Universidade de Brasília
Faculdade UnB Planaltina
Programa de Pós-graduação em Ciências Ambientais (PPGCA)

Microclima e Propriedades Físicas do Solo em um Sistema Agroflorestal Sintrópico

Sabrina Mendes Pereira

Tese de doutorado

Planaltina-DF 2024

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Orientador: Dr. Luiz Felippe Salemi

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“Nada é impossível de
mudar

Desconfiai do mais
trivial, na aparência
singelo.
E examinai,
sobretudo, o que
parece habitual.
Suplicamos
expressamente: não
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tempo de desordem
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de arbitrariedade
consciente, de
humanidade
desumanizada, nada
deve parecer natural,
nada deve parecer
impossível de
mudar.”.
Bertold Brecht

Dedico à minha avó Maria, minha mãe Serley e aos meus filhos Henrique e Mathyas.

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Agradeço a minha família, em especial as mulheres da minha família e meus filhos, por vocês cheguei um pouquinho mais longe. Ao meu companheiro de vida Lucas, sempre foi o grande incentivador nos meus momentos de maior insegurança.

Os últimos anos foram de grandes desafios, esse doutorado se iniciou e se fez na pandemia, um momento devastador na vida de muitas famílias. Aconteceram muitos rompimentos na minha vida e tive que recomeçar muitas vezes, registro aqui e digo: “siga em frente sempre, porque tudo passa e tudo se ajeita”.

“... E há de nascer, um novo amanhã, pra gente acordar e dançar…” (Gilsons)

Aproveito para registrar para posteridade um recado para “meus meninos”, minha maior herança e exemplo é a educação como um caminho de transformação.

RESUMO DA TESE

Os sistemas agroflorestais sintrópicos (SAS) são sistemas agrícolas concebidos para conciliar a produção agrícola com a conservação ambiental. Uma forma possível de tornar os sistemas agrícolas mais sustentáveis é imitar os ecossistemas naturais. Neste sentido, os sistemas agroflorestais sintrópicos são agroecossistemas que imitam, até certo ponto, a estrutura e a dinâmica natural das florestas. Nesta tese buscamos responder a duas perguntas, são elas: a infiltração da água e a penetração do solo são semelhantes nas linhas e entrelinhas do SAS? b) o microclima de um SAS é semelhante ao microclima de uma floresta tropical? Tais perguntas foram organizadas em dois capítulos sistematizados em formato de artigo científico. No primeiro capítulo, o objetivo foi caracterizar as propriedades físicas do solo nas linhas e entrelinhas de um sistema agroflorestal sintrópico - SAS. Considerando assim, que o comportamento físico do solo nas entrelinhas permanece desconhecido. A partir dos resultados encontrados concluímos que as linhas e entrelinhas de um SAS se comportam de forma semelhante em relação aos atributos avaliados. Isto demonstra que tais sistemas são altamente benéficos para a produção de alimentos, bem como para a manutenção das propriedades físicas do solo. Já no segundo capítulo, o objetivo foi investigar, variáveis climáticas como cobertura do dossel, umidade relativa do ar, temperatura do ar, temperatura do solo e iluminância medindo-as tanto em uma área de floresta tropical quanto em um sistema agroflorestal sintrópico adjacente. A partir dos resultados conclui-se que, apesar de se assemelhar a uma floresta tropical na aparência, os sistemas agroflorestais sintrópicos não apresentam condições microclimáticas semelhantes às florestas tropicais.

Palavras-chave: agricultura ecológica; agroecossistemas; serviços ecossistêmicos; sustentabilidade; mata de galeria.

THESIS SUMMARY

Syntropic agroforestry systems (SAS) are agricultural systems designed to reconcile agricultural production with environmental conservation. One possible way to make agricultural systems more sustainable is to imitate natural ecosystems. In this sense, syntropic agroforestry systems are agroecosystems that imitate, to a certain extent, the structure and natural dynamics of forests. In this thesis we seek to answer two questions: are water infiltration and soil penetration similar between the lines and between the lines of the SAS? b) is the microclimate of a SAS similar to the microclimate of a tropical forest? These questions were organized into two chapters systematized in the format of a scientific article. In the first chapter, the objective was to characterize the physical properties of the soil in the lines and between the lines of a syntropic agroforestry system - SAS. Considering this, the physical behavior of the soil between the rows remains unknown. From the results found, we conclude that the lines and subtext of a SAS behave in a similar way in relation to the evaluated attributes. This demonstrates that such systems are highly beneficial for food production, as well as maintaining the physical properties of the soil. In the second chapter, the objective was to investigate climatic variables such as canopy coverage, relative air humidity, air temperature, soil temperature and illuminance by measuring them both in a tropical forest area and in an adjacent syntropic agroforestry system. From the results it is concluded that, despite resembling a tropical forest in appearance, syntropic agroforestry systems do not present microclimatic conditions similar to tropical forests.

Keywords: ecological agriculture; agroecosystems; ecosystem services; sustainability; gallery forest.

LISTA DE FIGURAS

Soil physical properties in an oxisol under a syntropic agroforestry system: row *versus* inter-row

Are syntropic agroforestry system microclimatically similar to tropical forest?

SUMÁRIO

1. INTRODUÇÃO GERAL

A agricultura ocupa uma importante posição entre os principais potenciais de alteração dos ambientes naturais, comprometendo a biodiversidade, manutenção dos ciclos biogeoquímicos e o aumento das emissões de gases de efeito estufa (GEE) (Crippa et al., 2021; Liu et al., 2023; Reis et al., 2023; Hua et al., 2024).

O atual modelo de agricultura convencional, baseado em monocultivos de commodities e uso intensivo de agrotóxicos tem aumentado as consequências para o ambiente com o aumento do desmatamento, contaminação dos solos e perda da biodiversidade (Rattis et al., 2021; Reis et al., 2023). Embora haja uma tentativa de adaptação agronômicas, com o avanço das tecnologias, ainda assim, não é possível estabilizar o clima, manter a biodiversidade e os serviços ecossistêmicos sem a presença da diversidade de fauna e flora (Clapp & Rander, 2020; Rattis et al., 2021; Kuschnig et al., 2021; Rosa et al., 2023).

Um estudo realizado na China reforça a teoria de que há a necessidade de combinar medidas para que se possa, ao mesmo tempo, alcançar neutralidade carbônica, segurança alimentar e sustentabilidade (Ming Ren et al., 2023). A combinação entre tecnologia e práticas agroecológicas pode apresentar respostas aos desafios da produção de alimentos e a sustentabilidade dos ambientes naturais sem a necessidade de abrir novas áreas agrícolas (Pompeu et al., 2021).

Diante disto, para além dos avanços tecnológicos com a agricultura de precisão e as tecnologias emergentes, há uma potencial alternativa que vem se desenvolvendo dentro das tecnologias sociais e na prática cotidiana dos agricultores, a partir da interação entre conhecimentos tradicionais e conhecimentos científicos, que são chamadas de agricultura ecológica ou agroecologia (Silva, 2010; Serafim et al., 2013; Ventura et al., 2018; Melo & Pereira, 2023).

Dentro desta abordagem, há pesquisas que mostram experiências de produção de alimentos que reduzem a dependência de fertilizantes e pesticidas, minimizam os impactos nos ecossistemas e, ainda, melhoram a capacidade produtiva ao longo do tempo (Sachs et al. 2010; Chen et al. 2022 ; Puech & Starkb, 2023). Tais práticas têm como base uma visão sustentável, pautada na segurança alimentar, na saúde humana e no bem-estar social e econômico de quem produz, consome e vive em torno dessas produções (Basche & DeLong 2019; Waldron et al. 2020; Das et al., 2022).

Assim, nesta pesquisa, avaliamos um sistema agroflorestal sintrópico (SAS) que apresenta-se como uma das práticas da agricultura ecológica. O SAS possibilita a produção de alimentos, fibras, madeiras, entre outros, a partir da combinação entre diversas espécies de plantas perenes com plantas de interesse agrícola de ciclo curto, que imitam os padrões naturais de sucessão e estratos arbóreos presentes em florestas naturais, acelerando esses processos e aumentando a potencialidade de ciclagem de nutrientes no solo (Götsch 1997; Micollis et al. 2016; Roseto et al., 2021; Pereira et al. 2021; Mayer et al., 2022).

Neste sentido, uma vez que os SAS assemelham-se aos ecossistemas naturais e aos seus processos, espera-se que este sistema traga outros benefícios para além da produção de alimentos. Neste estudo, buscamos responder a duas perguntas, são elas: a) a infiltração da água e a penetração do solo são semelhantes nas linhas e entrelinhas do SAS? b) o microclima de um SAS é semelhante ao microclima de uma floresta tropical? Para isso, a tese buscou apresentar a respostas às perguntas anteriores organizando-as em dois capítulos apresentados em formato de artigo, são eles: a) Soil physical properties in an oxisol under a syntropic agroforestry system: row versus inter-row, publicado na "Revista Brasileira de Geografia Física", em inglês e; b) Are syntropic agroforestry systems microclimatically similar to tropical forests?, submetido à revista "Agroforestry System", também em inglês.

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2. OBJETIVOS

2.1. Objetivo geral

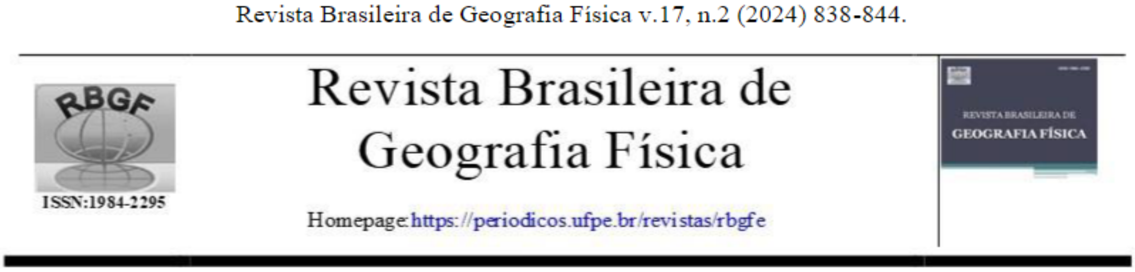
Analisar um sistema agroflorestal sintrópico observando sua capacidade em relação às propriedades físicas do solo e o microclima.

2.2. Objetivos específicos

- Comparar linha e entrelinha do SAS para observar infiltração da água no solo e resistência do solo à penetração.
- Avaliar se as variáveis microclimáticas umidade relativa, temperatura do ar, temperatura do solo, cobertura do dossel e luminosidade são semelhantes à uma floresta tropical.

CAPÍTULO I

Soil physical properties in an oxisol under a syntropic agroforestry system: row *versus* inter-row



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ABSTRACT

Synthropic agroforestry systems are agricultural systems designed to reconcile agricultural production with environmental conservation. However, the benefits related to soil physical properties of these systems have only been documented for the planting rows. Thus, the physical behavior of the soil in the inter-rows remains unknown. The objective of this paper was to characterize the physical properties of the soil in the rows and inter-rows of a syntropical agroforestry system - SAS. For this, infiltration capacity (mini-disk infiltrometer) and soil resistance to penetration (STOLF Penetrometer) were measured in five ramdomly located blocks involving the rows and inter-rows. The results showed that there were no significant differences between row and inter-rows for both variables. The high species diversity, continuous addition of organic matter to the soil via pruning, the absence of heavy machinery use, and the vigorous growth of exotic grasses in the inter-row are the likely factors that explain the absence of differences reported here. We conclude that the rows and inter-rows of a SAS behave similarly in relation to the attributes evaluated. This demonstrates that such systems are highly beneficial for food production as well as maintaining soil physical properties.

Keywords: Sustainability; water permeability; agriculture; best management practices.

Introduction

The challenge of agroecosystems is to increase production from ecologically designed agricultural systems that can recover traditional practices combined with ecological knowledge that enhance ecosystem services (Neves & Imperador, 2022). The fragmentation of habitats - caused mainly by agriculture impacts biogeochemical cycles, biodiversity and the production of food and fiber (Zilli et al. 2020; Ma et al., 2023) affecting soil compaction and, consequently, the water infiltration capacity. Such changes alter the hydrological cycle locally and bring about serious reductions in aquifer recharge (Failache & Zuquete, 2020).

In this context, it is evident the need to develop agricultural systems capable of combining food production with other ecosystem services. Some authors present studies that demonstrate other forms of food production in which there is the possibility of reducing dependence on fertilizers and pesticides and, consequently, minimize impacts on ecosystems, improving productive capacity over time (Sachs et al. 2010; Chen et al. 2022; Puech & Starkb, 2023). This approach takes place, from a sustainable vision, based on food security, human health, and the social and economic well-being of those who produce, consume, and live around these productions (Basche & DeLong 2019; Waldron et al. 2020; Das et al., 2022). Among these agricultural practices are syntropic agroforestry systems (SASs) which consist of a combination between several perennial plant species of agricultural interest. These systems are based on species succession, nutriente cycling, plant diversity and management through the use of severe pruning (Götsch 1997; Micollis et al. 2016; Roseto et al., 2021; Pereira et al. 2021; Mayer et al., 2022). Since SASs mimic natural ecosystems and their processes, this system is expected to bring other benefits beyond food production. For example, the high addition of organic matter from pruning may benefit soil infiltration capacity.

Murta et al. (2020) demonstrated that the infiltration capacity of a SAS was similar to that of a natural ecosystem (Brazilian Tropical Savannah). However, that study evaluated the infiltration only in the rows. Therefore, it is not yet known whether the same pattern would be found inter-row, which are generally more subjected to physical disturbances due to the transit of heavy machinery. In this sense, understanding the SAS in a more systemic way, that is, including the row and inter-row, allows a more holistic assessment regarding the effective benefit that the SASs can bring about.

The objective of this article is to characterize the infiltration capacity and soil penetration resistance in the rows and inter-rows of a SAS. Given that previous studies indicated that rows generally have better soil physical properties compared to the inter-rows (Silva et al., 2014; Santos et al., 2020; Guillot et al., 2021; Las Casas et al., 2022), starting from these premises, we hypothesized that rows are more permeable than inter-rows.

Material and Methods

Study area

The study was carried out at Elo Florestal Inkóra Farm, which is located in the Núcleo Rural Taquara, in Planaltina-DF, in the Preto river watershed, at UTM coordinates 244,850.00 mE and 8,275,995.59 mS (Figure 1).

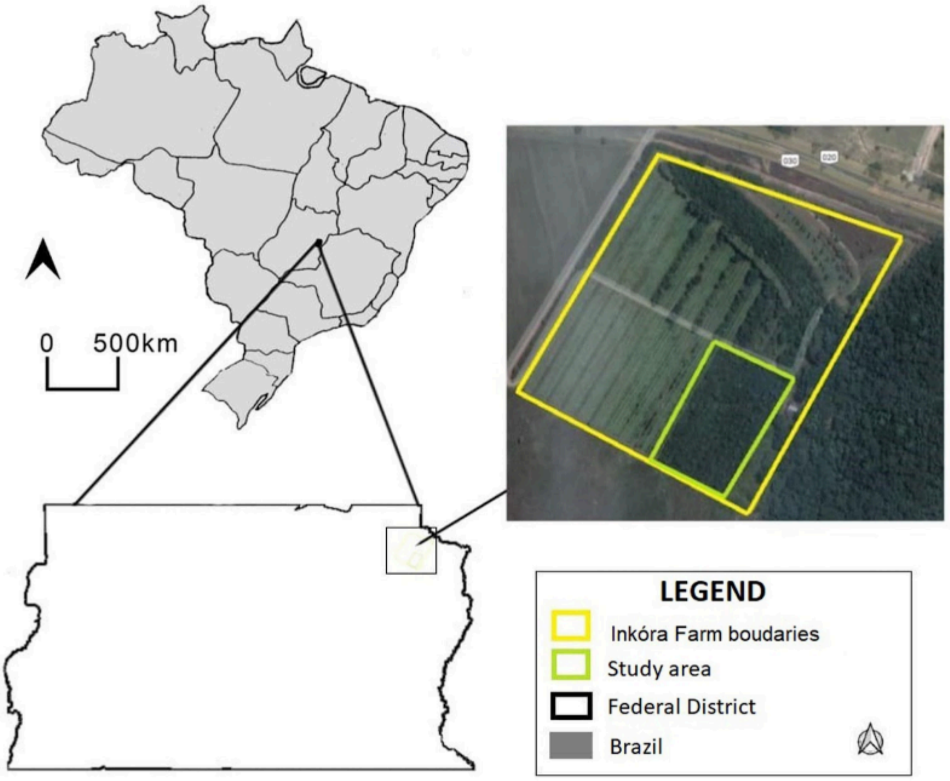

Figure 1: Location of the study area, Fazenda Inkóra Florestal, Planaltina, Federal District, Brazil.

The soil is classified as Oxisol. This type of soil is characterized as thick, highly weathered, with moderate A horizon and latosolic B horizon, rich in sesquioxides, highly porous and well drained (Santos et al., 2018).

The mean annual precipitation in the Federal District is 1477.4 mm (Instituto Nacional de Meteorologia [INMET], 2021) with two well defined seasons (rainy season from October to April and dry from May to September), according to Köppen-Geiger (Alvares et al. 2013).

The syntropic agroforestry system (SAS) in the study area is characterized as a mature system (20 years old) with a 4 m inter-row spacing and 1 or 2 m between individuals within the row. The area was used for soybean cultivation between 1985 and 2000. After the 2000s, it underwent a fallow period of two years and, in 2002, SAS was introduced (Figure 1). SAS is organized in rows and inter-rows constituting an agroforestry system with high diversity. There are more than 20 species including *Senna obtusifolia, Leucaena leucocephala, Hymenaea courbaril,* *Ceiba pentandra, Swietenia macrophylla, Dipteryx alata, Inga marginata, Cajanus cajan, Tephrosia candida, Morus nigra, Cosmos sulphureus, Hylocereus undatus, Citrus sinensis, Bixa orellana, Persea americana, Citrus limon, Ananas comosus, Psidium guajava, Annona squamosa, Carica papaya and Musa* sp (Figure 2A).

Figure 2: Syntropic agroforestry system: rows (A) and inter-row (B).

Typically, inter-rows serve as transit areas for management which can involve both manual and/or mechanized methods. In the current SAS, apart from the regular crops, the inter-rows exhibit vigorous growth of exotic grasses (*Urochloa* sp*, Pennisetum purpureum*) and other spontaneous plants. In addition, inter-row are subjected to litter deposition (Figure 2B).

Variables and sample design

Two variables were measured: infiltration capacity and soil resistance to penetration in the rows and between the rows. In this sense, five randomized blocks were established through the use of a randomizer. The randomizer used was chosen from a Google search; we chose the first option presented. In each block, a total of 6 infiltration samples were collected – three from within the row and three from the inter-row (Figure 3). The same procedure was followed for measuring soil penetration resistance.

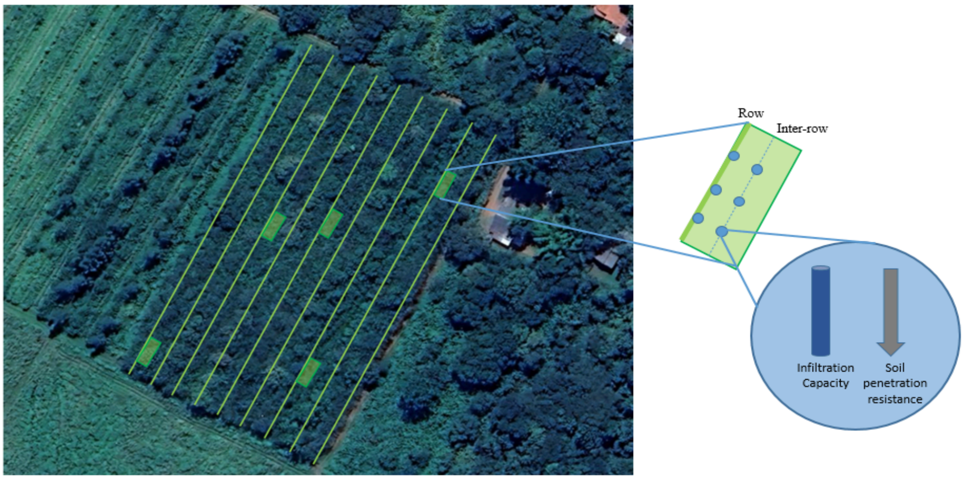

Figure 3: Sampling design employed in the present study involved randomly situating five blocks (depicted as green rectangles) in the field. Each block covered both the rows and inter-rows. Within each treatment, three repetitions were collected for both infiltration capacity and soil penetration resistance.

Infiltration capacity

We measured infiltration capacity using a mini-disk infiltrometer (Decagon devices Inc., USA) that uses the analytical solution proposed by Zhang (1997).

During collection, we carefully removed the litter and performed the tests on horizontal surfaces, ensuring the stability of the device. In addition, a thin layer (<1 mm) of fine sand was used to improve contact between the infiltrometer and the soil surface. To capture the largest range of soil pores, we used a suction pressure of 0 kPa. Water discharge rates through the Mini-Disk, as inferred from changes in water levels in the storage chamber of the device, were recorded until the flow rates reached a steady state. We performed three replicates, with a distance of 1 m between the collection points.

In cases where no steady-state flow rate was achieved, the measurement procedure was repeated until steady-state flow rates were recorded three times consecutively. Therefore, our infiltration capacity estimates were similar to the saturated hydraulic conductivity of the soil. After each measurement, we inspected the area being measured to verify proper (round) contact between the steel disc and the soil surface. When no round shape was detected, we repeated the measurement until a perfect round shape was achieved. To minimize the effect of soil moisture on soil penetration resistance, measurements were performed in the dry season when soil moisture is negligible.

Soil Penetration Resistance

The soil resistance to penetration was measured using the Stolf impact penetrometer (Stolf et al. 1983) by KAMAQ. Three measurements were taken in the rows and inter-rows. To minimize the effect of soil moisture on soil penetration resistance, measurements were carried out in the dry season, when soil moisture is negligible.

Data analysis

The normality of the residuals and the homogeneity of variance were evaluated using the Shapiro-Wilk and Levene normality tests, respectively. Residuals were found to be normally distributed for both variables, but homoscedasticity was detected. Consequently, Welch analysis of variance (Welch-ANOVA) was performed at a significance level of $\alpha = 5\%$ to assess whether there were differences between row and inter-row. The analysis was performed using the PAST statistical software (Hammer et al. 2001) and the R Program software (R Development Core Team 2016).

Results

The average (± standard deviation) of the infiltration capacity in the row was 330.38 (± 135.48) $mm.h^{-1}$ and interrow it was 643 (± 342.42) $mm.h^{-1}$. There were no significant differences between rows and interrows ($p = 0.07$) regarding water infiltration (Figure 4).

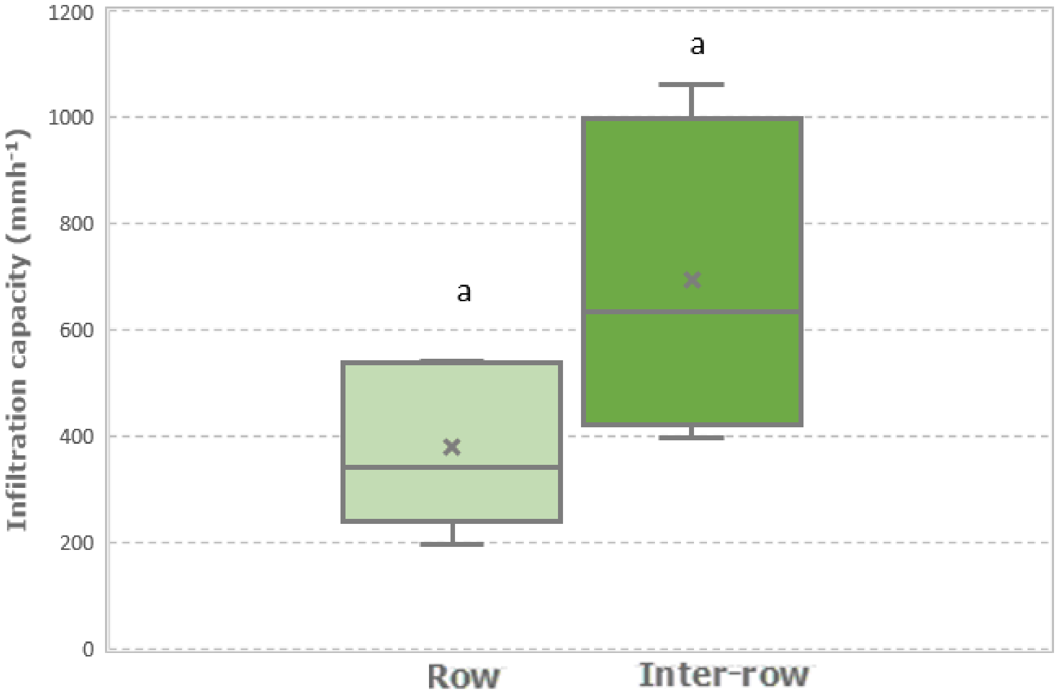

Figura 4: Box-plot showing infiltration in the rows and inter-rows of the syntropic agroforest. The horizontal lines within the box represent the median. The x represents the mean. The horizontal boundaries of the boxes represent the first and third quartiles. The ends of the vertical lines

represent the maximum (top) and minimum (bottom) values. Different letters indicate that there were no significant differences.

The soil resistance to penetration in impacts 0, 1 and 2, respectively, showed the following means (± standard deviation) in the rows, 1.79 (± 0.97), 6.27 (± 1.38) and 10.37 (± 2.60) cm; and in the inter-rows 1.80 (± 0.61), 5.67 (± 1.85) and 8.13 (± 1.56) cm. There were no significant differences in the rows and inter-rows (Figure 5).

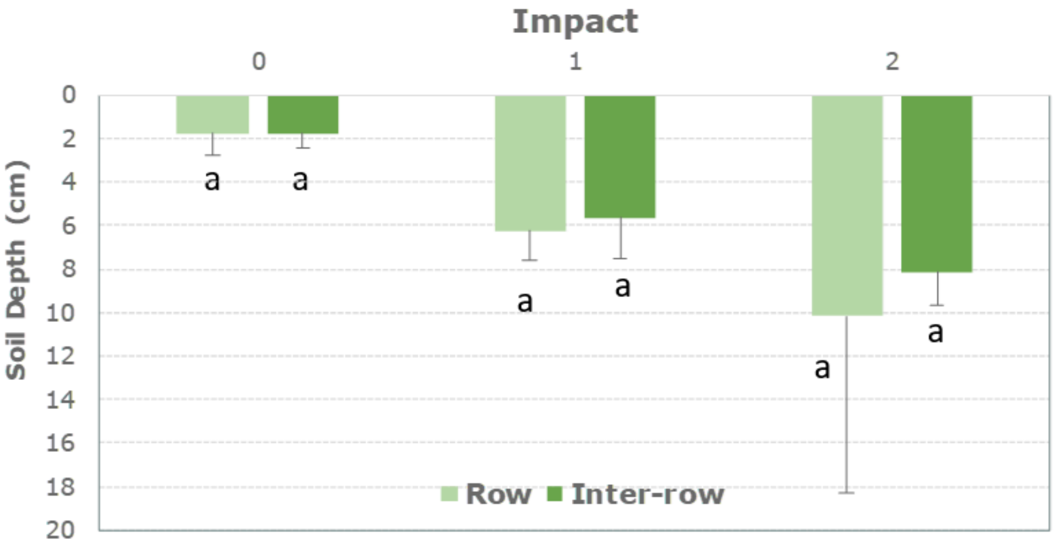

Figure 5: Mean and standard deviation of soil depth reached in each impact during penetration resistance measurements. Different letters indicate significant differences between row and inter-row.

Discussion

We could not find significant differences between row and inter-row regarding soil penetration resistance and infiltration capacity. Thus, our hypothesis that rows would have greater permeability compared to inter-row could not be accepted.

Previous studies have already focused on the effect of row and inter-row in soil physical properties (Silva et al., 2014; Santos et al., 2020; Las Casas et al., 2022). For example, Blum et al. (2014) documented increases in macroporosity and saturated hydraulic conductivity in row compared to inter-row after furrowing in a no-tillage soybean system. These results are in line with those by Silva et al. (2014) and Santos et al. (2020) which showed that soil physical properties like soil penetration resistance and soil bulk density were greater in the inter-row compared to the row.

Our study, on the other hand, showed a different pattern, that is, no significant difference between the row and the inter-row for infiltration capacity and penetration resistance. The likely cause of such absence of difference may reside in the active plant growth of exotic grasses (Urochloa sp, Pennisetum purpureum) in the inter-row combined with the lack of heavy machinery passage. In other words, the inter-row remained under fallow for two years. More studies are needed to assess differences between row and inter-row when heavy machinery is actively used to manage the SASs.

Pruning management may also have contributed to our results. Severe pruning is practiced twice a year and usually adds a large amount of above ground biomass to the soil (Murta et al., 2020). Such organic matter input potentially modifies the physical, chemical and microbiological structure of the soil (Micollis et al., 2016; Murta et al., 2020; Pereira et al., 2021). Previous studies demonstrated the effect of organic matter on aggregate formation promoting increased soil porosity which, in turn, enhances the water infiltration process (Fransluebbers, 2002; Arévalo-Gardini et al., 2015; Basche & DeLong, 2019; Wang et al., 2021). Through field observations, it was noted that the accumulation of litter on the soil was greater in the rows compared to the inter-rows.

A further cause may have also influenced our results: plant diversity. A high diversity of species generates a greater variation of rooting depth (Chen et al., 2022) which affects the soil in three interrelated forms: (i) roots expand to the inter-rows and, consequently, affect the soil in such region, (ii) root turnover may promote pore formation which, in turn, may lead to increase in infiltration capacity (Shi et al., 2021) and (iii) roots exudates and mycorrhizas may increase soil aggregates formation and stability which, once more, may increase soil infiltration capacity (Le Bissonnais et al., 2018; Zhu et al., 2019).

Conclusion

Rows and inter-rows within a syntropic agroforestry system exhibited comparable physical attributes. This observation highlights the significant benefits of SAS in enhancing soil water infiltration. The demonstrated improvement is not confined to the rows alone, emphasizing the broader positive impact of SAS. Thus, SASs play a crucial role in contributing to agricultural systems that not only yield food production but also contribute to essential ecosystem services, including water and soil maintenance.

Acknowledgements

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CAPÍTULO II

Are syntropic agroforestry systems microclimatically similar to tropical forests?

Capítulo submetido para a revista "Revista Brasileira de Ciências Agrárias" (Qualis A2, na área de Ciências Ambientais)

Abstract

One possible way to make agricultural systems more sustainable is to mimic natural ecosystems. In this regard, syntropic agroforestry systems are agroecosystems that imitate, to some extent, the structure and natural dynamics of forests. This study aims to address the following question: Are SAS microclimatically similar to tropical forests? To investigate, climate variables such as canopy coverage, relative air humidity, air temperature, soil temperature, and illuminance were measured in both a tropical forest area and an adjacent Syntropic Agroforestry System. The results showed significant differences in relative humidity, air temperature, and illuminance compared to the forest. These differences may be attributed to the higher density of tree individuals and the number of strata, which are greater in the tropical forest compared to the syntropic agroforestry system. It is concluded that, despite resembling a tropical forest in appearance, syntropic agroforestry systems do not have microclimatic conditions similar to tropical forests.

Keywords: tropical agriculture; sustainable agriculture; regenerative agriculture; sustainable development

Introduction

The current challenge of agricultural systems is to produce food to meet society's demands, utilizing ecologically planned and designed agroecosystems, thereby reviving traditional practices while integrating interdisciplinary scientific knowledge to enhance production, landscape, and ecosystem services (Vallejo-Ramos et al. 2016; Neves e Imperador 2022; McGunnigle et al. 2023). Agricultural expansion and land use change fragment habitats, leading to biodiversity loss and increasing concerns about climate change (Luo et al. 2022; Roi et al. 2022; Ma et al. 2023).

In this context, developing agricultural systems capable of combining food production with other ecosystem services becomes an increasingly pressing demand in scientific discussions. Studies demonstrate alternative food production methods that can reduce the impacts of agriculture on ecosystems and thus enhance productive capacity over time, strengthening ecosystem services (Chen et al. 2022; Puech e Starkb 2023). Based on an environmentally sustainable approach, with a focus on food security, human health, and social and economic well-being (Basche & De Long 2019; Waldron et al. 2020; Das et al. 2022), among such agricultural practices are syntropic agroforestry systems (SASs), which involve combining different plant species of agricultural interest. SASs are based on species succession, nutrient cycling, plant diversity, and management through the use of severe pruning (Micollis et al. 2016; Roseto et al. 2021; Pereira et al. 2021).

Building upon this approach, studies show that the use of shade trees in agroforestry systems offers the possibility to mitigate extremes in terms of temperature, humidity, and other microclimatic variables (Lin 20007; Glazle et al. 2021; Wang et al. 2022). Such adaptations in agricultural areas are important for mitigating the annual changes that arise in the climate, thus ensuring food production. Given that syntropic agroforestry systems (SASs) mimic, to some extent, tropical forests, it is expected that these systems also provide substantial improvement in microclimatic conditions, perhaps resembling those of a tropical forest. However, there are no studies attesting to this in SASs.

Therefore, this study aims to answer the following question: Are SASs similar, in terms of microclimatic conditions, to tropical forests? To achieve this, several microclimatic variables were evaluated in both a SAS and a tropical forest. Some authors suggest that traditional agroforestry systems resemble forests, especially regarding shade provision and microclimatic conditions (Lin 2007; Frenne et al. 2021; Glazle et al. 2021; Ulman et al. 2021; Merle et al. 2022; Wang et al. 2022). In this context, the present study tests the hypothesis that the microclimate of the Syntropic Agroforestry System is similar to that of a tropical forest.

Methods

Study Area

The study was conducted at the Elo Florestal Inkóra Farm, located in the Rural Nucleus of Taquara, in Planaltina-DF, in the Preto River basin, at UTM coordinates 244,850.00 mE and 8,275,995.59 mS (Figure 1).

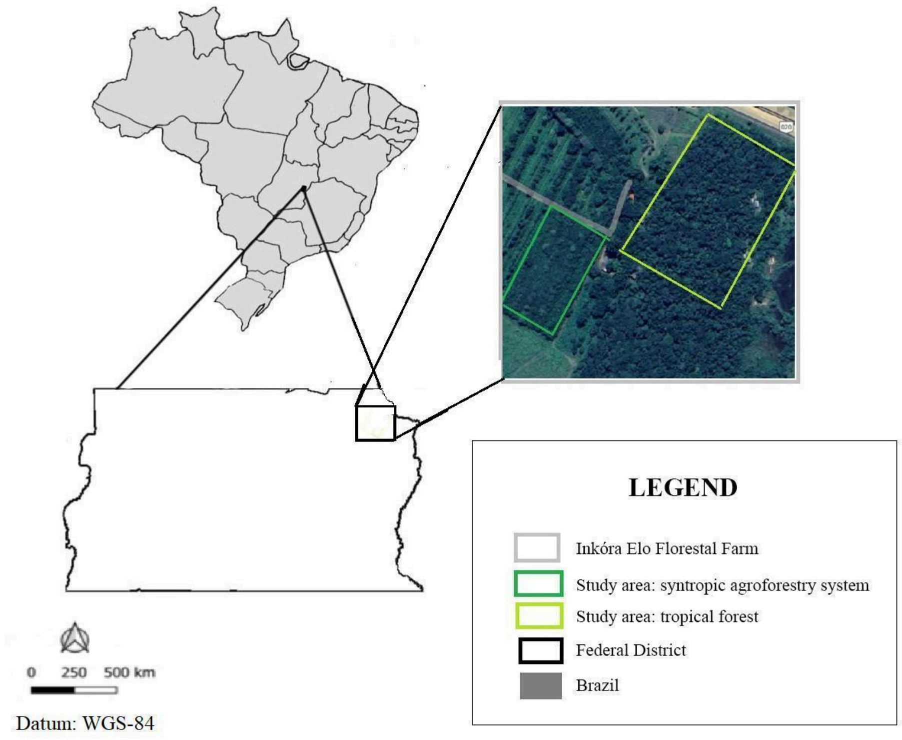

Figure 1: Location map of the study area.

The soil is classified as Latosol. This type of soil is characterized as deep, highly weathered, with a moderate A horizon and a latosolic B horizon, rich in sesquioxides, highly porous, and well-drained (Santos et al. 2018).

The average annual precipitation in the Federal District is 1,477.4 mm (INMET 2021) with two well-defined seasons (rainy period from October to April and dry season from May to September), according to Köppen-Geiger (Alvares et al. 2013).

The Syntropic Agroforestry System (SAS) in the study area is characterized as a mature system (20 years old). It is a highly diverse system, with over 20 species present, including *Senna obtusifolia, Leucaena leucocephala, Hymenaea courbaril, Ceiba pentandra, Swietenia macrophylla, Dipteryx alata, Inga marginata, Cajanus cajan, Tephrosia cândida, Morus nigra, Cosmos sulphureus, Hylocereus undatus, Citrus sinensis, Bixa orellana, Persea americana, Citrus limon, Ananas comosus, Psidium guajava, Annona squamosa, Carica papaya, Musa sp* (Figure 2A).

The selected forest for the study is a gallery forest characterized by high plant species diversity, bordering a small stream, forming a protective corridor along the watercourse. It is a forest type with trees ranging from 20 to 30 meters in height, with a canopy coverage of 75% to 90%. Common species found in this type of forest include *Cheiloclinum cognatum,* *Copaifera langsdorffii, Cupania vernalis, Emmotum nitens, Matayba guianensis, Tapirira guianensis, Tapura amazonica, and Virola sebifera*, along with the presence of epiphytic plants such as those from the Orchidaceae family (Ribeiro et al 2001) (Figure 2B). Additionally, this forest has about 2 to 3 layers of vegetation

Figure 2: The two ecosystems studied: a) Syntropic agroforestry system and b) Tropical forest.

Sampling Design

Five variables were measured: illuminance, canopy coverage, relative air humidity, air temperature, and soil temperature. In this regard, seven replicates were established and randomly allocated using a randomizer. Within the seven replicates, three repetitions were conducted with a distance of 1 meter between them, where all variables were measured (Figure 3). Sampling was conducted between the rows of the Syntropic Agroforestry System, while in the forest, sampling was conducted at a distance of at least 2 meters from the trees. This measure was taken to ensure that sampling in both the forest and the SAS were comparable.

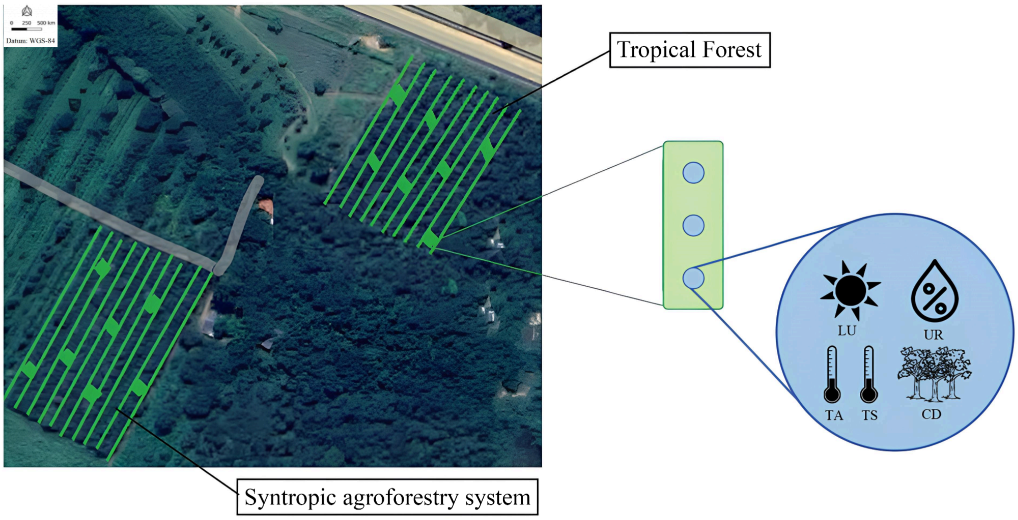

Figure 3: Sampling design used in the present study. Seven replicates (green rectangles) were randomly located in the field within each of the study areas. Within the replicates, three repetitions (blue circles) were conducted. Within each repetition, the following variables were measured: LU - illuminance; RH - relative air humidity; AT - air temperature; ST - soil temperature; and CC - canopy coverage.

Variables

The variables illuminance, air temperature, and relative humidity were measured using a multiparameter probe model THDL-400 from Instrutherm Instrumentos de Medição Ltda. Canopy coverage was measured using the Canopy Capture software (https://play.google.com/store/apps/details?id=com.canopytax.practitioner&hl=pt_BR&gl=US), integrated with a smartphone. All these variables were measured at a height of 2 meters above the ground surface. Soil temperature was measured using a portable digital thermometer INSTRUTERM model TE-400, inserting the thermometer into the soil at a depth of 10 cm, at the same location where the other variables were collected. All variables were collected in the same replica within each of the repetitions.

Data Analysis

The normality of residuals and the homogeneity of variances were assessed, respectively, by the Shapiro-Wilk and Levene tests. The residuals exhibited a normal distribution for canopy coverage, air temperature, soil temperature, and relative humidity. The groups showed variance homogeneity for all variables except illuminance. Therefore, the

One-Way ANOVA test was used to assess differences between SAS and forest for canopy coverage, air temperature, soil temperature, and relative humidity. For illuminance, given the absence of normality of residuals and homogeneity of variances, Welch's analysis of variance (Welch-ANOVA) was conducted. The Pearson test was used to assess the significance of the relationship between air temperature and relative humidity. All analyses were performed using the Paleontological Statistic software - PAST (Hammer et al. 2001) at a significance level of 0.05.

Results

The mean (± standard deviation) canopy coverage was 78 (± 2.50)% in the sintropic agroforestry system, whereas in the forest it was 81 (± 2.85)%. There was no significant difference ($p > 0.23$).

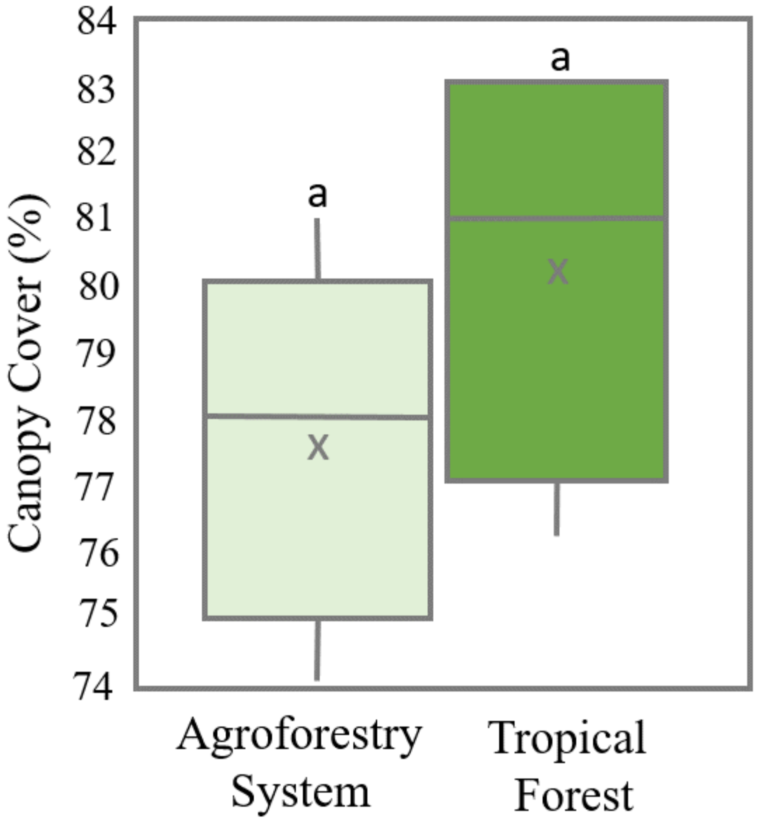

Figure 4: Box plots of canopy coverage in the Syntropic Agroforestry System (light green) and forest (dark green). The horizontal lines inside the box represent the median. The x represents the mean. The horizontal limits of the boxes represent the first and third quartiles.

The ends of the vertical lines represent the maximum (upper) and minimum (lower) values. Different letters indicate that there were no significant differences.

The variables illuminance, air temperature, and relative humidity showed significant differences. Their means (± standard deviation) are, respectively, for the SAS 188 (± 114) lux and for the forest 28 (± 5.13) lux ($p < 0.01$) (Figure 5); for the SAS 25.6 (± 0.92) °C and for the forest 23.5 (± 0.92) °C ($p < 0.05$) (Figure 6); and for the SAS 61.3 (± 2.86) % and for the forest 76.9 (± 1.85) % ($p < 0.01$) (Figure 7).

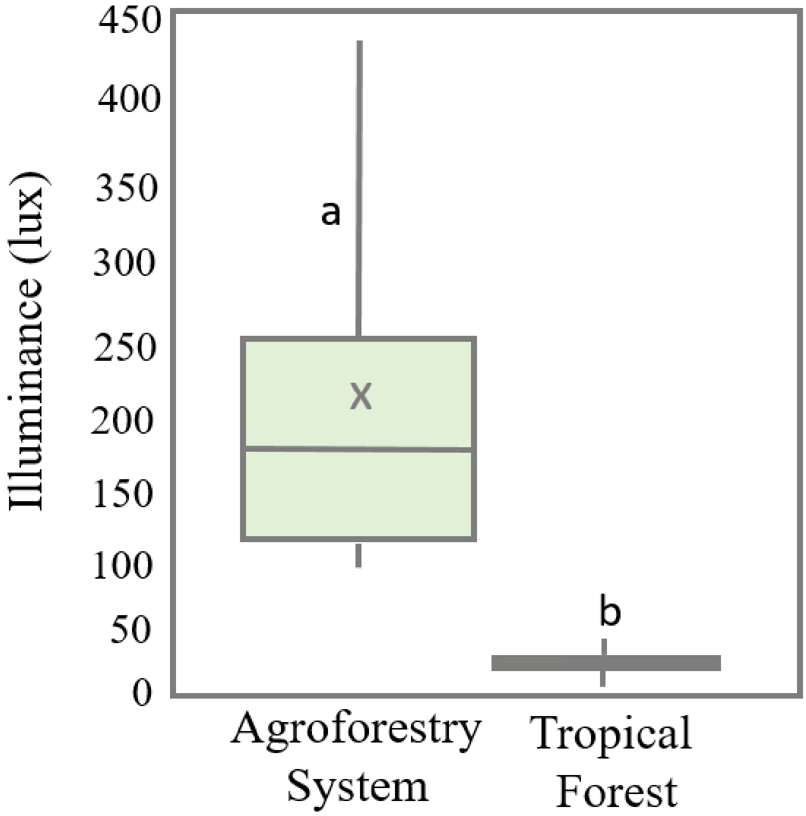

Figure 5: Box plots of illuminance in the Syntropic Agroforestry System (light green) and forest (dark green). The horizontal lines inside the box represent the median. The x represents the mean. The horizontal limits of the boxes represent the first and third quartiles. The ends of the vertical lines represent the maximum (upper) and minimum (lower) values. Different letters indicate that there were no significant differences.

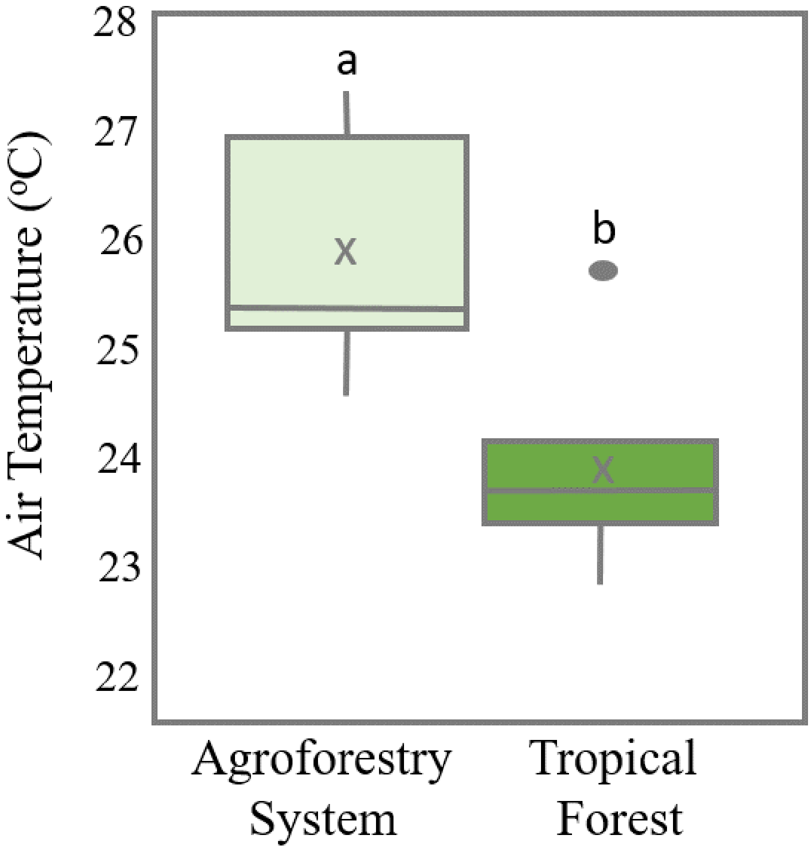

Figure 6: Box plots of air temperature in the Syntropic Agroforestry System (light green) and forest (dark green). The horizontal lines inside the box represent the median. The x represents the mean. The horizontal limits of the boxes represent the first and third quartiles. The ends of the vertical lines represent the maximum (upper) and minimum (lower) values. Different letters indicate that there were no significant differences.

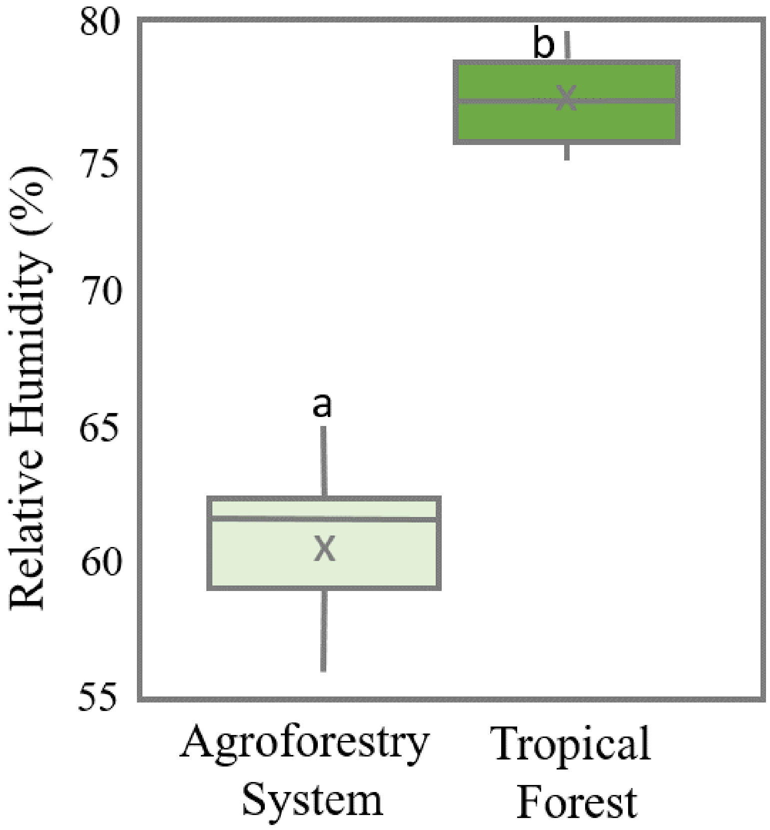

Figure 7: Box plots of relative air humidity in the Syntropic Agroforestry System (light green) and forest (dark green). The horizontal lines inside the box represent the median. The x represents the mean. The horizontal limits of the boxes represent the first and third quartiles. The ends of the vertical lines represent the maximum (upper) and minimum (lower) values. Different letters indicate that there were no significant differences.

The soil temperature was 23.2 (± 3.41) °C in the SAS and 22.3 (± 0.20) °C in the forest. There was no significant difference ($p > 0.05$) (Figure 8).

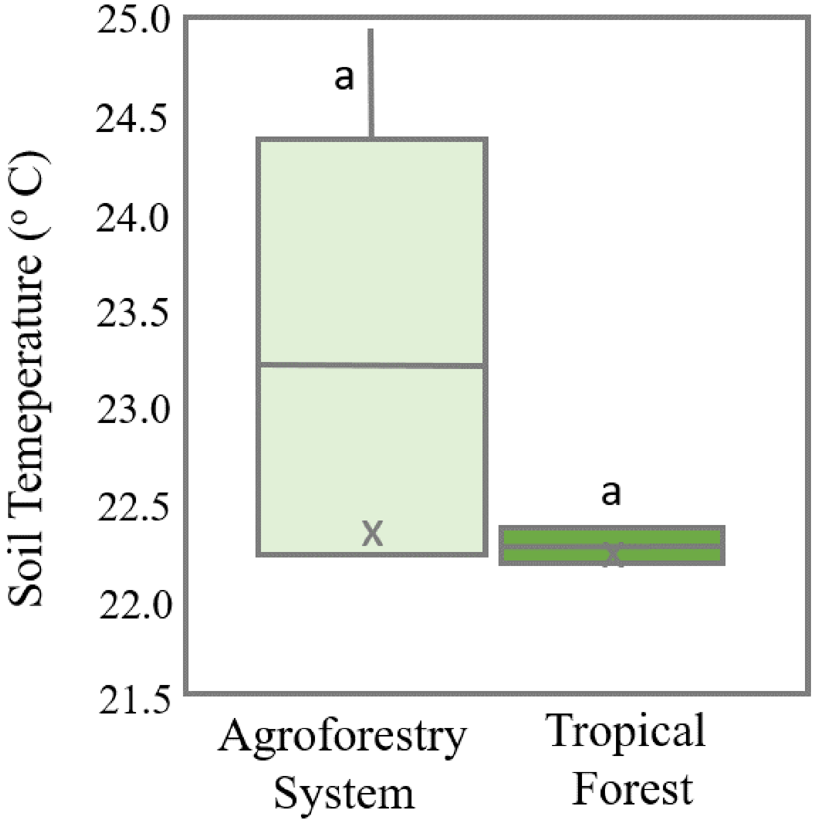

Figure 8: Box plots of soil temperature in the Syntropic Agroforestry System (light green) and forest (dark green). The horizontal lines inside the box represent the median. The x represents the mean. The horizontal limits of the boxes represent the first and third quartiles. The ends of the vertical lines represent the maximum (upper) and minimum (lower) values. Different letters indicate that there were no significant differences.

Relative humidity was associated with air temperature in both the SAS and the forest. Both showed a negative correlation, without significance (SAS: R = -0.54; $p > 0.05$ and forest: R = -0.39; $p > 0.05$) (Figure 9).

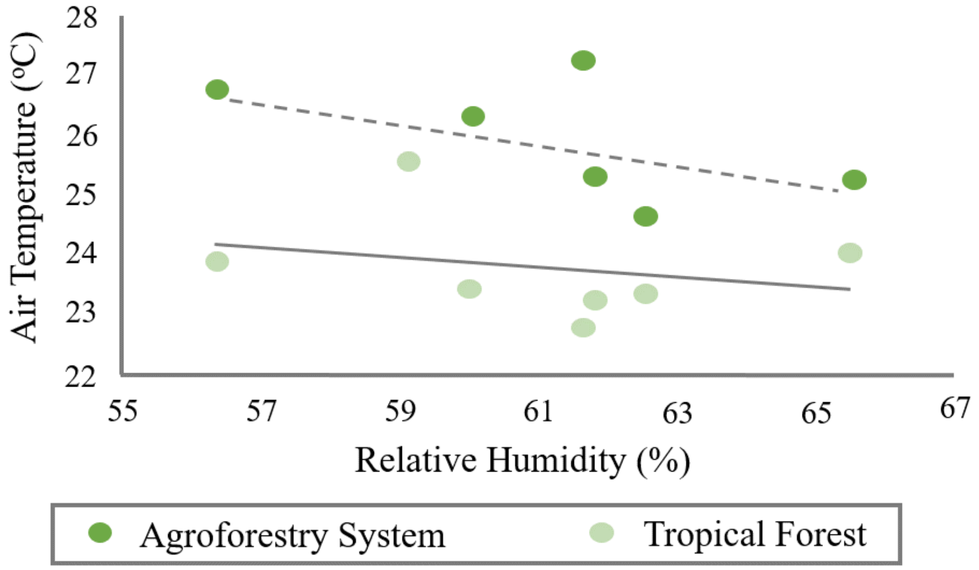

Figure 9: Correlation between relative humidity and air temperature in the Syntropic Agroforestry System and in the forest.

Discussion

The results of the present study demonstrate that illuminance and air temperature were significantly higher in the SAS compared to the tropical forest. On the other hand, relative humidity was significantly higher in the tropical forest compared to the agroforestry system. Finally, the systems did not show significant differences regarding canopy coverage and soil temperature.

An explanation for the significant differences found regarding illuminance, air temperature, and relative humidity may be associated with the density of tree individuals and the number of strata in each system under consideration. Regarding density, in the agroforestry system, density varies between 160 to 508 individuals/ha (Amador & Viana, 1998; Duarte, 2011; Cruz et al., 2019; Pezzopane et al., 2021), while in gallery forests, density varies between 643 to 1,500 individuals/ha (Silva Jr 2004; Araujo et al. 2009). Concerning stratification, tropical forests have 3 to 4 strata (Do Vale et al. 2009), which provides them with superior capacity, compared to agroforestry, to intercept more solar radiation, reducing air temperature and consequently increasing relative humidity (Ribeiro et al. 2021; Lóis et al. 2011). The Syntropic Agroforestry System, on the other hand, presents trees cultivated in different configurations, designed by the layout chosen by the producer for agricultural purposes, and it only has 2 tree and herbaceous strata (biomass-producing grasses in the alleyway).

The absence of significant differences in soil temperature can be explained by the high density of herbaceous plants (e.g., *Urochloa sp, Pennisetum purpureum*, and other spontaneous plants) and the presence of a large amount of organic material accumulated on the soil from the severe pruning typical of syntropic agroforestry systems (Micollis et al. 2016). These elements contribute to soil protection against solar irradiation, thereby keeping the soil covered and at lower temperatures similar to those in the forest.

Regarding soil temperature, despite the absence of significant differences, it is noted that there was a much higher temperature amplitude in the SAS compared to the tropical forest. Given that there was no significant difference in canopy coverage, this fact is attributed to stratification. Tropical forests, due to having more strata, have a higher leaf area index (LAI) than agroforests. For example, gallery forests in the region of the present study have LAI values ranging from 3.1 to 4.2 (Silva et al. 2008; Paiva et al. 2015), while in agroforestry systems, it varies from 2.28 to 3.17 (Righi et al. 2008). Consequently, agroforests are subject to greater variation in light input than tropical forests and, consequently, greater variation in soil temperature.

The canopy coverage, as well as the soil temperature, did not exhibit significant differences between the study areas, which could be attributed to the tree strata. The production lines within the syntropic agroforestry system comprise tall-strata trees that grow and develop, forming canopies that close. Thus, they provide a canopy coverage akin to that of the forest.

Despite the air temperature, relative humidity, and illuminance of the SAS not being similar to those of the tropical forest, other studies have shown results demonstrating that agroforests have the ability to alter microclimates when compared to conventional monoculture systems (Niether et al. 2018). For example, it has been documented that shaded coffee agroforestry systems promote a reduction in both air and soil temperature compared to coffee monoculture (Carvalho et al. 2021).

Similarly, the agroforestry system consisting of a consortium between black pepper and rubber trees, compared to conventional pepper production (in full sunlight exposure), decreased both solar radiation incidence and air temperature below the canopy. Consequently, there was an increase in relative humidity (Oliosi et al., 2021).

Conclusion

The differences observed in air temperature, relative humidity, illuminance, and greater soil temperature range between the Syntropic Agroforestry System and the tropical forest indicate that the hypothesis that these systems would have similar microclimatic conditions was rejected. In other words, despite resembling a tropical forest in appearance, syntropic agroforests do not possess microclimatic conditions similar to tropical forests.

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Declarations

Conflict of interest

All authors have no conflict of interest.

Ethical Approval

All authors read and approved the final manuscript.

Author Contribution

Pereira and Salemi in the methodological and theoretical construction. Pereira, Hoffmann and Salemi contributed to collecting data in the field. Pereira and Salemi construction of the figures.

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3. CONSIDERAÇÕES FINAIS

Os sistemas agroflorestais sintrópicos (SAS) são possibilidades de produção de alimentos e fibras, baseados em princípios da natureza. Assim, o SAS apresenta-se como um potencial para ser uma forma de fazer agricultura, que contribui para potencializar os serviços ecossistêmicos.

Em nossas pesquisas foi possível observar que o SAS possui benefícios consideráveis para a infiltração da água no solo. Além disso, também foi observado que apesar de se parecerem com uma floresta tropical na aparência, as agroflorestas sintrópicas não possuem condições microclimáticas semelhantes às florestas tropicais. Demonstrando que tal estudo pode potencializar desenhos de SAS que melhorem esses elementos, em especial em relação ao microclima e que potencializam a produção de serviços ecossistêmicos.

4. FIGURAS SUPLEMENTARES

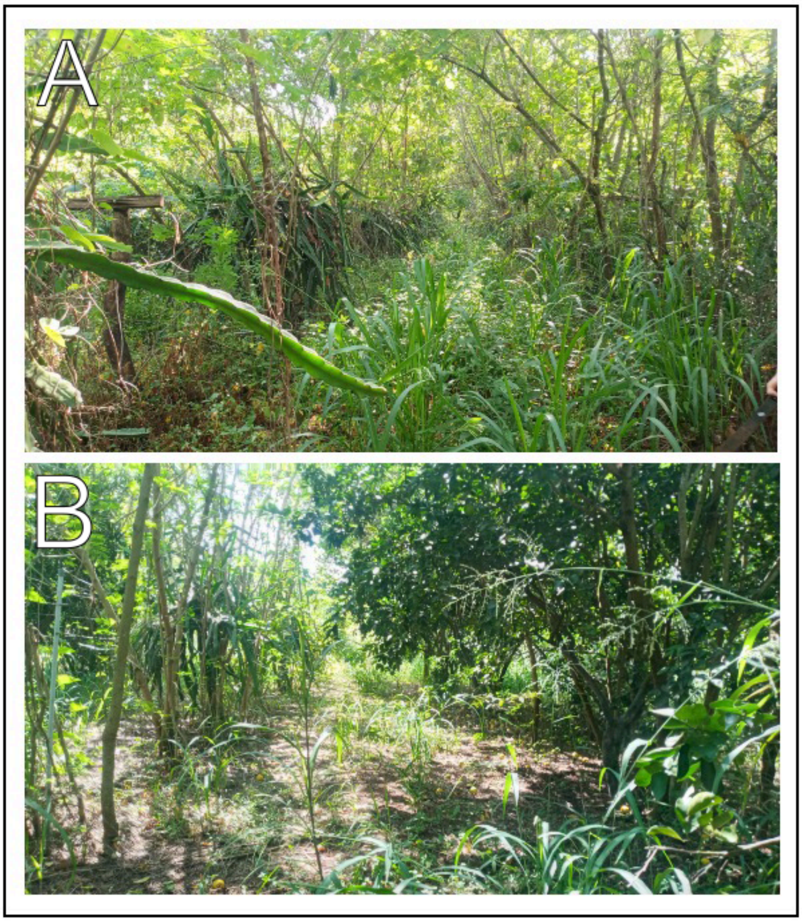

Figura suplementar 1: Sistemas agroflorestais sintrópicos estudados. A) entrelinhas do SAS;; B) linhas do SAS.

Figura suplementar 2: Floresta na área de estudo da pesquisa.

Figura suplementar 3: Coleta de dados à campo. Coleta com infiltrômetro.