in CER between 40 and 100 cm during the rainy season (Figure 3.8), Eucalyptus trees probably take up more water in the upper part of the rooted subsoil (40-100 cm) than the Cerrado vegetation during periods of high water availability. Further, as SM was much lower in ICLF than in CER at 1 m depth throughout the year (Figure 3.4), we hypothesize that the shift in water uptake to greater depth in response to low SM is taking place earlier in CER resulting in water conservation. This aspect, of seasonal dynamics of the water balance between natural Cerrado and ICLF systems needs to be considered in more detail if sustainability should be assessed, especially since other essential ecosystem processes related to water availability might have changed. Eucalyptus trees are by far the most dominant tree species used in ICLF systems and the potential of other (native) tree species to be used in ICLF systems appears not fully developed yet. However, by contributing to increase ET, Eucalyptus, or other trees, respectively directly compensate for the reduced water recycling to the atmosphere as reported from other land use systems established on previous Cerrado area (P.T.S. Oliveira et al., 2014a; Spera et al., 2016). From this perspective integrated systems including tree are closer to the natural Cerrado as compared to pasture and other integrated systems. In view of the serious consequences caused by altered water cycles via land use change, ICLF systems should be considered as an additional option to mitigate previous land use change effects in a context of sustainable intensification.

3.5 Conclusion

SM was generally lower in the land use systems including trees compared to systems without trees, most likely related to higher evapotranspiration. However, seasonal and spatial analysis of SM revealed different water uptake patterns between the land use types. While water uptake during the rainy season at 40-100 cm depth was highest in ICLF, water losses during the dry season in the upper 1 m were lower in CER than in the other systems, probably related to a larger share of deep water uptake of CER in general and also an earlier shift of water uptake to greater depth during periods of low water availability. Despite water having been conserved at a depth between 60 and 100 cm in the CER, the topsoil was drier than in all other systems possibly because of a lower water retention related to its very high macroporosity. Compared to the COP, more grass BM was produced in the integrated systems (ICL and ICLF). The differences in grass BM between the systems were not related to water availability, but rather to soil characteristics such as lower BD and higher SOC in the integrated systems. However, BD was much lower and SOC much higher in the CER than in all other land use systems providing insights on the long-term effects of land use change from the natural Cerrado vegetation to different pasture system. In general, integrated systems offer a good alternative to traditional pastures in terms of soil quality and productivity. Tree components introduced to land use system may counterbalance reduced ET after Cerrado deforestation and thus help to restore natural ecosystem functions with regard to water recycling into the atmosphere. Nevertheless, before introducing (Eucalyptus) trees to a system, local rainfall patterns and soil hydraulic conditions need to be considered, as water depletion by the trees in the upper 1 m of the soil poses a risk to the pasture. Further research is needed to explore the effect of Eucalyptus trees on SM in greater depth. Further, the different seasonal and spatial water uptake patterns between Cerrado vegetation and ICLF featuring Eucalyptus trees indicate additional scope for selecting tree species to be included in ICLF systems that may be better adapted to the local conditions.

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4 Beef cattle production on Piatã grass pastures in silvopastoral systems

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Keywords: Agroforestry systems, eucalyptus, grazing systems, ruminant production, shading, tree density.

Abstract: Tropical beef cattle production involving animals grazing in a shaded and biologically diverse environment, surrounded by high-quality edible biomass, is achievable through silvopastoral systems (SPSs). However, it is necessary to assess the effects of the presence of trees on forage and animal performance over time. In the Brazilian Cerrado, we evaluated the effects of 2 densities of eucalyptus trees in 2 SPSs (8 years of age - SPS22: 227 trees/ha; SPS14: 357 trees/ha) on forage morphology, production and nutritive value of Urochloa brizantha cv. BRS Piatã grass plus performance of Nellore heifers, compared with a grass-only pasture, over a year from 2015 to 2016. On the one hand, SPSs improved ($P<0.001$) forage nutritive value as reflected in higher crude protein and digestibility and lower neutral and acid detergent fiber concentrations compared with a grass-only pasture. On the other hand, the grass-only pasture had higher ($P<0.001$) herbage mass and accumulation rate than SPS. Forage growth and animal production decreased with higher tree density. Increasing competition from trees with age could be a serious issue limiting pasture and animal production and should be monitored. The suitability of eucalyptus trees for planting in SPSs may be questionable after the 8th year of establishment and further studies are warranted.

4.1 Introduction

Silvopastoral systems (SPSs) are among the most recent agricultural developments in Brazil. Such SPSs provide livestock and forest products from the same area of land in rotation, consortium or succession, over a defined period. The systems have been promoted as a valuable option of sustainable intensification, by increasing food production while maintaining or improving environmental quality and preserving natural biodiversity (Costa et al., 2018).

The interaction between these components has raised many questions, highlighting the need for further investigations of the benefits of recovering pasture and degraded land, particularly in fragile ecosystems. For instance, livestock are the mainstay of livelihoods, which often leads to pasture degradation due to uncontrolled and poor grazing management practices - as commonly observed in Brazilian Cerrado (Garcia and Ballester, 2016; Peron and Evangelista, 2004).

While tropical forages have high growth rates and good persistence, while enhancing soil cover, they require high incident light to reach maximum levels of production (Taiz and Zeiger 2010). In SPSs the presence of trees limits the amount of incident light reaching the sward. Dry matter (DM) yields of many tropical grasses and legumes, such as *Urochloa* spp., *Megathyrsus maximus, Paspalum notatum, Arachis pintoi, Neostanthus phaseoloides* (syn. *Pueraria phaseoloides*) and *Stylosanthes* spp., to name but a few, are greatly reduced as shade levels increase compared with sunny environments (Andrade et al., 2004; Araújo et al., 2017; Martuscello et al., 2009; Sousa et al., 2010). Moreover, in SPSs with eucalyptus and pastures, Pezzopane et al. (2015) observed soil moisture removal near the tree rows was greater than in the inter-row space, which was attributed to increased extraction by tree roots which penetrated to greater depths than the grass.

Nevertheless, several authors have reported an improvement in forage nutritive value under shading, particularly an increase in protein concentration levels (Baruch and Guenni 2007; Sousa et al. 2010; Paciullo et al. 2016), which enhances animal performance with average daily bodyweight (BW) gains per animal similar to those in sunny environments (Gamarra et al., 2017; C.C. Oliveira et al., 2014).

Amongst tropical forage grasses, the Piatã cultivar (*Urochloa brizantha* cv. BRS Piatã), adapted to medium fertility and well-drained soils, has been considered by researchers as a suitable option for planting in SPSs (Gamarra et al., 2017; Geremia et al., 2018). It is also an alternative for pasture diversification, showing high herbage mass production in Brazilian Cerrado soils (Euclides et al., 2008).

One of the grazing management practices used in sunny environments under continuous stocking is based on predetermined canopy heights (Martuscello et al., 2009; Pontes et al., 2016). However, there have been few recommendations for grazing management under shading (Baldissera et al., 2016).

As mentioned above, despite promoting a series of benefits, the presence of trees in pastures might decrease herbage mass and soil cover, along with reductions in soil moisture, and hence, constrain animal production over time – due to the continuous growth of trees with increased competition for light, water and nutrients. Therefore, the spatial arrangement of tree rows should match the intended objective, whether emphasis be on forest or livestock production. Long-term studies are required to avoid a decline in forage and animal production (Paciullo et al., 2011).

The systems evaluated in the present study were planted in 2008, aiming at recovering a degraded pasture. The 2 tree arrangements were designed to favor livestock production instead of forest production, following the majority of systems assembled at that time, with a short distance between the tree rows (Andrade et al., 2008; Devkota et al., 2009; Paciullo et al., 2011, 2008).

We hypothesize that herbage mass and animal growth rates are likely to decrease with time due to shading and other competitive effects in silvopastoral systems with eucalyptus trees, although in systems with lower eucalyptus tree density, BW gains per animal and per ha could be similar to those in a grass-only pasture as a result of improved forage nutritive value. Since the systems under study were in their 8th year since establishment, we measured pasture yield and quality plus animal performance at 2 densities of trees in comparison with a grass-only pasture.

4.2 Materials and Methods

4.2.1 Study site

Establishment of the experimental area was previously described in detail by Pereira et al. (2014). The experiment was carried out at Embrapa Beef Cattle, located in Campo Grande, Mato Grosso do Sul state, Brazil (20º27’ S, 54º37’ W; 530 masl), from June 2015 to May 2016. All procedures were approved by the Ethics and Animal Use Commission of Embrapa Beef Cattle under protocol no. 014/2014. According to the Köppen climate classification, climate of the experimental area falls in the transition between Cfa and humid tropical Aw, with average annual rainfall of 1,560 mm. The dry season occurs in the coldest months (May–September) and the rainy season in the hottest months (October–April). Air ambient temperature and precipitation data during the trial were collected from Embrapa Beef Cattle meteorological station, and along with mean rainfall data for the last 30 years for the Campo Grande region from the National Institute of Meteorology (A756 – INMET), are depicted in Figure 4.1.

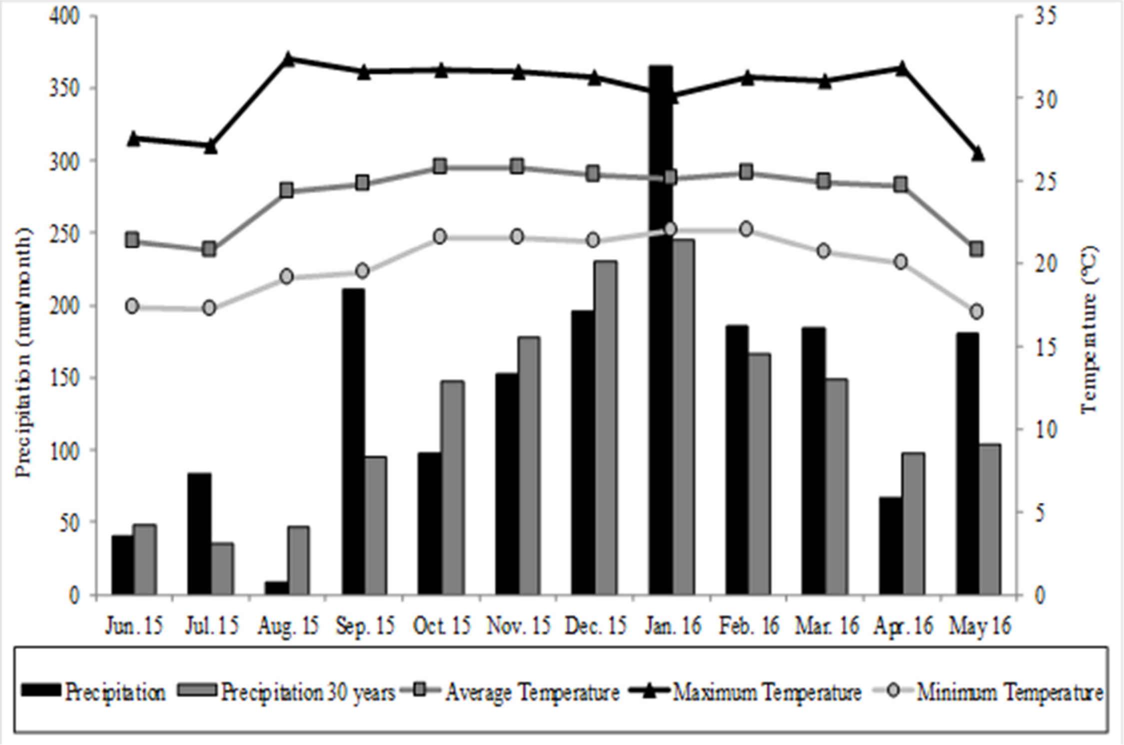

Figure 4.1: Maximum, average, and minimum air ambient temperatures and precipitation from June 2015 to May 2016, and mean rainfall data for the last 30 years for the Campo Grande region, Mato Grosso do Sul. Winter: June–August; spring: September–November; summer: December–February; autumn: March–May.

The soil at the experimental site was a Dystrophic Red Latosol, with clay texture, characterized by low pH, low base saturation and medium aluminum concentration. Mean values from soil chemical analyses performed in 2013 in the 0–20 cm deep layer showed that the area was relatively uniform, with clay contents of 41 ± 5%; P (Mehlich-1) 0.29–0.42 mg/dm3; base saturation 26–34%; and aluminum saturation 10–23%.

In August 2008, soil preparation was performed through a heavy disking, subsoiling and applications of 3,000 kg lime/ha, 1,000 kg gypsum/ha and 300 kg fertilizer/ha as N:P:K (5:25:15) broadcast over the pasture canopy, followed by leveling with disk harrows. The 18-ha experimental area was divided into 12 paddocks each of 1.4 ha with 4 paddocks (experimental units) for each system evaluated. Three systems were established: grass-only system without trees, representing the Control treatment (CON); and 2 silvopastoral systems with eucalyptus trees, i.e. SPS22 with an arrangement of 22 m spacing between tree rows × 2 m tree spacing within rows, totaling 227 eucalyptus trees/ha; and SPS14 with an arrangement of 14 × 2 m, totaling 357 eucalyptus trees/ha. Eucalyptus urograndis clone (E. urophylla × E. grandis) was planted in single lines oriented at –20.41° south and –54.71° west in relation to the east-west axis. All systems followed the same management, involving a crop rotation strategy every 4 years, i.e. cultivation of soybean as a crop for one year, followed by 3 years with solely Urochloa brizantha cv. BRS Piatã grass.

The present experiment was carried out in the third year after pasture establishment in the second rotation cycle. In January 2016, the pasture received maintenance fertilizer of 50 kg N/ha, in the form of urea, plus 300 kg N:P:K fertilizer/ha (0:20:20).

The eucalyptus trees had reached average heights of 27 and 25 m in the SPS14 and SPS22 systems, respectively. In order to characterize the level of luminosity reaching the Piatã grass canopy, the photosynthetically active radiation (PAR) was recorded at canopy height at 5 points in each SPS paddock, and at a point under full sun conditions immediately before and at the end of SPS recordings. All readings were taken in the morning and afternoon on one sunny day each month using a plant canopy analyzer (Accupar Ceptometer Model LP-80, Meter group Inc., Pullman, USA). Means of PAR were used to calculate the percentage of shading at grass canopy level in the SPS14 and SPS22 for each month, as a ratio between PAR reaching the canopy at the sampling points and PAR under full sun conditions at the corresponding measurement time.

The experimental design utilized was a randomized block (3 systems with 4 replications). The pastures were continuously grazed, with stocking rates (SR) intentionally varied over time to achieve predetermined pasture heights, according to Mott and Lucas (1952). For autumn and winter, height ranged from 30 to 35 cm, and for spring and summer from 35 to 40 cm.

4.2.2 Measurements of forage and animal parameters

A total of 80 Nellore (Bos indicus) heifers (initial mean body weight, BW = 290.8 ± 26.1 kg, ± SD) were randomly allocated to the paddocks and an extra area for SR management. Heifers had ad libitum access to water and a commercial mineral supplement, which was replenished weekly on the basis of 140 g/animal/d, and unrestricted and uninterrupted access to their particular pasture area. Animals were weighed every 28 days in the morning, on a weigh scale (MRG Campo, Toledo, São Bernardo do Campo, Brazil; precision of 0.5 kg), following a 16 h fast from feed but with access to water. All heifers were vaccinated according to the official health calendar and dewormed at the beginning of the experiment. Over-grazing of SPS14 paddocks occurred in winter and animals were removed on 23 June 2015 and were returned to the paddocks on 9 December 2015. A similar situation occurred on SPS22 in spring and stock were removed on 15 September 2015 and were returned on 9 December 2015.

Average daily BW gain (ADG) was calculated by dividing the difference between the initial and final BW of animals by the number of days between weighings. Monthly SR (animal unit, AU = 450 kg) was the product of average BW and the period for which the animals remained on the paddocks. Animal BW gain per hectare (AWG) was calculated by multiplying ADG by the number of animals per hectare per month.

Canopy height measurements were taken from ground level to the top surface of the pasture leaf canopy, using a 1-m rule graduated in cm, every 2 weeks at 50 random points per paddock. Forage sampling was performed every 28 days, along 2 transects sited at right angles between the tree rows; along each transect, samples were taken at 5 points defined as 1 m from the north tree row, 1 m from the south tree row, 6 m from the north tree row, 6 m from the south tree row, and at the central point between the tree rows, 11 m from each row, in SPS22 (Figure 4.2). For SPS14, sites were 1 m from the north tree row, 1 m from the south tree row, 3 m from the north tree row, 3 m from the south tree row, and at the central point between the tree rows, 7 m from each. In CON, the points were chosen at random. Ten samples per paddock were harvested at 0.4 m from ground level using a coastal harvester, within a metallic frame of 1 × 1 m. Conjointly, forage accumulation was measured using the exclusion cage technique, according to Davies (1993) and Stuth et al. (1981), by placing 5 cages of 1 × 1 m per paddock along the canopy height transects between the tree rows, following the same procedure as used for the sampling points described above. The exclusion cages were moved to a new location every 28 days, and comparable points were always harvested to simulate the growth of the pasture.

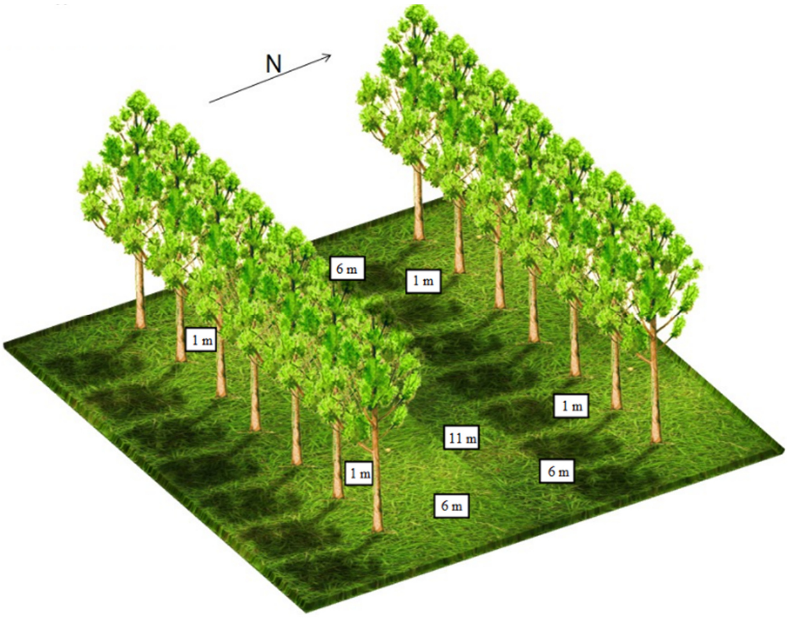

Figure 4.2: Schematic representation of forage sampling points along 2 transects sited at right angles to the eucalyptus rows in a silvopastoral system (SPS22: grass + 227 trees/ha). The distance separating each point from the trees rows is represented by the boxes. (Adapted from C.C. Oliveira et al. 2019).

All forage samples collected were individually weighed after harvesting. For each harvest, subsamples for each sampling point, for instance, along each transect, and from inside and outside the cages, were separately pooled and taken, put into paper bags, and dried in a forced-air oven at 65 ºC until constant mass for determination of dry matter (DM). Another subsample from each sampling point was selected and separated into its morphological components – leaf blade, stem with sheath and senescent material. Likewise, the morphological components were weighed and subsequently dried in a forced-air oven at 65 ºC for DM determination. Herbage mass (HM) was the average of measurements from all sampling points. The morphological component proportions were calculated as percentage of the total HM. Herbage accumulation rate (HAR) was the difference between the HM within the cages and outside the cages at previous harvest, i.e. when the cage was repositioned, divided by the days between samplings.

Canopy bulk density was calculated by dividing HM by canopy height at the sampling point where HM was measured. To determine herbage allowance (HAL, kg DM/100 kg BW), HM was summed up to the HAR, and divided by the SR transformed in kg BW in the area and season.

Dried leaf and stem samples were ground in a Wiley mill to pass a 1-mm screen. Crude protein (CP), neutral detergent fiber (NDF) and acid detergent fiber (ADF) concentrations and in vitro digestibility of organic matter (IVDOM) were assessed through the proximal infrared reflectance spectrophotometry system (NIRS) according to (Marten rt al., 1985). Forage nutritive value was measured monthly and means determined seasonally. However, it was not possible to assess the chemical composition in autumn.

4.2.3 Statistical analysis

Data were grouped by season as follows: winter, results for June to August 2015 inclusive; spring, for September to November 2015; summer, for December 2015 to February 2016; and autumn, for March to May 2016. Data were analyzed by PROC GLM procedure through SAS V9.4 program (SAS Institute Inc., Cary, NC, USA), with a model including effects of block, system, season and their interactions. Means were compared using LSMEANS by Tukey test, and considered different when $P<0.05$.

4.3 Results

The PAR levels reaching the sward in CON, SPS22 and SPS14 are depicted in Figure 4.3, which shows that the amount of light reaching the grass canopy was highest in spring and declined as tree density increased. Amount of incident light reaching the grass canopy in SPS14 in winter, summer and autumn was 16–22% of that in full sun, while in spring 44% of light penetrated the trees. In SPS22, 45–50% of light reached the pasture throughout the year.

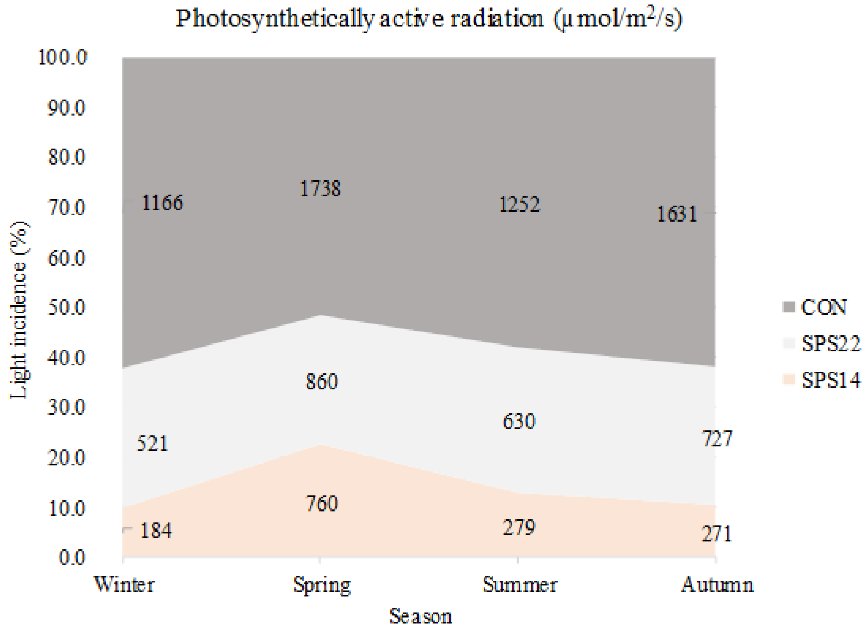

Figure 4.3: Light incidence reaching the sward in the silvopastoral systems (CON: grass-only, SPS22: grass + 227 trees/ha, SPS14: grass + 357 trees/ha), in the different seasons.

There was an interaction of system × season (P<0.01) for pasture canopy height, HM, leaf and stem proportion and leaf:stem ratio. Canopy height in CON was taller (P<0.001) than in SPS14 in winter, whereas in spring, when both SPSs were destocked, canopy height in CON was shorter (P<0.001) than in both systems with trees, SPS22 and SPS14 (Table 4.1). In CON, HM was greater (P<0.001) than in both systems with trees for all seasons (Table 4.1). However, HM did not differ (P>0.05) between the systems with trees, despite the amount of PAR reaching the canopy in SPS14 being little more than half of that in SPS22. During winter, summer and autumn, leaf proportion in available forage was similar (P>0.05) in all systems (Table 4.1). In spring, when the SPSs were destocked, leaf proportion in available forage was higher in SPS22 and SPS14 than in CON (P<0.001; Table 4.1). In all systems, leaf proportion in available forage in spring and summer was greater than in winter and autumn. Similarly, summer had the highest stem proportion in available forage for all systems (P<0.001). Leaf:stem ratio in available forage was highest in spring (P<0.001) for all systems. Differences between systems were inconsistent, with no differences observed between systems in winter and summer (P>0.05), while significant differences occurred in spring and autumn (P<0.001).

Table 4.1: Canopy height, herbage mass (HM), leaf proportion, stem proportion and leaf:stem ratio of Piatã grass in the systems CON, SPS22 and SPS14 during different seasons.

Season (S)	**System (T)**			**s.e.m.**	**P-value**	
	CON	**SPS22**	**SPS14**		**T**	**T × S**
Canopy height (cm)						
Winter	31Ba	25Bab	20Cb[1]	0.03	0.188	<0.001
Spring	36Bb	45Aa[1]	45Aa[1]			
Summer	46Aa	49Aa	45Aa			
Autumn	34Ba	27Ba	29Ba			
Herbage mass (kg DM/ha)						
Winter	2,466Ca	901Bb	626Bb[1]	306.5	<0.001	0.006
Spring	2,000Ca	1,032Bb[1]	642Bb[1]			
Summer	5,107Aa	2,772Ab	1,969Ab			
Autumn	3,370Ba	1,510Bb	908Bb			
Leaf proportion (g/100 g DM)						
Winter	17.4ABa	10.8Ba	14.2Ca[1]	4.64	<0.001	<0.001
Spring	28.2Ab	41.1Aa[1]	59.9Aa[1]			
Summer	28.4Aa	30.6Aa	31.8Ba			
Autumn	10.6Ba	13.3Ba	13.0Ca			
Stem proportion (g/100 g DM)						
Winter	17.4 Ba	7.3Bb	13.6BCa[1]	3.14	<0.001	<0.001
Spring	7.9Cb	10.7Bb[1]	22.9Ba[1]			
Summer	27.9Ac	36.5Ab	45.4Aa			
Autumn	18.8Ba	13.5Ba	14.4Ca			
Leaf:stem ratio						
Winter	1.1Ba	1.7Ba	1.2Ba[1]	0.34	0.003	0.006
Spring	3.8Aa	4.1Aa[1]	2.9Ab[1]			
Summer	1.1Ba	0.8Ba	0.7Ba			
Autumn	0.6Bb	1.2Ba	1.0Bab			

Means followed by the same upper-case letters within columns and parameters and lower-case letters within rows do not differ (P>0.05) by the Tukey test. CON: grass-only, SPS22: grass + 227 trees/ha, SPS14: grass + 357 trees/ha. [1]Pastures destocked.

Regarding forage nutritive value of leaf and stem, CP, NDF, ADF and IVDOM were affected (P<0.01) by a system × season interaction. Leaf CP varied from 84 to 145 g/kg DM across systems and seasons, with SPS14 and SPS22 having higher leaf CP than CON (P<0.001; Table 4.2). Leaf CP was generally higher in winter than in summer. Similarly, stem CP ranged from 45 to 104 g/kg DM with higher values for SPS14 and SPS22 than for CON (P<0.001) and higher values in spring than in winter and summer (P<0.001). On the contrary, fiber concentrations in both leaf and stem were sometimes higher for CON than for systems with trees. For leaf NDF, no differences between seasons were found for CON or SPS22, whereas leaf NDF was higher in winter than in spring and summer for SPS14. The effects of season on stem NDF were variable across systems. Similarly, leaf ADF followed variable and inconsistent patterns. Leaf IVDOM ranged from 579 to 757 g/kg DM. In general, the highest leaf IVDOM was observed in SPS14, where it was higher in spring than in winter and summer. In contrast, leaf IVDOM in CON and SPS22 was lower in summer than in winter and spring. Stem IVDOM ranged from 464 to 659 g/kg DM, and the superiority of systems with trees over CON was observed only in spring (P<0.01).

Table 4.2: Nutritive value of Piatã grass in grass and grass-tree systems during the different seasons.

	System (T)			**s.e.m.**	**P-value**	
Season (S)	**CON**	**SPS22**	**SPS14**		**T**	**T × S**
		Leaf				
		Crude protein (g/kg DM)				
Winter	110Ab	132Aa	137Aa[1]	0.38	<0.001	0.001
Spring	97ABc	123ABb[1]	145Aa[1]			
Summer	84Bb	118Ba	131Aa			
		NDF (g/kg DM)				
Winter	686Aa	682Aa	687Aa[1]	1.01	<0.001	0.004
Spring	693Aa	689Aa[1]	651Bb[1]			
Summer	697Aa	676Ab	642Bc			
		ADF (g/kg DM)				
Winter	306Ba	292Ba	306Aa[1]	0.6	0.007	0.001
Spring	313ABab	321Aba[1]	290Ab[1]			
Summer	339Aa	323Ab	309Ab			
		IVDOM (g/kg DM)				
Winter	642Ab	682Aab	696Ba[1]	2.26	<0.001	0.004
Spring	629Ac	699Ab[1]	757Aa[1]			
Summer	579Bc	625Bb	684Ba			
		Stem				
		Crude protein (g/kg DM)				
Winter	48Bb	60Ba	67Ba[1]	0.26	<0.001	<0.001
Spring	63Ab	96Aa[1]	104Aa[1]			
Summer	45Bc	55Bb	65Ba			
		NDF (g/kg DM)				
Winter	766Aa	771Aa	767Aa[1]	0.7	<0.001	0.004
Spring	758Aa	729Bb[1]	714Bb[1]			
Summer	771Aa	775Aa	743Ab			
		IVDOM (g/kg DM)				
Winter	478Ba	489Ba	485Ba[1]	2.91	0.002	0.001
Spring	557Ab	618Aa[1]	659Aa[1]			
Summer	490Ba	464Ba	493Ba			

Means followed by the same upper-case letter within columns and parameters and lower-case letters within rows do not differ (P>0.05) by the Tukey test. CON: grass only, SPS22: grass + 227 trees/ha, SPS14: grass + 357 trees/ha. 1Pastures destocked.

There was significant interaction between systems × seasons for canopy density and HAR ($P<0.05$). In all seasons, CON had denser canopy than SPS22 and SPS14 ($P<0.05$; Table 4.3). In general, canopy density was higher in summer and autumn than in winter and spring. The HAR in winter and spring did not differ between systems ($P>0.05$), whereas in summer and autumn, pasture in CON grew faster than in SPS22 and SPS14 ($P<0.01$; Table 4.3). Overall, Piatã grass grew faster in spring than in other seasons ($P<0.001$). No differences between systems were observed for HAL. However, when comparing seasons, HAL in summer was greater than in winter and autumn.

Table 4.3: Canopy bulk density, herbage accumulation rate (HAR) and herbage allowance (HAL) in the systems CON, SPS22 and SPS14 for different seasons.

Season (S)	**System (T)**			**s.e.m.**	**P-value**	
	CON	**SPS22**	**SPS14**		**T**	**T × S**
Canopy density (kg DM/m^3)						
Winter	0.52Ba	0.23Cb	0.20ABb[1]	0.02	<0.001	0.032
Spring	0.60Ba	0.28BCb[1]	0.14Bb[1]			
Summer	1.12Aa	0.56Ab	0.42Ab			
Autumn	1.00Aa	0.51ABb	0.35ABb			
HAR (kg DM/ha/d)						
Winter	6.9Ba	-15.8Ba	-11.0Ba	0.92	<0.001	0.01
Spring	51.7Aa	48.4Aa	33.4Aa			
Summer	63.1Aa	16.8Bb	3.9Bb			
Autumn	62.8Aa	13.9Bb	-1.4Bb			
HAL (kg DM/100 kg BW/d)						
Winter	4.49Ca	2.23Ba	D[1]	0.99	<0.001	0.22
Spring	8.64AB	D	D			
Summer	11.22Aa	7.94Aa	8.25Aa			
Autumn	4.85BCa	3.93Ba	1.19Ba			

Means followed by the same upper-case letter within columns and parameters and lower-case letters within rows do not differ ($P>0.05$) by the Tukey test. CON: grass only, SPS22: grass + 227 trees/ha, SPS14: grass + 357 trees/ha. 1SPS14 was destocked in winter and spring and SPS22 was destocked in spring.

Overall, SR in CON was greater than in SPS22 and SPS14 (Table 4.4). As previously mentioned, destocking of both systems containing trees occurred during the winter-spring period. The systems showed similar ADG. Nevertheless, as a result of superior SR, CON had higher AWG than SPS22 and SPS14, except for during summer, when gains on SPS22 were similar to those on CON.

Table 4.4: Stocking rate (SR), average daily BW gain (ADG) and animal BW gain per hectare (AWG) in the systems CON, SPS22 and SPS14 during different seasons.

Season (S)	**System (T)**			**s.e.m.**	**P-value**	
	CON	**SPS22**	**SPS14**		**T**	**T × S**
		SR (AU/ha)		0.3	<0.001	0.09
Winter	1.3Aa	0.7Aa	D^1			
Spring	1.1A	D	D			
Summer	2.6Aa	2.4Aab	1.5Ab			
Autumn	2.6Aa	1.2Ab	0.9Ab			
		ADG (kg BW/animal/d)				
Winter	0.160Ba	0.058Ba	D	0.13	<0.001	<0.001
Spring	0.525A	D	D			
Summer	0.588Aa	0.783Aa	0.648Aa			
Autumn	0.373ABa	0.238Ba	0.435Aa			
		AWG (kg BW/ha)				
Winter	17Ba	3Ba	D	19.78	<0.001	<0.001
Spring	54Ba	D	D			
Summer	169Aa	186Aa	93Ab			
Autumn	136Aa	39Bb	25Bb			

Means followed by the same upper-case letter within columns and parameters and lower-case letters within rows do not differ (P>0.05) by the Tukey test. AU = 450 kg BW. CON: grass only, SPS22: grass + 227 trees/ha, SPS14: grass + 357 trees/ha. D = destocked.

4.4 Discussion

This study has shown the huge impact of established eucalyptus trees on pasture growth in a silvopastoral system. During summer and autumn, when pastures in full sunlight (CON) grew at 63 kg DM/ha/d, those in SPSs grew at 15 (SPS22) and 1 (SPS14) kg DM/ha/d. Reductions in growth of this magnitude must raise the issue of the suitability of eucalyptus for planting in these silvopastoral systems. Not only do they produce shade but also have a well-developed root system which competes strongly for moisture (Ferraz et al., 2019; Mattos et al., 2019) and nutrients in the soil.

The systems with trees, SPS22 and SPS14, are likely to be more negatively affected by the winter season than CON. During water stress conditions, as in the winter, plants cannot compensate for the limited PAR by triggering mechanisms to increase radiation use efficiency. Leaf stomata must open to allow carbon dioxide diffusion into the leaf to utilize PAR. However, during water shortage, leaf stomata close or partially close to reduce water loss, which hampers carbon dioxide uptake (Feldhake, 2009). This would result in negative HAR for SPS22 and SPS14 in winter, low canopy height, HM, leaf and stem proportions, canopy density and consequently limited animal production. During this season, only a few heifers continued to graze in SPS22 due to the canopy height, even though canopy height might not be an appropriate criterion for determining when to graze SPSs.

Canopy height is a grazing management target applied in grazing systems in the tropics, as it is highly correlated with HM (Martuscello et al., 2009; Pontes et al., 2016). Nantes et al. (2013) and Euclides et al. (2016) recommended a canopy height within the range 15–45 cm for Piatã grass under continuous stocking in full sun. Our findings suggest that canopy height is not an appropriate criterion for grazing management in shaded environments, because of large oscillations in the amounts of available biomass despite having a similar height, as a result of different structure of pasture in shade. Pontes et al. (2016) also reported an over-grazing condition in cool-season pastures under trees, showing low HM under >50% shade, when the systems were managed using a canopy height target defined for full-sun conditions.

It has been reported that shading imposed on forage grasses increases canopy height by stem and leaf elongation and leaf length enlargement, as a mechanism to improve light capture by the plant. The higher stem proportion in SPS14 during spring and summer, where incident light was severely restricted, supports this hypothesis. In contrast, tiller density declines at low radiation, which in turn decreases available HM (Baldissera et al., 2016; Castro et al., 2009; Gastal and Lemaire, 2015).

Even though SPS22 and SPS14 had a taller pasture canopy than CON in the spring, their low HM (1,032 and 642 kg DM/ha for SPS22 and SPS14, respectively) was insufficient to support animals grazing during this season. Hodgson (1990) indicated a minimum HM of 2,000 kg DM/ha to avoid restricting forage intake. Critically, HM in SPS22 surpassed this threshold only in summer, whereas SPS14 barely achieved it in summer, regardless of the absence of animals in winter and spring. Animals were returned to SPS14 in summer based on HAL of 8 kg DM/100 kg BW, as a result of the onset of rains in September coupled with an increase in PAR and the absence of animals in spring.

The HAR in CON in the winter is in good agreement with 6.0 kg DM/ha/d of Piatã grass growing in a full-sun condition, reported by Euclides et al. (2016) in the dry season, which occurs in winter. Subsequently, rainfall in September boosted HAR in spring for all systems, and HAR in CON closely matched the 64.1 kg DM/ha/d reported by Euclides et al. (2016) and the 64.5 kg DM/ha/d by Santos et al. (2016) during the rainy season. Rather than grouping data by winter, spring, summer and autumn, those authors grouped their data according to rainy and dry seasons. Santos et al. (2016) also evaluated HAR of Piatã grass in systems with eucalyptus trees. Despite having low values ranging from 20.0 to 31.1 kg DM/ha/d in the rainy season and 7.3 to 10.0 kg DM/ha/d in the dry season, the HAR was not negative as found in our study. Those authors affirmed that PAR declined by approximately 22 and 40% for their systems with lower and higher tree density, respectively, whereas PAR in our study declined on average by 53 and 75% for SPS22 and SPS14, respectively. Additionally, minimum air temperature from May to July reached 17 °C, the threshold for the growth of the pasture, as the temperature base for Brachiaria brizantha is 17.2 °C, the temperature at which HAR is zero (Cruz et al., 2011).

The HAR in SPS22 and SPS14 in summer declined dramatically, whereas in CON it increased by about 25%. Competition for nutrients and incident radiation by trees obviously prevented grass from accumulating forage at a greater rate, highlighting the effects of radiation on the growth of tropical grasses of C4 metabolism (Taiz and Zeiger, 2010).

The PAR in summer for all systems was considerably lower than in spring, with levels in SPS14 being quite low. Since PAR declined dramatically in the CON system as well as SPSs, cloud cover may have contributed to reduced levels of incident light overall, and change in sun position relative to the configuration of the trees possibly had a significant impact on the amount of light reaching the grass canopy in the SPSs.

Regardless of the lack of statistical differences for HM and HAR between SPS22 and SPS14 throughout the study, SPS22 constantly showed higher absolute values than SPS14, which ensured animals were retained in SPS22 during winter.

A morphological change influenced by shading is leaf elongation, which in turn increases leaf proportion (Baldissera et al., 2016). However, the general preference for leaves by animals could limit leaf accumulation in the forage canopy of the systems with trees. Due to low HM in both SPS22 and SPS14, removal of leaves by the animals would be expected to be more pronounced in those systems than in CON, despite the fact that HALs on all systems showed no significant difference. The only period when SPS22 and SPS14 had higher leaf proportion than CON was in spring, when the systems with trees were destocked. Animals preferentially select leaf when grazing forage, resulting in increased animal performance due to its highest nutrient concentrations (Geremia et al., 2018).

As expected, forage nutritive value in SPSs was superior to that in CON, mainly with regard to higher CP in shaded environments (Lima et al., 2019; Paciullo et al., 2017). Even though reports in the literature for effects of shading on NDF, ADF and IVDOM are inconsistent, several authors have recorded reductions in NDF (Lima et al., 2019; Paciullo et al., 2017, 2008) and ADF (Lima et al., 2019) in shade, which was attributed to higher numbers of sclerenchyma cells and thicker secondary walls under greater light incidence (Deinum et al., 1996; Kephart and Buxton, 1993). A delay in morphological maturation within shaded environments compared with full sun conditions has also been claimed (Neel et al., 2016).

Despite the lower HM and higher stem proportion in SPS22 and SPS14, ADGs of animals in all systems were similar during summer and autumn, when HAL in all systems was similar. Systems with trees also had a higher forage nutritive value in summer than the grass-only system. However, as a consequence of lower SR in SPS14, its AWG was lower than that in CON and SPS22. Likewise, SPS22 provided lower AWG than CON in autumn due to a drop in SR.

Studies carried out in the area in previous years allowed grazing in all the systems during the whole experimental period (Gamarra et al., 2017; C.C. Oliveira et al., 2014). Moreover, in the third year after pasture establishment for the first rotation cycle (2011-2012), CON produced 537 kg BW/ha/yr, SPS22 459 kg BW/ha/yr and SPS14 334 kg BW/ha/yr (C.C. Oliveira et al., 2014). In the corresponding period of the second cycle in our study (2015-2016), BW production was appreciably lower, i.e. 376 kg BW/ha/yr, 228 kg BW/ha/yr and 118 kg BW/ha/yr in CON, SPS22 and SPS14, respectively. While a range of factors could have contributed to this reduction in animal production, continuous tree growth could have had an important impact, especially in the SPS. Eucalyptus trees may have a root system which spreads out a horizontal distance about 20 m from the trunk of individual trees (Zohar, 1985). Tree root zone as a sink removes water arriving at the soil surface within the radius of its root zone, influencing the soil water movement and availability (Bosi et al., 2019; Stirzaker et al., 1999). Since these trees were 8 years old and were 25–27 m tall at the commencement of the study, and plot size was 1.4 ha, competition for water and nutrients in the grass-only pasture from adjacent trees cannot be dismissed. Eucalypts are very competitive with underlying pasture, and it is important that the changes in the degree of competition with underlying crops and pastures be monitored throughout the whole tree growing cycle, as proposed by Gomes et al. (2019).

For CON, the decline in animal production in the second cycle could reasonably be attributed to stocking management C.C. Oliveira et al. (2014) observed higher AWG and SR in short swards managed at 27 ± 4.6 cm, whereas in the current study, the sward height of CON ranged from 31 to 46 cm across the seasons. Our results for winter and spring differed only slightly from those reported by C.C. Oliveira et al. (2014), the seasons where the authors found no differences for AWG according to the height managed. It seems that CON could be grazed at different heights from SPSs. We conclude that pasture height should not be the sole criterion on which appropriate stocking rate for grazing pastures under trees is assessed. Further studies are warranted to determine a more appropriate criterion for deciding when and how to graze these pastures.

4.5 Conclusions

In Silvopastoral systems with eucalyptus trees like those studied are unable to support both forage and animal production equivalent to a straight grass pasture by the 8th year after establishment. Further studies are needed to determine appropriate management of the trees to reduce competition for the pasture. One might question the suitability of eucalypts for these silvopastoral systems because of their high levels of competition for water, light and nutrients. Pruning and thinning of the trees have been implemented in an endeavor to reduce competition and these practices have been recommended in the literature (Lima et al., 2019; Pezzopane et al., 2020, 2015; Santos et al., 2016) to reduce radiation interception starting from the 6th to 8th year after establishment. However, eucalyptus trees retain a competitive advantage over pasture even after thinning and tree stands recover rapidly and increase their competition with pasture (Back et al., 2009). Studies to evaluate those interactions between pasture and trees seem warranted.

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5 General Discussion

As the integrated-crop-livestock-forestry (ICLF) system is currently promoted as a measure for sustainable intensification and a strategy of adapting agriculture to climate change, a detailed understanding of the productivity of the system and its limitations is required. Introduction of trees to the traditional pasture system results in microclimatic changes as the pasture becomes at least partially shaded. Further, transpiration and thus water uptake of trees differ substantially from that of grasses potentially leading to changes in soil moisture. As both, radiation received by the canopy and soil moisture, have large implications on plant growth, they can affect the productivity of the system. The productivity of the system can be measured as grass biomass production. However, since the grass is used as a pasture, forage and animal performance are further parameters of relevance to assess the system's productivity. In the previous chapters, the effects of the introduction of trees on microclimate, soil moisture and productivity were assessed on two different levels. As the trees are planted in lines, spatial heterogeneity of the measured parameters within the ICLF system was assessed. Further, comparisons with other land use systems, such as the traditional pasture (COP), a natural Cerrado vegetation (CER) or another integrated system without trees, the integrated-crop-livestock (ICL) system, were drawn to assess the productivity of the ICLF system on the one hand, but also gain information on its sustainability, since this is claimed by the supporters of the system.

5.1 ICLF and microclimate

The main interaction between ICLF systems and the environment is related to the microclimatic parameters, such as radiation, wind speed, temperature, and relative air humidity. The establishment of these systems cause changes in the microclimate which can reflect positively and negatively on plant and animal productivity (Benavides et al., 2008). The microclimate within an ICLF system mainly depend on the design of the system (arrangement, orientation, characteristics, and density of the trees), the tree age of the system, species composition and all these factors interact at macro- and meso-scale (Bosi et al., 2020; Pezzopane et al., 2020).

One of the main impacts is shade, caused by the trees in these systems. The trees decrease the amount of radiation received by the grass canopy depending on season and distance to the trees (Glatzle et al., 2021). The shade caused by the trees not just affects the quantity of the radiation received by the grass canopy but also the light quality. While in the PAR range (400 – 700 nm), plants absorb radiation of most of the wavelengths, they are translucent to the near infrared radiation (slightly longer as 700 nm). Radiation filtered through the tree canopies is enriched in the near infrared relative to the red (slightly shorter as 700 nm) range of the radiation and the red/far-red ratio has been correlated to the plant responses to shading (Feldhake, 2001). The reduction in radiation also depends on the tree height and the tree spacings, with spacing of more than 20 m between the tree rows, being beneficial for the radiation received in the center between the tree rows (Rodrigues et al., 2014). Bosi et al. (2020) observed a significant increase in size of the shaded area when the trees reached a height of around 25 m. Furthermore, time of day and time of year also impacts the radiation received at grass canopy level, due to the inclination of the sun. Several studies including ours observed a reduction of radiation next to the trees during spring and summer compared to the center, whereas during autumn and winter the radiation received by the grass canopy was less and more evenly distributed between the tree rows (Pezzopane et al., 2015; Rodrigues et al., 2014; Santos et al., 2016).

ICLF systems are known to reduce excessive wind speed and strong gusts, which have been linked to physical damage to the vegetation (Tamang et al., 2010) and stress for the grazing cattle (Mader et al., 1997). Bosi et al. (2020) observed consistently lower wind speed within an ICLF system with a similar Eucalyptus tree arrangement as in our study. The reduction of wind speed was mainly observed during the daytime, especially in the morning when the increasing air temperature caused air movement.

The effects of the trees in ICLF systems on air temperature and relative air humidity likewise depend on the arrangement and the specific structure of the tree species used. In the study of Bosi et al. (2020) no differences in air temperature and relative air humidity was found among the measurement points between the tree rows, which the authors related to the arrangement of the trees and the tree species leading to a high canopy porosity and thus, sufficient air movement to overpower potential differences. On the other hand, Karki and Goodman (2015) found lower air temperatures in a silvopastoral system with mature loblolly pine compared to the open field. Likewise, Pezzopane et al. (2015) reported higher air temperature and lower relative air humidity near the tree rows compared to the center or the open field in a silvopastoral system with North-to-South oriented rows of native trees.

Related to its effects on microclimate, ICLF systems have the potential to improve the resilience of agricultural production to climate change (Montagnini et al., 2013). As in many regions of the world, temperature will significantly increase, while rainfall is predicted to decrease (IPCC, 2013), protection from solar radiation, provided by the trees in ICLF systems, may mitigate negative effects of reduced rainfall and cloud cover. Further, reductions in radiation and wind speed related to the trees can reduce the evapotranspiration of the understory vegetation, contributing to soil water conservation in the system.

5.2 ICLF and soil moisture

Soil moisture dynamics are a major indicator of ecological processes, however, for ICLF systems, they have not been consistently analyzed in literature, and continuous observations of seasonal soil moisture dynamics are lacking. Since in complex ecosystems, soil moisture is influenced by several factors, such as weather (rainfall, radiation, wind speed, temperature, relative air humidity), arrangement of the components (e.g. arrangement and density of the trees) and biomass productivity, these factors need to be considered to comprehensively understand the interlinked processes. This is further complicated by variable managements.

Soil moisture changes in ICLF systems in the Cerrado biome are highly seasonal with high soil moisture in the rainy season and relatively low soil moisture in the dry season in response to the rainfall regime of the area. Intra-annual changes in soil moisture for the points between the tree rows are similar but on different levels. Due to greater AGBM (Santos et al., 2016) and higher radiation (Rodrigues et al., 2014), potential soil moisture loss by transpiration from the grass canopy is higher in the center of the tree rows. However, in all seasons, generally higher SM is found in the center between the tree rows compared to points near the tree rows. Forage grasses gown under shade can increase specific leaf area, leaf elongation rate and leaf length to increase PAR interception (Paciullo et al., 2011, 2007), resulting in an increased leaf area, despite lower grass BM. Nevertheless, it is rather unlikely that the lower SM close to the tress, is a result of higher transpiration of the grass next to the trees. More likely, the lower soil moisture next to the trees is related to the water uptake by the tree roots and caused by their greater exploitation , also at greater depths (Pezzopane et al., 2015). Eucalyptus, which is often used as tree component in ICLF systems in Brazil, is a C3 species and has a lower water use efficiency than the C4 grass species Brachiaria (Way et al., 2014). Despite Eucalyptus tree roots can grow beyond 3 m depth within one year, the fine root density declines drastically with depth (Laclau et al., 2001), and the large share of fine roots in the topsoil has been used to explain the depletion of soil moisture also in the upper soil layer near the trees (Bouillet et al., 2002). Lower soil moisture near the trees was not just found in ICLF systems with Eucalyptus (Bosi et al., 2019; Glatzle et al., 2021), but also in silvopastoral systems with Brazilian native trees (Pezzopane et al., 2015) and loblolly pine (Tian et al., 2017). In our study, greater soil moisture removal near the trees than in the center between the tree rows during a drying event, was mostly attributed to the effects of the tree roots. During the dry season, SM in the topsoil near the trees could reach PWP leading to water stress conditions for the grass and therefore, negative effects on its biomass. However, soil moisture recharge during the rainy season was found to be generally higher close to the trees, which has been explained by the improved soil structure and porosity related to the tree roots (Strudley et al., 2008), which can increase water infiltration and decrease runoff, and by the rain interception by the tree canopy and the subsequent deposition of water to the soil next to the trees (Bosi et al., 2019).

The land use change from a complex wood/grass ecosystem like the Cerrado Savannah or an ICLF system to a shallow rooting grass and crop culture or vice versa is likely to change the hydrological cycle (Klink and Moreira, 2002) and with this, the soil moisture dynamics. In our study, the ICLF system had a generally lower SM than the ICL system or the continuously grazed pasture, which has been related to the presence of trees, but also to differences in root distribution. Due to the different rooting patterns, trees and shrubs often access deeper soil layers resulting in increased water uptake and transpiration (R.S. Oliveira et al., 2005). But not only the presence or absence of trees affects the SM. The comparison of the seasonal and spatial soil moisture dynamics in an ICLF system and a natural Cerrado vegetation in our study showed higher soil moisture in the topsoil of the ICLF throughout the year, while in the subsoil up to 1 m depth, soil moisture was lower in the ICLF than in the Cerrado. A likely reason for the lower SM of the subsoil in the ICLF is a higher water uptake of the Eucalyptus trees in this soil layer, while the natural Cerrado vegetation with its deep root system probably takes up water from deeper soil layers. However, as the difference in soil moisture in the subsoil up to 1 m depth between the ICLF and the Cerrado was minimized during the dry season, we hypothesized that also Eucalyptus trees shift their water uptake to deeper soil layers in periods of water deficit. However, by increasing evapotranspiration, Eucalyptus, or other trees in ICLF systems, respectively directly compensate for the reduced water recycling to the atmosphere as reported from land use systems without tress, established on previous Cerrado areas (P.T.S. Oliveira et al. 2014a, Spera et al. 2016). From this perspective integrated systems including trees are more similar to the natural Cerrado than pastures and other integrated systems. In view of the potentially serious consequences caused by altered water cycles via land use change, ICLF systems should be considered as an additional option to mitigate previous land use change effects in a context of sustainable intensification.

Further, difference in soil characteristics between land use systems were found in our study. As the sites of the studied land use types were located in close vicinity, differences in soil characteristics most probably represent long-term effects of the management regime. The water retention curves of ICL and ICLF systems showed higher SM at the same water potentials compared to degraded continues pasture indicating the potential of integrated systems (ICL and ICLF) to mitigate the effect of soil compaction in pasture systems and thus, to restore degraded sites due to lower soil movement, the formation of biopores and input of SOC (He et al. 2011; Strudley et al. 2008). The potential of ICLF systems to improve the soil physical quality was also described by Moreira et al. (2018) and Assis et al. (2015), who found improved soil physical quality in ICLF and ICL systems compared to degraded pastures in the Cerrado biome.

5.3 ICLF and productivity

In ICLF systems, intra-annual variation of the grass BM is related to seasonal climate variability, to development related growth and senescence processes of the grass and to the interaction of both, as canopy growth and senescence depend on temperature, daylength, radiation and rainfall (Pedreira et al., 2011). During the cool dry winter period, canopy senescence is faster than canopy renewal, while grass AGBM is generally higher in the rainy season than in the dry season (C.C. Oliveira et al., 2014; Paciullo et al., 2009; Santos et al., 2016). Year-round, the highest AGBM is found in the center between the tree rows, with a decreasing trend towards the tress. Most tropical grasses decrease AGBM under shading almost proportionally to the amount of shade (Wilson and Wild, 1991). Lower grass BM as a result of lower radiation under and next to the trees compared to the center points has been reported for silvopastoral systems by serval authors (Santos et al., 2016; Sarath et al., 2014; Wilson and Wild, 1991). However, during autumn and winter, when radiation is generally lower than during spring and summer, the distribution of the radiation between the tree rows is more uniform (Bosi et al., 2020). Along a transect between the tree rows, strong positive correlation between grass BM and radiation has been found in ICLF systems during spring and summer (Santos et al., 2016; Silva-Pando et al., 2002), while during winter, a positive correlation was found between grass BM and SM in our study, indicating that grass productivity is shifting from light limitation during the rainy season to a water limitation during the dry season. However, the low productivity of the pasture in ICLF systems in winter is not only attributed to the water deficit, but also to the generally lower radiation and the phenology of the grass.

The establishment of trees in ICLF systems has a huge impact on the grass productivity and consequently, on animal production. In our study, which was conducted in the 8th year after tree establishment, lower grass biomass was found in the ICLF system than in the grass-only pasture, but forage nutritive values as reflected in higher crude protein (CP) values, higher digestibility and increased neutral and acid detergent fiber concentrations were observed in the ICLF system. Therefore, despite the lower grass biomass in the ICLF system, average daily body weight gain (ADG) of the cattle was similar in the different systems during the rainy season, which was most likely a result of the increased CP value of the shaded pasture. However, during the dry season, low forage productivity did not allow for animal production. However, on the same experimental site, similar parameters were investigated in the 4th year after tree establishment, when the trees were smaller and caused less shading to the pasture. By then, similar ADG was observed for the ICLF and the open pasture year-round and it was concluded that ICLF systems with intermediate tree density are a good alternative for farmers willing to diversify their revenue without decreasing animal production (C.C. Oliveira et al., 2014). Therefore, the impact of the trees on the productivity of the pasture not only depends on their arrangement, but it also changes over time from tree establishment until harvest. Similar results were found in two successive studies in an ICLF system in Southeastern Brazil. In the 6th year after establishment, the ICLF showed the same forage biomass as the open pasture and ADG of the cattle was improved in the ICLF system, because of higher CP value of the forage (Paciullo et al., 2009). However, in the 17th and 18th year after establishment, the ICLF provided better thermal comfort and higher CP to the animals, but severe shading reduced forage BM, which negatively influenced average daily body weight gain (ADG) of the cattle (Lima et al., 2019). Thus, assessments of ICLF systems at a given point of time need to be treated with caution, and for an evaluation of the potential and productivity of the entire system, life cycle assessments are needed. A better understanding of the changes in productivity of each component of the system over time would therefore allow for the assessment and development of management interventions to assure the productive, economic, and sustainable stability of the system (Lima et al., 2019).

6 Concluding Remarks and Final Recommendations

The radiation distribution within an ICLF system is highly seasonal with the largest reductions being observed next to the trees during spring and summer. Further, radiation received by the grass canopy largely depends on the distance of the tree rows and the age of the system. Potential options to maintain a high productivity of the pasture, are either a large spacing between the tree rows, thinning, pruning or harvest at an early stage / low height of the trees.

Throughout the year, SM up to 1 m depth was lower closer to the tree rows within the ICLF system, due to increased water uptake by the tree roots. Critical values, where SM reached the PWP, were observed in the topsoil during winter (dry season), which limited grass productivity during winter and thus, year-round grazing in ICLF systems. Pruning of the trees during autumn could be an option to reduce transpirational water loss during the critical period and therefore, preserve plant-available water in the soil that is sufficient to maintain grass growth. To maintain grass productivity in ICLF systems during winter, management measures focusing on water conservation during the dry season need further research.

Our observations in the 8th and 9th year after establishment of the ICLF system, demonstrated that at this stage, the system was unable to support both, forage and animal production, equivalent to a grass only pasture, due to the high impact of the Eucalyptus trees on radiation and soil moisture, especially in winter. Long term evaluations of ICLF systems regarding microclimate, soil moisture dynamics, and forage production are needed for the entire life cycle of the system to better understand its potentials and constraints to productivity. Further, research is needed on management interventions to stabilize forage production not only year-round, but also improve the system’s resilience to drought spells and the potentially increasing evapotranspiration resulting from future temperature increases related to climate change.

However, in the integrated systems (ICLF and ICL) more grass biomass was produced compared to COP. These differences were rather associated with soil characteristics, such as lower BD and higher SOC in the integrated systems than with SM availability, demonstrating the positive impact of integrated systems on soil quality and pasture productivity in comparison to traditional systems.

Related to the higher transpiration of the trees and differences in root distribution and rooting depth, SM was generally lower in the ICLF system than in the land use systems without trees (COP and ICL). In CER, SM in the topsoil was lower than in ICLF throughout the year, while in the subsoil up to 1 m depth, SM was higher than in the ICLF, which was much more pronounced during the wet season. We hypothesized that in comparison to CER, Eucalyptus trees take up more water in the subsoil up to 1 m and shift their water uptake to greater depth at a later stage during periods of low water availability. Therefore, future SM monitoring should be conducted beyond 1 m in ICLF systems and CER. The establishment of integrated systems with a tree component may counterbalance reduced evapotranspiration after Cerrado deforestation and thus helps to restore natural ecosystem functions with regard to water recycling into the atmosphere. Nevertheless, before introducing (Eucalyptus) trees to a system, local conditions regarding rainfall patterns and soil physical properties need to be considered as water depletion by the trees in the upper 1 m of the soil poses a risk to the productivity of pasture. Further research in high spatial and temporal resolution is needed to explore the effect of Eucalyptus trees on SM in greater depth. Furthermore, studies on water-related functions and processes of ICLF systems would help to fully develop the promising land use potentials of these systems to improve sustainability of agricultural production.

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