LUCAS ABREU KERKOFF

THE EFFECT OF LAND USE/LAND COVER AND ITS ENVIRONMENTAL ATTRIBUTES ON THE CLASSIFICATION OF PRIORITY ZONES FOR SILVOPASTORAL SYSTEM ADOPTION

Thesis submitted to the Forest Sciences Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Carlos Moreira Miquelino Eleto Torres

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"Um novo dia nasce e com ele um novo tempo".

(Rancore)

ABSTRACT

KERKOFF, Lucas Abreu, M.Sc., Universidade Federal de Viçosa, MONTH, 2024. **The effect of Land Use/Land Cover and its environmental attributes on the classification of priority zones for silvopastoral system adoption**. Adviser: Carlos Moreira Miquelino Eleto Torres.

The Brazilian Cerrado, a biodiversity hotspot, faces severe threats from agricultural/livestock expansion and land degradation. This study investigates the potential for implementing autochthonous silvopastoral systems (SPS) as a sustainable land management strategy to conserve biodiversity and enhance ecosystem services in the landscape. Despite documented benefits, the adoption of these systems remains low. The first chapter aimed to conduct a bibliometric analysis to understand the global research state of the art on SPS adoption using the PRISMA methodology. A total of 58 documents were analyzed, with an average of 18.45 citations per document and 3.07 citations per document per year. The study identified the main countries in terms of publications on SPS adoption as the United States of America, Germany, Colombia, Brazil and Mexico. International collaborations were observed through co-authorships, which represented 48.28% of the listed works. The analysis highlighted the most relevant journals, with Agroforestry Systems being the leading journal. The results show a significant increase in research on SPS adoption in recent years, focusing on understanding the barriers and motivations for adoption. Additionally, in the second chapter, the study assesses the potential for conservationist use (PCU) in the Pardo River and São João do Paraíso hydrological watersheds, in the North mesoregion of the Minas Gerais state, estimates and map ecosystem services and identify priority zones for autochthonous SPS. Santo Antônio do Retiro, Montezuma, and Rio Pardo de Minas exhibit the highest PCU scores among the municipalities. The study highlighted good soil and slope conditions in the region but also faced challenges with low annual water yield. Thus, it is emphasized that the adoption of autochthonous SPS can bring benefits in high-suitability areas. In conclusion, the adoption of autochthonous SPS in high-suitability land cover types such as savanna formation, perennial crops, and forest plantations offers a viable strategy to enhance ecosystem services, support biodiversity conservation, and promote sustainable land use. This research also highlights the role of public policies, such as payment for environmental services, in promoting and facilitating the adoption of autochthonous SPS.

Keywords: Agroforestry systems; Cerrado; Land degradation; Ecosystem services; Public policies;

RESUMO

KERKOFF, Lucas Abreu, M.Sc., Universidade Federal de Viçosa, MÊS de 2024. **O efeito do Uso/Cobertura da terra e seus atributos ambientais na classificação de zonas prioritárias para a adoção de sistemas silvipastoris**. Orientador: Carlos Moreira Miquelino Eleto Torres.

O Cerrado brasileiro, um *hotspot* de biodiversidade, enfrenta sérias ameaças da expansão agropecuária e da degradação do solo. Este estudo investiga o potencial de implementação de sistemas silvipastoris autóctones (SSP) como uma estratégia de manejo sustentável da terra para conservar a biodiversidade e melhorar os serviços ecossistêmicos na paisagem. Apesar dos benefícios documentados, a adoção desses sistemas permanece baixa. O primeiro capítulo teve como objetivo realizar uma análise bibliométrica para entender o estado da arte da pesquisa global sobre a adoção de SPS usando a metodologia PRISMA. Um total de 58 documentos foram analisados, com uma média de 18,45 citações por documento e 3,07 citações por documento por ano. O estudo identificou os principais países em termos de publicações sobre a adoção de SPS: Estados Unidos da América, Alemanha, Colômbia, Brasil e México. Colaborações internacionais foram observadas através de coautorias, que representaram 48,28% dos trabalhos listados. A análise destacou as revistas mais relevantes, sendo Agroforestry Systems a principal. Os resultados mostram um aumento significativo na pesquisa sobre a adoção de SSP nos últimos anos, focando na compreensão das barreiras e motivações para a adoção. Além disso, no segundo capítulo, o estudo avalia o potencial para uso conservacionista (PCU) nas sub-bacias dos rios Pardo e São João do Paraíso, na mesorregião Norte do estado de Minas Gerais, estima e mapeia serviços ecossistêmicos, e identifica zonas prioritárias para SPS autóctones. Santo Antônio do Retiro, Montezuma e Rio Pardo de Minas apresentam os maiores escores de PCU entre os municípios. O estudo destacou boas condições de solo e declive na região, mas também enfrenta desafios com baixo rendimento hídrico anual. Assim, enfatiza-se que a adoção de SSP autóctones pode trazer benefícios em áreas de alta aptidão. Em conclusão, a adoção de SSP autóctones em tipos de cobertura de terra de alta aptidão, como formação de savana, culturas perenes e plantações florestais, oferece uma estratégia viável para melhorar os serviços ecossistêmicos, apoiar a conservação da biodiversidade e promover o uso sustentável da terra. Esta pesquisa também destaca o papel das políticas públicas, como o pagamento por serviços ambientais, na promoção e facilitação da adoção de SSP autóctones.

Palavras-chave: Sistemas agroflorestais; Cerrado; Degradação da terra; Serviços ecossistêmicos. Políticas públicas.

SUMMARY

Contents

GENERAL INTRODUCTION

The Brazilian Cerrado biome covers 2 million km² and is the richest and most endangered woodland and tree savanna globally (BENDINI et al., 2020). Internationally recognized as a biodiversity hotspot of great environmental importance, the Cerrado is home of over 12,000 plant species, with a remarkable 35% being endemic (MYERS et al., 2000; ZAPPI et al., 2015). The biome's genetic diversity holds high potential for the future improvement and adaptation of economically important crops and pharmaceuticals. The biome plays a crucial role in maintaining ecological balance, contributing to water security, carbon storage, and climate regulation (DURIGAN et al., 2022).

The Cerrado's ecological significance extends to regional water cycles, as its river basins supply eight of Brazil's twelve hydrographic regions, influencing water availability both within and beyond national borders (LAHSEN; BUSTAMANTE; DALLA-NORA, 2016). Additionally, the Cerrado supports the livelihoods, income, and nutrition of over 80 ethnic and traditional communities, including Geraizeiros and Quilombolas (BARBOSA et al., 2020; LIMA et al., 2012). Despite its critical ecological and socioeconomic roles, the Cerrado faces severe threats from extensive agricultural expansion, particularly soybean cultivation and cattle ranching, which lead to deforestation, habitat fragmentation, and land degradation (NOOJIPADY et al., 2017). Over recent decades, the Cerrado's original vegetation extent has been nearly halved due to deforestation, making it the Brazilian biome with the highest deforestation rate (MAPBIOMAS PROJECT, 2023). The conversion of native vegetation to agricultural and livestock lands has resulted in significant biodiversity loss, soil erosion, and depletion of water resources (GOMES et al., 2020).

Despite the potential for sustainable management through smallholder farming systems, these practices are often less profitable and less encouraged from a regulatory perspective (DE OLIVEIRA SILVA et al., 2017). The biome produces 55% of Brazil's cattle, although 46% of cultivated pasture areas are degraded, undermining both ecological integrity and economic viability (PARENTE et al., 2017; PEREIRA et al., 2018). To counter these challenges, promoting locally adapted silvopastoral systems (SPS) emerges as a promising strategy. SPS integrate sustainable livestock production with indigenous tree species, offering multiple environmental and economic benefits (BRUZIGUESSI et al., 2021). These autochthonous systems can rehabilitate degraded lands, enhance biodiversity, increase carbon stocks, and improve the livelihoods and resilience of smallholders (SHI et al., 2018). Furthermore, the diverse ecosystem services provided by SPS, such as carbon sequestration and water regulation, hold potential for monetization, contributing to rural income and employment (VILLA; BERNAL, 2018).

Autochthonous SPS, developed by family farmers and local communities, include extensive cattle farming in native savanna forests and the incorporation of native shrubs and trees in pastures. However, these systems have not been systematically analyzed regarding their spatial extent, structure, potential distribution or socioeconomic benefits and hinder further adoption. Addressing these knowledge gaps and barriers to adoption, this thesis aims to conduct a comprehensive analysis of SPS. The objective is twofold: first, to perform a global bibliometric analysis to understand trends, challenges, and opportunities in SPS adoption research; second, to assess the potential for SPS adoption in the Brazilian Cerrado. By identifying key factors influencing adoption and mapping priority zones for implementation, this research seeks to promote sustainable agricultural practices that mitigate environmental impacts, conserve biodiversity, and enhance the livelihoods of local communities.

THESIS STRUCTURE

The document begins with a general introduction that provides an overview of the Brazilian Cerrado biome, its significance as a bidioviersity hotspot, and the severe threats it faces from agricultural expansion and land degradation. The introduction sets the stage for the research by highlighting the importance of the biom and the unexplored potential of autochthonous silvopastoral systems (SPS) as a sustainable land management strategy to be adopted. The study is divided into two main chapters: First, a bibliometric review on the perspectives of silvopastoral adoption, and the second is an analysis of the identification of priority zones for silvopastoral system adoption in the Rio Pardo and São João do Paraíso watersheds.

In chapter 1, *Global perspectives on silvopastoral system adoption – A bibliometric analysis*, it is presented a bibliometric and systematic analysis of global research on the adoption of silvopastoral systems is presented. The chapter delves into exploring the main barriers and opportunities that promote or hinder the adoption of SPS. The focus of this chapter is on understanding the factors influencing the adoption of SPS globally, through the bibliometric indicators and findings of the research.

Chapter 2, *Identification of priority zones for silvopastoral system*s in the Brazilian Cerrado, assesses the priority zones for SPS through the use of the potential for conservationist use indicator (PCU) in the study region. This chapter outlines the biophysical parameters of the, evaluates the PCU in the watersheds, and identifies priority zones for SPS adoption.

The research concludes with a general synthesis of the findings from both chapters. The thesis is structured to provide a comprehensive exploration of the topic, from a global bibliometric perspective to a focused regional analysis, demonstrating the potential and adoptability of silvopastoral systems.

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CHAPTER 1: Global perspectives on silvopastoral system adoption: A bibliometric analysis

1. INTRODUCTION

Beef and milk production are high-quality protein sources with increasing demand and positive impacts on global food security (GREENWOOD, 2021; OPADOYIN TONA, 2022). However, land use change, especially the expansion of pastures and their subsequent degradation, raises a significant challenge for environmental conservation on a global scale. Conventional livestock farming can be associated with a range of negative impacts, including biodiversity loss, soil and water quality degradation, and impacts on the livelihoods of rural communities (CHRISTEL; MARON; RANJARD, 2021; FILAZZOLA et al., 2020). Despite these negative effects, pastures occupy 66% of the world's agricultural areas (FAO, 2023), with high percentages of land degradation. Degraded pastures lead to decreased soil fertility, increased erosion and intensification of surface water runoff (BRUZIGUESSI et al., 2021).

The adoption of agricultural innovations (technologies, practices, and knowledge) is a common practice for improving farmers' livelihoods (AMARE; DARR, 2024), especially considering increasingly adverse climatic conditions. SPS are recognized for their sustainable approach that integrates trees, shrubs, and palms with livestock farming, offering benefits such as soil conservation, enhanced carbon storage, climate change mitigation, and income diversification for farmers (RESENDE et al., 2020; RÖHRIG; HASSLER; ROESLER, 2020). Given its multiple advantages, the importance of SPS for farmers worldwide is immense. These systems represent a sustainable and effective alternative to address global challenges such as deforestation, soil degradation, and climate change, while promoting environmental conservation and the resilience of rural communities (CHEBLI et al., 2021; LEMES et al., 2021).

As research on SPS advances, knowledge related to the socio-environmental and economic interactions present in these systems increases (MAURICIO et al., 2019). However, as crucial as understanding the system concept and its interactions is crucial, it is necessary to discuss the adoptability of these livestock production models. The effective implementation of these systems depends on farmers' interest and adoption (B.K. DAGANG; NAIR, 2003). In this context, it is essential to investigate the factors that influence the adoption of SPS, going beyond purely environmental aspects (FEDER; O'MARA, 1982). Among these factors, socioeconomic, cultural, environmental, and technical aspects play a crucial role in farmers' decision-making (LEE et al., 2020). However, the complex and multidisciplinary nature of SPS reveals difficulties for studies that focus on identifying these key factors, acting as a barrier to current knowledge and applicability, thus hindering the advance of system adoption.

In this scenario, bibliometric analysis (BA) merges as a strategy to systematically evaluate changes in the SPS research framework (TORRES et al., 2023). Additionally, it proves useful in identifying research leaders, relevant collaboration channels and networks, as well as in assessing the quality of institutions and journals. This type of study has gained prominence in recent years (LUO et al., 2020; MKHONGI; MUSAKWA, 2022). BA highlights relevant literature and provides crucial information such as keywords, institutions, and country connections, in addition to mapping knowledge distribution characteristics (ELLEGAARD; WALLIN, 2015). As a result, several studies incorporate BA to analyze various areas of knowledge, such as land use and cover in tropical forests and ecosystem services (MOHD RAZALI et al., 2022; XU; XIAO, 2022).

The present study aims to conduct an exploratory review of the evolution of international research on the adoption of silvopastoral systems and their implementation barriers, from a quantitative and qualitative perspective, focusing on changes in approach over time.

2. MATERIAL AND METHODS

In this study, a bibliometric analysis was conducted based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, which enables a transparent, agile, and efficient analysis of a selection of scientific documents (PAGE et al., 2021). The study was divided into four phases to optimize the analysis of global scientific production on the adoption of SPS (Figure 1): (I) search criteria and database selection; (II) exclusion criteria; (III) eligibility; and (IV) data interpretation.

2.1. Search Criteria and database selection

A successful BA relies on the collection of comprehensive and reliable academic research information. For this study, the Scopus scientific database was used. Considered the largest database of abstracts and citations of peer-reviewed literature, it contains more than 22,000 titles from over 5,000 publishers worldwide and covers all areas of science, technology, medicine, social sciences, and arts and humanities (ZHU; LIU, 2020).

The search for documents in the Scopus database was conducted in October 2023, using information from titles, abstracts, and keywords. Given the specific topic of SPS, two words were used in the search process: one representing the system and the other related to its adoption. The process was conducted based on the search mode function with advanced settings as follows: TITLE-ABS-KEY (silvopastoral OR silvopasture OR "livestock-forestry") AND (adoption AND barriers OR likelihood OR "determinant factors" OR willingness OR "decision-making" OR "adoption drivers" OR "adoptability"). The search did not restrict the publication date, and the search with these keywords returned 110 documents.

2.2. Exclusion Criteria

Initially, the titles were read to confirm the topic addressed, and when nuclear, the respective document's abstract was read. All 110 documents underwent this process and resulted in 64 remaining scientific documents.

Following, a consistency analysis of the Scopus database was conducted, where only documents categorized as ARTICLE, BOOK CHAPTER, and REVIEW were kept. These categories were selected because they represent the most widely used documents in academia (DHILLON, 2022; LINNENLUECKE; MARRONE; SINGH, 2020) They are extensively used as they provide greater depth on the analyzed topic, are more comprehensive, and undergo rigorous review processes, providing greater reliability of the information (DONTHU et al., 2021). Additionally, only documents in the final stage of publication and published before October 2023 were retained. Under these criteria, 6 documents were eliminated, and 58 remained.

2.3. Eligibility

In the eligibility analysis, methods were employed to eliminate duplicates and erroneous files. The data was then analyzed using the Rstudio software with the Bibliometrix package version 4.1.3 for bibliometric analysis (ARIA; CUCCURULLO, 2017; POSIT TEAM, 2022).

After obtaining the data from the Scopus platform, the files were exported in BibTex format, which includes bibliographic information, citations, abstracts, keywords, and references for each selected document.

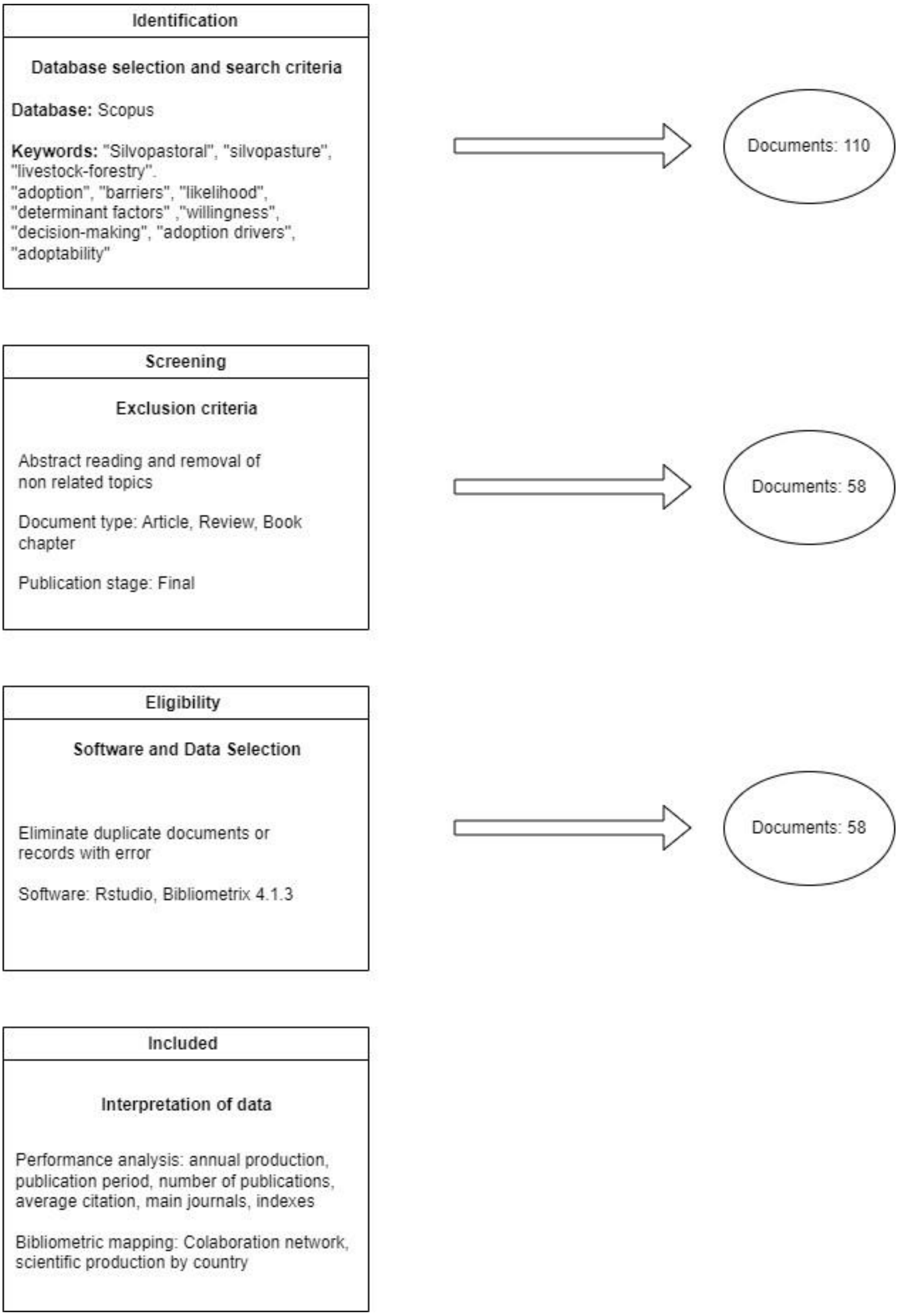

Figure 1: Diagram based on the PRISMA methodology, describing the four phases of bibliometric research.

2.4. Data Analysis

Performance and Relevance analysis

Initially, an exploratory analysis was conducted using the BibTex file format in the Rstudio environment. Key metrics such as annual scientific production, publication period on the topic, number of published documents, and Leading publishing journals were extracted. To assist in the journal analysis, two indices were used for evaluation: Scimago Journal & Country Rank (SJR) and Journal Impact Factor (JIF) calculated by Clarivate Analytics. Both indices are commonly used to assess journal quality by evaluating the number of citations received (BORNMANN et al., 2012).

The SJR is estimated from the average number of citations received in a year by articles published in the journal over the last three years (BUTLER, 2008). On the other hand, the JIF considers the number of citations of articles published in the source journal in the previous two years, divided by the number of items published in that journal over the last two years (KURMIS, 2003).

Analysis of key adoption factors

The factors influencing the adoption of SPS were systematically extracted through a thorough reading of all documents. This includes variables of the economic, environmental and sociocultural fields, reported in the literature. The factors identified as influencing the adoption of SPS were examined and categorized into the domains of influence, such as socioeconomic, technical/operational, environmental, cultural, and regulatory aspects (CHILLO et al., 2021).

Initially, each factor was individually evaluated regarding its nature and effect on SPS adoption. Subsequently, they were grouped according to observed patterns during the literature review, considering conceptual and operational similarities between them. This systematic classification approach provided a solid foundation for subsequent analysis, based on similarities and patterns analyzed to discern the importance of each adoption factor.

Bibliometric mapping

For the bibliometric mapping of the topic, data on scientific production at country level was obtained based on the affiliation country of each author. This allowed the calculation of intranational and international collaboration indices, represented by the number of single-country publications (SCP) and multi-country publications (MCP), respectively.

Finally, a collaborative scientific network was generated to evaluate the relationships and intensities of knowledge and technology transfer between authors from different countries. The analysis of collaboration between countries tends to highlight interactions between authors of different nationalities in joint publications, while network analysis can offer a broader view of connections between authors, institutions, and other entities.

3. RESULTS

3.1. Relevance and Overall performance

The publication period identified on the Scopus platform regarding the adoption of SPSs spans from 2007 to 2023, with a total of 58 documents authored by 259 authors and resulted in an average of approximately four authors per publication (Table 1).

Table 1: Key information from the database linked to the 58 analyzed documents.

DESCRIPTION	RESULTS
Main information about data	
Timespan	2007:2023
Sources (Journals, Books, etc)	35
Documents	58
Annual Growth Rate %	14.7
Average citations per doc	18.4
Average citations per year per doc	3.1
Document types	
Article	53
Book chapter	1
Review	4
Authors	
Authors	259
Author Appearances	297
AUTHORS COLLABORATION	
Single-authored docs	2
Documents per Author	0.2
Co-Authors per Doc	5.1
International co-authorships %	48.3

Research in the field of SPS adoption has shown considerable growth in recent years, with an annual publication growth rate of 14.7%. This growth is more pronounced in recent years, from 2019-2023 (Figure 2). In ascending order of the number of publications per year: 2019 (3 documents), 2021 (5 documents), 2023 (9 documents), 2020 (11 documents), and 2022 (18 documents).

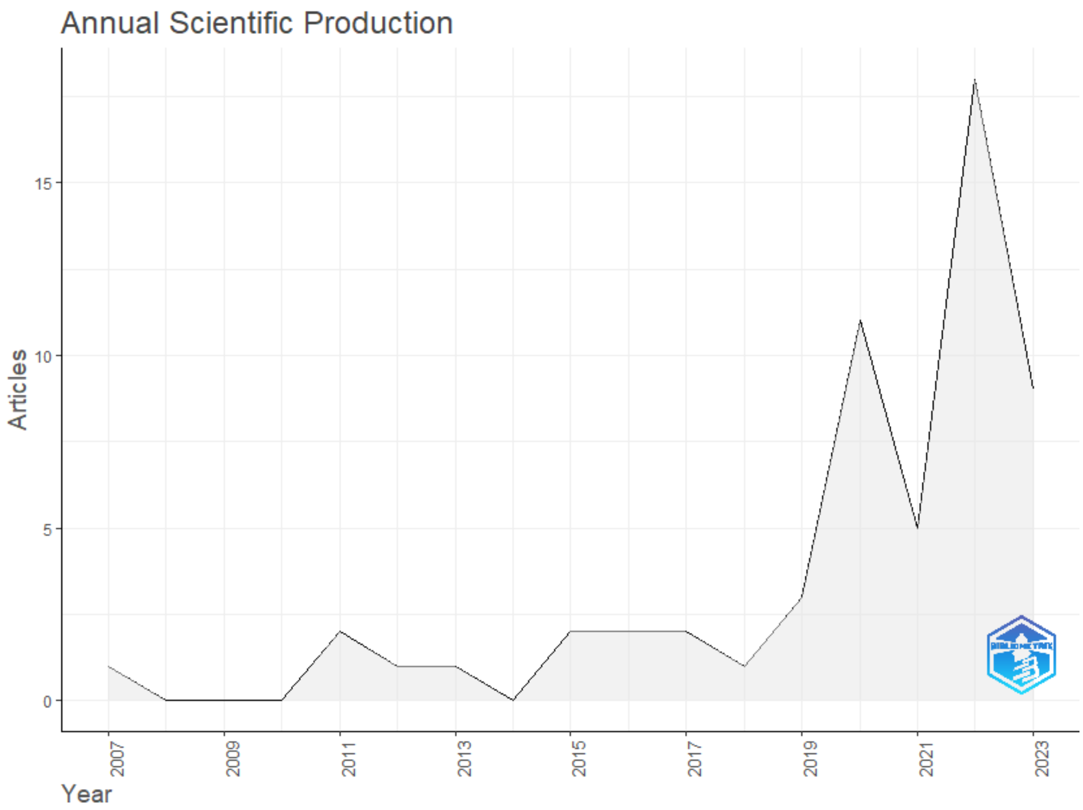

Figure 2: Annual scientific production for studies on the adoption of SPS in international literature (2007-2023).

The analysis revealed that 35 scientific journals published the examined documents, in parallel with the increase in publications in recent years. Among the top 10 journals with the most publications, Agroforestry Systems stands out with 10 documents published, followed by AMBIO, Forest Policy and Economics, Land Use Policy, and Sustainability (Switzerland), each with 3 studies (Table 2). These top 5 journals account for 37.9% of all analyzed publications.

Table 2: Top ten journals with their SCImago Journal rankings and Impact Factor (2007-2023)

Sources	Articles	SJR 2023	JIF 2022
Agroforestry Systems	10	0.51	2.2
Land Use Policy	3	1.85	7.1
AMBIO	3	1.79	6.5
Forest Policy and Economics	3	1.31	4
Sustainability (Switzerland)	3	0.67	3.9
Tropical and Subtropical Agroecosystems	3	0.18	0.6
Ecological Economics	2	1.98	7
Forest Ecology and Management	2	1.20	3.7
Environmental Management	2	0.83	3.5
Agronomy	2	0.69	3.7

Noteworthy SJR indices include those of Ecological Economics (1.98), Land Use Policy (1.85), AMBIO (1.79), Forest Policy and Economics (1.31), and Forest Ecology and Management (1.20). Despite leading in the number of publications, Agroforestry Systems has a SJR index of 0.51, the lowest among the top five journals.

3.2. Listed Factors

A total of 21 factors were identified and categorized into five groups: socioeconomic, technical/operational, environmental, cultural, and regulatory. The socioeconomic group stands out with 11 factors (Table 3), followed by the environmental and technical/operational groups, each with three factors.

Table 3: Main factors found in literature.

Table 3 – Cont.

Class	Factor	Frequency	References	Context
	Gender	5	Khatri et al., 2023; Opdenbosch et al., 2023; Sandino et al., 2023; Tschopp et al., 2020; Tschopp et al., 2022;	Affects decisions and power relations to adopt SPS.
Socioeconomic	Age	4	Charry et al., 2019; Rois Diaz et al., 2018; Smith et al., 2022b; Zabala et al., 2022; Zapata et al., 2015;	Plays a role in the willingness and ability to adopt SPS.
	Education	6	Bussoni et al., 2015; Charry et al., 2019; Opdenbosch et al., 2023; Rozaki et al., 2021; Tschopp et al., 2022; Varela et al., 2022;	Impacts understanding and acceptance of agroforestry practices.
	Farm size	7	Bussoni et al., 2015; Gebremedhin et al., 2023; Hadera et al., 2023; Khatri et al., 2023; Tschopp et al., 2020; Varela et al., 2022; Zabala et al., 2022;	Influences the economic viability of SPS adoption.
	Family income	6	Apan-Salcedo et al., 2021; Charry et al., 2019; Gebremedhin et al., 2023; Khatri et al., 2023; Opdenbosch et al., 2023; Rodríguez et al., 2022;	Assesses financial capacity to cover costs associated with the implementation and maintenance of SPS.

To be continued…

Table 3 – Cont.

Class	Factor	Frequency	References	Context
Socioeconomic	Herd size	5	Gebremedhin et al., 2023; Gonzales et al., 2019; Jara-Rojas et al., 2020; Khatri et al., 2023; Zapata et al., 2015;	Impacts adoption decisions, considering the integration between trees and pastures.
	Credit access	4	Fuentes et al., 2022; Jara-Rojas et al., 2020; Silveira et al., 2022; Tobar Lopez et al., 2022;	Influences the ability to invest in agroforestry practices.
	Mechanization level	3	Mora et al., 2021; Rodríguez et al., 2022; Wilson et al., 2016;	Affects the ease of implementing SPS, considering the compatibility of practices with more mechanized systems.
	Implementation costs	11	Seonhwa Lee et al., 2020; Bussoni et al., 2015; Calle et al., 2020; Davis et al., 2020; Fuentes et al., 2022; Gonzales et al., 2019; Gosling et al., 2021; Lojka et al., 2022; Murgueitio et al., 2011; Rois Diaz et al., 2018; Wilson et al., 2016;	Represents a significant barrier for farmers and acts as a primary initial barrier.
	Lack of knowledge	9	Apan-Salcedo et al., 2021; Bussoni et al., 2015; Fuentes et al., 2022; Mayerfeld et al., 2023; Murgueitio et al., 2011; Rodríguez et al., 2022; Rois Diaz et al., 2018; Silveira et al., 2022; Smith et al., 2022b;	Affects the implementation and maintenance of SPS and limits the emergence of new systems.

To be continued…

Table 3 – Cont.

Class	Factor	Frequency	References	Context
Socioeconomic	Land tenure	11	Fuentes et al., 2022; Keeley et al., 2019; Mayerfeld et al., 2016; Rois Diaz et al., 2018; Silveira et al., 2022; Smith et al., 2022a; Tobar Lopez et al., 2022; Torres et al., 2023; Tschopp et al., 2020; Tschopp et al., 2022; Conway and Nieman 2022;	Fundamental for long-term decision-making, influencing farmers' willingness to invest in agroforestry practices.
	Market for the product	5	Apan-Salcedo et al., 2021; Fuentes et al.,2022; Gosling et al., 2021; Mayerfeld et al., 2023; Smith et al., 2022b;	Essential to ensure economic sustainability and encourage SPS adoption.
Technical/Operational	Extension services access	3	Fuentes et al., 2022; Khatri et al., 2023; Stutzman et al., 2020;	Facilitates the dissemination of knowledge about SPS and influences adoption among farmers.
	Labor intensive	10	Seonhwa Lee et al., 2020; Calle et al., 2020; Davis et al, 2020; Gonzales et al., 2019; Gosling et al., 2021; Lojka et al., 2022; Rois Diaz et al., 2018; Thiesmeier et al., 2023; Varela et al., 2022; Wilson et al., 2016;	Labor intensity can discourage farmers to try new practices.
	Access to seeds/seedlings	3	Fuentes et al., 2022; Gosling et al., 2021; Mora et al., 2021;	Directly impacts the ability to implement SPS.

To be continued…

Table 3 – Cont.

Class	Factor	Frequency	References	Context
Environmental	Shadow for livestock	5	Seonhwa Lee et al., 2020; Bussoni et al., 2015; Calle et al., 2020; Davis et al., 2020; Wilkens et al., 2022;	Influences animal welfare and production.
	Relief	3	Apan-Salcedo et al., 2021; Jara-Rojas et al., 2020; Zapata et al., 2015;	Affects the implementation of SPS, considering drainage and adaptation to different topographies.
	Spring presence	2	Jara-Rojas et al., 2020; Varela et al., 2022;	Influences the availability of water on the property.
Cultural	Risk/time preference	4	Seonhwa Lee et al., 2020; Fuentes et al., 2022; Gebremedhin et al., 2023; Hadera et al., 2023;	Willingness to take risks and invest time in SPS is crucial and directly affects adoption decisions.
Regulatory	Payment for environmental services	13	Baker et al., 2023; Calle et al., 2013; Calle et al., 2020; Fuentes et al., 2022; Hayes et al., 2012; Lojka et al., 2022; Montagnini et al., 2023; Nunez et al., 2022; Raes et al., 2017; Tarbox et al., 2020; Thiesmeier et al., 2023; Vieira et al., 2022; Zabala et al., 2017;	Can stimulate the adoption of SPS and contribute to economic sustainability.

To be continued…

Table 3 – Cont.

Class	Factor	Frequency	References	Context
Regulatory	Government subsidies	8	Carriazo et al., 2020; Fuentes et al., 2022; Gosling et al., 2021; Mayerfeld et al., 2023; Murgueitio et al., 2011; Stutzman et al., 2020; Thiesmeier et al., 2023; Torres et al., 2023;	Availability of government subsidies can encourage SPS adoption.

Payment for environmental services, implementation cost, and land tenure are the three most mentioned factors affecting the adoption of SPS. Other factors, such as labor intensity, lack of knowledge, and government subsidies, are also frequently used to assess the adoption of SPS. Less frequent factors, such as the presence of springs, access to extension services, and access to credit, have only been listed since 2020, highlighting the inclusion of new factors in recent studies.

3.3. Bibliometric mapping

In total, 19 countries published on the topic, with the top five accounting for 58.7% of the total number of publications. The USA and Germany stand out with 18 and 6 publications each. USA, Germany, Colombia, and Mexico are the leading countries in multiple-country publications (MCP), while Brazil produced only three publications, all of which were single-country collaborations (SCP) (Figure 3).

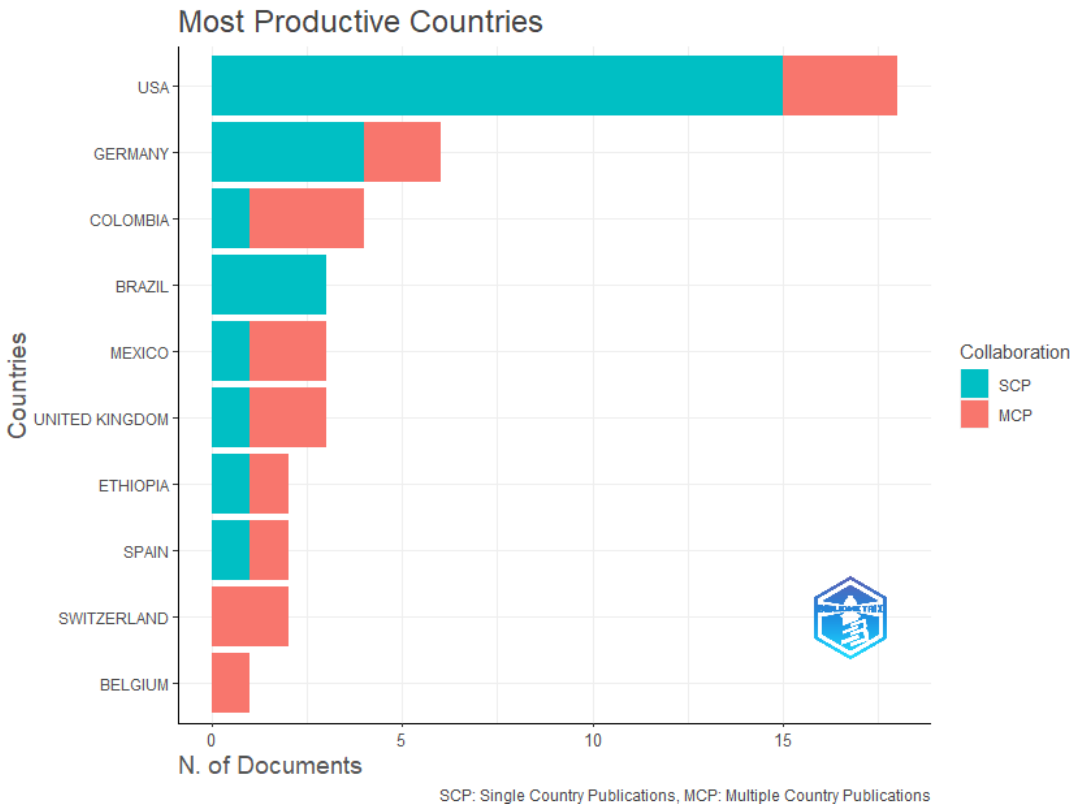

Figure 3: Single country (SCP) and Multiple country (MCP) publications from 2007-2023.

From 2007 to 2023, the collaborative network consisted of 35 nodes and 268 links. Although a considerable number of countries publish on the topic, six interactive groups can be identified. A discernible collaboration pattern emerges, with one large primary group accompanied by two subgroups, as shown in Figure

4. The primary group includes Argentina, South Africa, Brazil, India, Nepal, Uruguay, Costa Rica, France, Sweden, Germany, Canada, Trinidad and Tobago, the Netherlands, Colombia, and the USA. The satellite subgroups are Belgium, Ecuador, and Peru; followed by the Czech Republic, Switzerland, Mexico, Spain, Portugal, Hungary, Greece, Finland, Italy, and the United Kingdom. Additionally, three smaller groups consisting of Japan, Malaysia and Indonesia (3 countries); Ethiopia and Norway (2 countries); and Chile and Australia (2 countries), are evident and lack collaboration with the aforementioned groups.

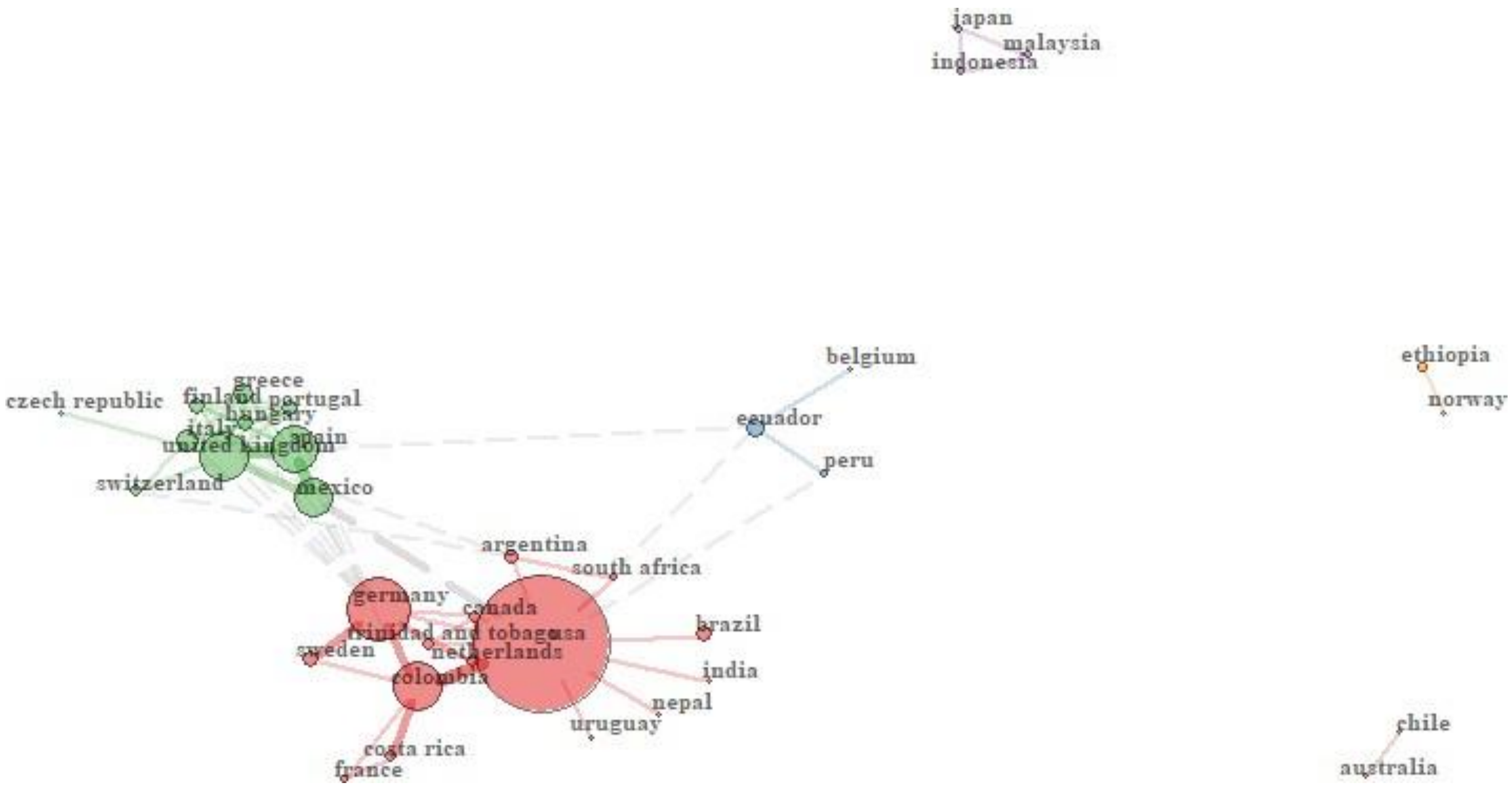

Figure 4: Global collaborative network in studies on the adoption of SPS (2007-2023) Where: Each node on the map represents a country, with the size of the node indicating the number of publications from that country. The links between nodes represent cooperation between countries and its thickness represents the intensity of the cooperation

4. DISCUSSION

4.1. Relevance and Overall performance

Studies about SPS’s have been conducted and documented since the 1980s (NAIR, 1985; WAIRIU; MULLINS; CAMPBELL, 1993). However, based on the analysis, we observed that studies focusing on the adoption of silvopastoral systems were first reported by the Scopus database in 2007. This indicates that while the benefits of SPS’s have been recognized for decades, attention to the factors influencing their adoption—both the motivations and the barriers—has only emerged more recently. However, the high number of identified authors (259) and different nationalities indicate the global relevance of the topic, even though significant growth in this area has occurred mostly in recent years.

Since 2015, the volume of research has increased, possibly motivated by the Sustainable Development Goals (SDGs) and the Paris Agreement (UN GENERAL ASSEMBLY, 2015). The research started to detail barriers and demonstrated that the high establishment cost, farmers' inexperience with agroforestry systems, and the demand for time and knowledge for management have contributed to SPS low adoption (MAYERFELD; RICKENBACH; RISSMAN, 2016; WILSON; LOVELL, 2016).

However, despite the documented benefits, there are still gaps in the number of studies related to SPS adoption. These gaps reflect the complexity associated with studying this topic and reinforce the difficulty involved in farmers' decision to adopt SPS, such as the importance of behavioral and cultural factors in this decision (OPDENBOSCH; HANSSON, 2023)

Between 2017-2019, research focused on farmers' motivation, showing that both in conventional livestock farming and SSPs, adoption is primarily driven by cultural traditions that perpetuate existing agricultural systems, seen as financially stable (ROIS-DÍAZ et al., 2018). The stability provided by payment for environmental services (PES) becomes an encouraging factor for rural owners despite the lack of knowledge about SPSs. However, farmers report that the lack of funding and technology affects their decision to make changes to the current production system (CHARRY et al., 2019; FLORES-GONZÁLEZ et al., 2019; ZABALA; PASCUAL; GARCÍA-BARRIOS, 2017).

The growing trend in research to understand farmer's perspective reached its peak in 2022, with a 500% increase in the number of publications since 2019 The period from 2020 to 2023 accounted for 74.13% of total publications related to the reasons for adopting SSP or their potential barriers. Possibly pressured by the effects of climate change on ecological functions, ecosystem services, and agricultural production systems, researchers sought to understand why more resilient and sustainable production systems, such as SPS, were still not being widely implemented (DI SANTO; RUSSO; SISTO, 2022)

Between 2020-2021, studies in different countries began to demonstrate similar indicators as barriers to adoption, highlighting the association between the adoption of sustainable integrated systems and factors such as access to credit, land security, system profitability, management intensity, and geographic region (CARRIAZO; LABARTA; ESCOBEDO, 2020; DAVIS; RAUSSER, 2020; GOSLING et al., 2020; KEELEY et al., 2019; TSCHOPP et al., 2020). Despite these challenges, there has been a growing interest among financiers and environmental managers in promoting silvopastoral systems as alternatives for the livestock sector (GOSLING et al., 2020). This interest stems from the potential of SPS to enhance sustainability and resilience in agricultural practices. By addressing the identified barriers, policy makers and researchers aim to facilitate the wider adoption of these systems, thereby contributing to more sustainable agricultural landscapes and improved ecological functions.

The multidisciplinary nature of SPS research is reflected in the number of journals where studies are published, covering not only agricultural and forestry aspects but also socioeconomic, environmental, and cultural issues (SALES-BAPTISTA; FERRAZ-DE-OLIVEIRA, 2021). This can also be observed by the wide variance in the main categories of topics addressed in each journal. The importance of the SPS can also be highlighted as studies are published in journals such as Ambio and Ecological Economics that have high influence and prestige, indicated by their high SJR and impact factor values.

It is interesting to note that the preference for certain journals may be influenced not only by the quality of publications but also by each journal's specific focus and approach to the studied theme (XU et al., 2023). This may explain the leadership of the journal Agroforestry Systems in the number of publications on the topic and the preference authors show when selecting where to publish their work. Such decisions allow researchers, academics, and professionals immersed in this field to know where to find quality information.

4.2. Listed Factors

Due to the multidisciplinary nature of SPS and its ecological attractiveness, many factors have been listed and classified into different groups that affect the adoption of this system model (KHATRI et al., 2023; TSCHOPP et al., 2020; TSCHOPP; CEDDIA; INGUAGGIATO, 2022). The difficulty in determining relevant variables that influence the adoption of SPS and the need to evaluate the variables individually and meticulously is one of the challenges of SSPs compared to other production systems (ZAPATA; ROBALINO; SOLARTE, 2015).

The predominant approach focused on highlighting the advantages of SSP, without an in-depth analysis of issues related to its adoption, may have limited the availability of specific data on the barriers and facilitators encountered by farmers (SMITH et al., 2022). This may have directly impacted the number of publications found for bibliometric analysis, as detailed information on adoption processes may not have been widely documented. The studies found have focused on understanding the barriers related to the adoption of silvopastoral systems and proposing strategies aimed at enabling and disseminating these more ecologically favorable systems (RÖHRIG; HASSLER; ROESLER, 2020) as a strategy to mitigate the environmental impacts in the livestock sector (CALLE et al., 2013; HAYES, 2012).

Due to their typically higher implementation costs, lack of knowledge, and labor intensity, the systems require incentive mechanisms (FUENTES et al., 2022; ROIS-DÍAZ et al., 2018; THIESMEIER; ZANDER, 2023), such as payment for environmental services (PES) and government subsidies, one of the reasons for their high frequency among the listed factors (BAKER et al., 2023; FUENTES et al., 2022; LOJKA et al., 2022). Studies evaluated the effect of PES implementation and noted a significant increase in SPS adoption in Colombia (ZAPATA; ROBALINO; SOLARTE, 2015), highlighting the positive impact of public policies in promoting these systems. It is worth noting that similar studies played a crucial role in formulating public policies and government subsidies (BUSSONI et al., 2015).

Aversion to ambiguity, characterized by uncertainty about the benefits and challenges associated with the intensive adoption of SPS, emerges as a barrier. This uncertainty reduces incentives for adoption, particularly regarding soil and water conservation structures, where high fixed costs can discourage farmers. This is especially true when the benefits are not immediately clear or valued (FUENTES et al., 2022; GEBREMEDHIN et al., 2023). Additionally, ambiguity aversion can influence the persistence of SPS over time, as the lack of recognized benefits further deters farmers. Therefore, it is essential to consider the various socioeconomic factors that impact the decision to adopt SSP, with a focus on identifying farmers who are more likely to succeed with these systems.

In the most current scenarios, the uncertainty around the risks associated with SPS adoption is meticulously explored (GEBREMEDHIN et al., 2023; HADERA; TADESSE, 2023; THIESMEIER; ZANDER, 2023). Additionally, land tenure emerges as a crucial factor contributing to this uncertainty. Landowners may face challenges such as lack of land security, legal disputes, or bureaucratic difficulties that increase hesitation in investing in long-term agroforestry practices, such as SPS (FUENTES et al., 2022; TSCHOPP et al., 2020).

The complex nature of such systems and their potential products can present challenging management and harvesting logistics for non-timber forest products (NTFPs). Alongside the harvesting challenges for NTFPs, market insecurity for these products is also reported due to the lack of a consolidated market for the diversity of products in SSP. The need for mechanization can be a challenge in integrated systems with high species diversity, and the current level of technicality of rural producers, especially small ones, acts as barriers to adoption (CHITAKIRA; TORQUEBIAU, 2010; VALDIVIA; BARBIERI; GOLD, 2012).

As research on SPS progresses, it has become evident through the publications identified in this study that besides technical and environmental barriers, inherent due to the lack of knowledge and complexity of the systems, financial and economic barriers have a great impact on SPS adoption (B.K. DAGANG; NAIR, 2003). For instance, Financial Capital and Knowledge are the two major groups affecting adoption of SPS in Latin America (MURGUEITIO et al., 2011).

The literature shows that a portion of farmers is willing to adopt these systems if guaranteed financial compensations (ALVARADO SANDINO et al., 2023; BAKER et al., 2023; KHATRI et al., 2023; OPDENBOSCH; HANSSON, 2023). Although these compensations are an incentive for SPS adoption, decision-making is not exclusively driven by profit maximization but is also influenced by non-monetary considerations (ZABALA; PASCUAL; GARCÍA-BARRIOS, 2017). Additionally, the inclusion of new factors over the years, such as the presence of springs and extension services, demonstrates the advancement of studies on the topic and the need for contextualized analysis, considering specific factors, whether local or regional, such as market access and opportunities for SPS producers (KALOUDIS et al., 2021; VARGAS-DE LA MORA et al., 2021).

4.3. Bibliometric mapping

Scientific collaboration between countries is a fundamental aspect for the advancement of knowledge and technological innovation on a global scale (CHOI; YANG; PARK, 2015; LEITE; PINHO, 2017). As demonstrated, of the five main countries in scientific production on SSP adoption – USA, Germany, Colombia, Brazil, and Mexico – only Brazil showed exclusively intranational collaboration (SCP). This characteristic can be attributed to various reasons, such as language barriers and lack of incentives for international collaborations (HWANG, 2013).

The analysis of collaboration networks plays a fundamental role in understanding the dynamics of scientific research in such an interdisciplinary theme as SPS. It is noted that the countries with the highest number of publications on the topic make up, among others, the main group of the collaborative network. These same countries were observed as leaders in SSP publications in previous studies (TORRES et al., 2023). Despite the large total number of connections (links) between nodes, there is a low density of interconnections on the network map. This reflects the still limited collaboration between countries, authors, and institutions in SPS adoption research, possibly related to the need for differentiated and specific approaches for each context (MAYERFELD et al., 2023; SINGH; SINGH, 2023; VARELA et al., 2022).

Finally, agroforestry systems, specifically SPS, reveal a complex and challenging scenario regarding their widespread adoption. Furthermore, scientific collaboration between countries and institutions emerges as a crucial strategy to advance knowledge and develop innovative solutions that contribute to environmental and socioeconomic sustainability in the agricultural sector. These efforts are essential to address global and local challenges and promote more resilient agricultural practices in the future.

5. CONCLUSION

This study indicates trends in the field of silvopastoral systems (SPS) adoption, highlighting the notable evolution in the volume and approach of scientific publications over time. Since the first identified publication in 2007, global interest in SSP has grown, especially after 2015 and more markedly between 2020 and 2023.

Although the high global relevance and collaborative approach with the participation of 19 countries in SPS adoption research were identified, this topic is challenging and constantly developing, with the inclusion of new factors. It is crucial to understand the specific variables that influence SPS adoption and evaluate them meticulously, considering the regional context. A total of 21 main factors affecting SSP adoption are listed, subdivided into 5 distinct groups.

The high number of citations in the regulatory class factors highlights the important role that public policies and government programs play in disseminating and adopting new technologies, such as SPS. Programs like payment for environmental services (PES) indicate a positive impact on SPS promotion and adoption. Support mechanisms, such as specialized technical assistance, play a crucial role in facilitating the dissemination of SPS and breaking paradigms such as lack of knowledge or difficulty accessing credit, subsidies, and seeds/seedlings.

In conclusion, the evolution of research on SPS adoption reflects a growing interest and a significant shift in approach, highlighting the importance of socioeconomic factors, public policies, and support mechanisms. This broader and more holistic panorama reinforces the ongoing need to understand and address the complexities of SPS adoption to promote more sustainable and effective practices.

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CHAPTER 2: Identification of priority zones for silvopastoral systems in the Brazilian Cerrado.

1. INTRODUCTION

Land use/cover change and climate change are two critical planetary boundaries that have been surpassed, causing shifts in biomes across the globe (STEFFEN et al., 2015). Among the affected regions, savannahs are experiencing significant losses due to land degradation and conversion, making them particularly more susceptible to the impacts of climate change (DUDLEY et al., 2020; SCHEITER et al., 2019). Several studies have documented changes in land use and native vegetation composition within savanna ecosystems (DIMOBE et al., 2015; HOUESSOU et al., 2013; LESSMEISTER et al., 2019), ultimately leading to a decline in biodiversity, ecosystem functioning, and ecosystem services (ES) on a global scale (BALIMA et al., 2020; MACE; NORRIS; FITTER, 2012; OSBORNE et al., 2018).

The Brazilian Cerrado biome encompasses an area of 2 million km², representing approximately 22% of Brazil's national territory and is the largest Neotropical savanna (DURIGAN et al., 2022). Cerrado is the richest and most endangered world savanna and a biodiversity hotspot of global importance, (BORGIANI et al., 2022; MYERS et al., 2000). This biome includes over 12,000 plant species of which 35% are endemic (ZAPPI et al., 2015) and it plays a key role to climate mitigation as it stores up to 5.5 billion Mg of carbon (LAHSEN; BUSTAMANTE; DALLA-NORA, 2016; MORAIS et al., 2020).

The Cerrado biome has been impacted and threatened by land use change and intensification, primarily through the conversion of native vegetation into agriculture and pasture lands (NOOJIPADY et al., 2017). The original vegetation cover has been reduced by almost 50% over the past decades (MAPBIOMAS, 2020). Although it is the Brazilian biome with the highest deforestation rate (MAPBIOMAS PROJECT, 2023), only 3% of its area is fully protected (CNUC/MMA, 2019).

Land use and land cover change is a major cause of deforestation in this biome leading to fragmented landscapes with sparse remnants of native vegetation

(ASSIS; ESCADA; AMARAL, 2021). Pastures, one of the drivers of deforestation, cover 28% of the Cerrado landscape and the region produces 55% of all Brazilian cattle (PARENTE et al., 2017). Additionally, 46% of the pasture lands in the Cerrado are degraded with low beef productivity (PEREIRA et al., 2018).

Given the importance and impacts of livestock in the Cerrado, sustainable landscape planning and management practices are necessary to reduce environmental impacts. Silvopastoral systems (SPS) with native trees promote the integration of livestock within the system as an alternative that supports biodiversity conservation and preserves essential ES (BRUZIGUESSI et al., 2021). However, these systems are often financially less profitable and more complex compared to more intensive management practices under current conditions (PLIENINGER; HUNTSINGER, 2018)

Since the biome is a strong cattle productive area, promoting locally adapted silvopastoral systems (SPS) that integrate sustainable livestock production with native tree species is one of the most promising and effective strategies to sustainably manage the Cerrado forests (FREITAS et al., 2020). A variety of traditional SPS exist that were developed by family farmers and local Cerrado communities over the centuries. However, these traditional systems and their environmental, and socioeconomic performance have not yet been systematically analyzed and knowledge on their socioeconomic importance and overall contributions to societal welfare remains limited.

Identifying potential areas for SPS implementation, including defining priority zones for their allocation, is crucial due to their socioeconomic and environmental benefits. However, various adoption barriers currently discourage farmers from establishing and maintaining such SPS, limiting their wider distribution. Additionally, the limited availability of related information presents a challenge. Thus, this chapter aims to answer the following questions: i) What is the potential land for conservationist use through autochthonous silvopastoral system adoption? ii) Where are the priority zones for land cover transition to SPS located?

2. OBJECTIVES

2.1. Overall Objective

Assess the potential for conservationist use of the study site through mapping and defining priority zones for silvopastoral system (SPS) expansion.

2.2. Specific objectives

- Estimate and map carbon storage, annual water yield and habitat quality.
- Map the potential for conservationist use (PCU) considering environmental attributes.
- Map priority zones for SPS expansion.
- Assess the adequacy of the current land use with the mapped priority zones.

3. MATERIAL AND METHODS

3.1. Study Site

This study was conducted in the Rio Pardo (Pardo River) and São João do Paraíso watersheds (Figure 1), located in the northern region of the state of Minas Gerais. It encompasses a total area of 809,848 hectares and includes seven municipalities (IBGE, 2019).

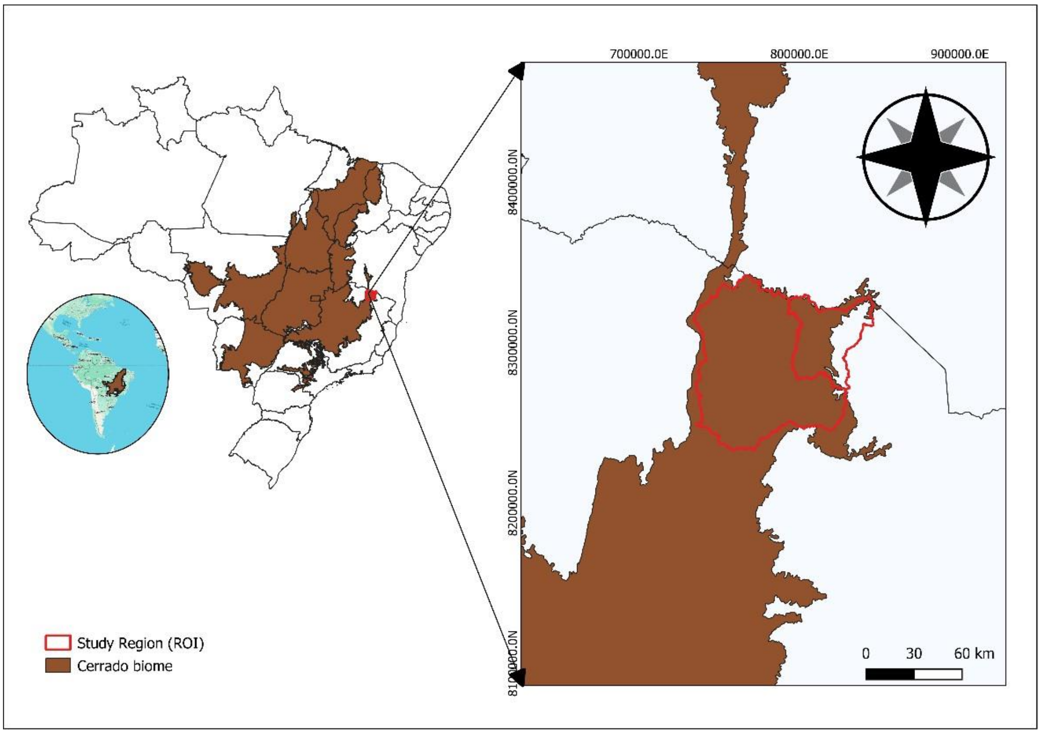

Figure 1: Study site location, encompassing the Pardo River and São João do Paraiso watersheds in the northern region of the state of Minas Gerais, in the eastern portion of Cerrado biome, Brazil.

The vegetation in the region is characterized by the presence of the Cerrado and Caatinga biomes and transition areas, with predominant phytophysiognomies of Cerrado, Cerrado field, Montane deciduous seasonal forest, Vereda, and submontane Deciduous seasonal forest (DE CARVALHO; JÚNIOR; SCOLFORO, 2005)

The predominant climate in the study area is semi-humid tropical with patches of semi-arid conditions, featuring two defined seasons: a wet season and a dry season (BETHONICO, 2009). In the coldest months the average annual temperature is 24°C, approximately 20.4°C in winter's peak and 25.5°C in the hottest month (LOPES DOS SANTOS et al., 2021). The predominant soils are Cambisols, Ferralsols, Arenosols, with the presence of Acrisols and Plinthosols (DOS SANTOS et al., 2011). The topography is characterized by a mix of mountainous areas and flat plains. The region includes various landforms such as plateaus, valleys, and hills. The altitude ranges from 500 to 1,000 meters above sea level. The diverse topography affects land use, water availability, and agricultural practices in the area. This heterogeneous landscape further shapes the high endemic levels for plants (MATIAS et al., 2024).

3.2. Data source

Soil and topography variables

The soil class data of Minas Gerais was obtained at a scale of 1:650,000 (UFV et al., 2010). According to the Brazilian Soil Classification System, this map represents the spatial distribution of soils for the Minas Gerais State (SANTOS et al., 2018). Data on drainage attributes, texture, effective depth, and fertility were obtained from soil class literature (COSTA et al., 2022). Additionally, slope data was obtained from the Shuttle Radar Topography Mission (SRTM) elevation. The slope values were then categorized into plane (0 to 3%), smooth wavy (3 to 8%), moderately wavy to wavy (8 to 20%), strong wavy (20 to 45%), and mountainous to steep (> 45%) (COSTA et al., 2017; MUCIDA et al., 2023).

Land use/Land cover classification

We used the 2022 land use/land cover (LULC) classification provided by MapBiomas Collection 8 (https://mapbiomas.org/ , accessed 01/10/2023) to map and estimate carbon stock, annual water yield and the habitat quality of the study area. MapBiomas is a collaborative network that produces annual land use and land cover maps for Brazil. It validates its data by involving a large network of specialists who review the maps. The process includes cross-referencing with high-resolution imagery, field data, and other reliable datasets (MAPBIOMAS PROJECT, 2023). The LULC map presented 13 different classes in the region (Figure 2) and was further used to compare the PCU map and assess the priority zones for silvopastoral system adoption.

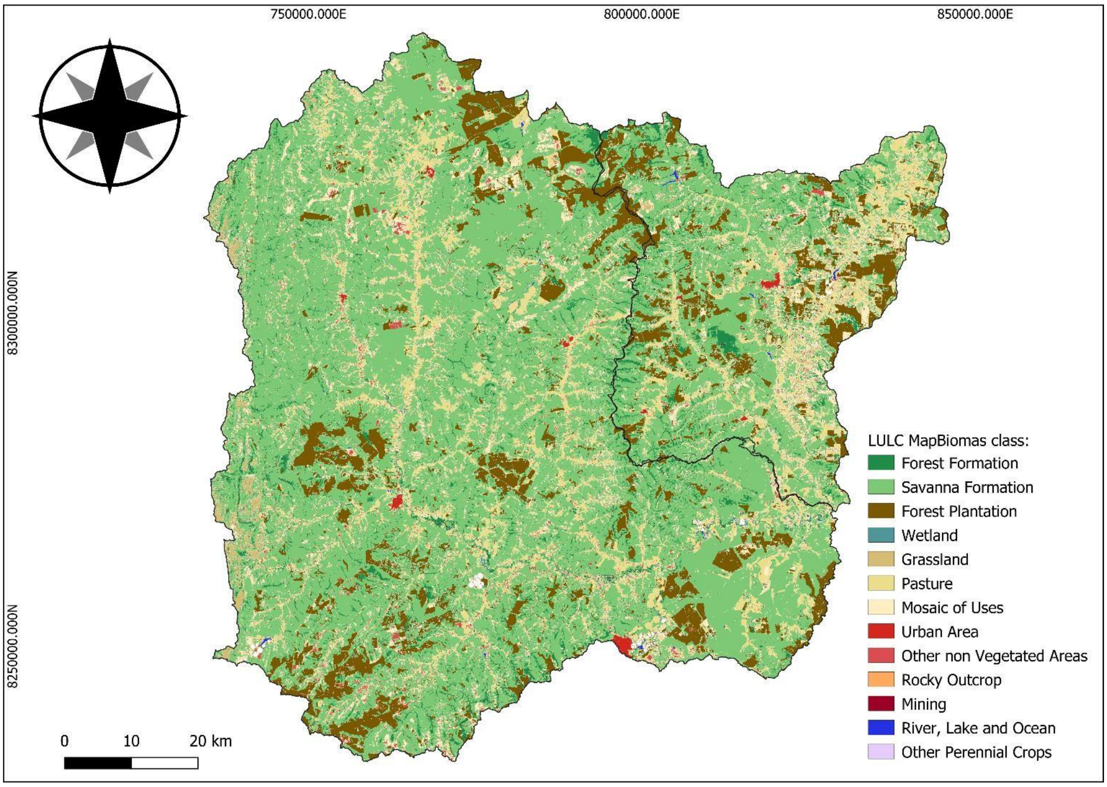

Figure 2: Mapbiomas Land Use/Land cover (LULC) collection 8 classification of the study region for the year of 2022.

Carbon storage

Carbon storage was assessed using the LULC maps and the carbon density per LULC class, considering above ground biomass. The above ground biomass is calculated as a product of the absorbed photosynthetic active radiation (APAR, Mj / m² / day) (MONTEITH, 1972) and light use efficiency (LUE) (FIELD; RANDERSON; MALMSTRÖM, 1995). The relationship between the factors is given as:

$$AGB = APAR * LUEmax * 0.864 \quad (1)$$

where *AGB* (Mg.ha-1) is the dry above-ground biomass production for the day of the satellite overpass; *APAR* is the absorbed photon flux by the canopy photosynthetic elements; *LUEmax* is the maximum light use efficiency (g/MJ); and 0.864 is a unit conversion factor (DE OLIVEIRA FERREIRA SILVA; LILLA

MANZIONE; ALBUQUERQUE FILHO, 2018). There are several studies on the determination of the LUEmax, varying between 1.44 and 3.22 for C3 and C4 crops (CASANOVA et al., 1998; ROCHETTE et al., 1995). In this study, we used values that are aligned with previous findings for the different MapBiomas land cover classes (GAN et al., 2021). For broadleaf forest types of land cover, we used a value of 1.58 gC/MJ. For grasslands and woody savannas, the value was 1.2 gC/MJ. For wetlands, the value used was 0.83 gC/MJ. Finally, for C3 crops the value used was 1.66 gC/MJ while for C4 crops the value was 2.67 gC/MJ.

APAR is approximated directly from photosynthetic active radiation (PAR) and fraction of photosynthetic active radiation (*fPAR*; intercepted by the leaves and used in the carbon dioxide assimilation process).

$$\mathrm{APAR} = \mathrm{fPAR} * \mathrm{PAR}_{daily} \tag{2}$$

The link between *fPAR* and *LAI* and the normalized difference vegetation index (NDVI) has been thoroughly documented in the literature as useful indicators of growth (FENSHOLT; SANDHOLT; RASMUSSEN, 2004; HATFIELD; ASRAR; KANEMASU, 1984). fPAR can be calculated using the NDVI (ASRAR; MYNENI; CHOUDHURY, 1992; CARLSON; RIPLEY, 1997), as:

$$\mathrm{fPAR} = \begin{cases} -0.161 + 1.257 * NDVI & for\ NDVI \geq 0.125 \\ 0 & Otherwise \end{cases} \tag{3}$$

where an NDVI value of 0.125 indicates bare soil (CARLSON; RIPLEY, 1997).

The photosynthetic active radiation (APAR, Mj / m^2 / day) represents the spectral range from 400 to 700 nm used by the canopy’s photosynthetic elements (GAO et al., 2011). *PAR* is a fraction of the incident shortwave solar radiation (Rs) (MCCREE, 1981). *Rs* was obtained from climatic data (Copernicus ECMWF ERA5-Land models, available in GEE), as follows:

$$\mathrm{PAR_{daily}} = 0.48 * Rs \tag{4}$$

Finally, the carbon storage was estimated per pixel by using results from equation 1, as it follows:

$$\mathrm{CS} = \mathrm{AGB} * 0.47 \tag{5}$$

where 0.47 is a constant number of the carbon fraction of dry matter (IPCC, 2006).

Annual water yield

The water yield index is defined as the net amount of water flowing off from each pixel in the landscape given a period of time, which is one year for this index

(VILLAMIZAR; PINEDA; CARRILLO, 2019). The annual water yield map was produced through the InVEST software. The InVEST model estimates the quantity and value of water used from each watershed, as shown in Figure 3. First, it calculates runoff for each pixel based on precipitation minus evapotranspiration. Second, the model determines the surface water available in each area taking into account all land uses and land cover. Finally, it estimates and value of water reaching the reservoir.

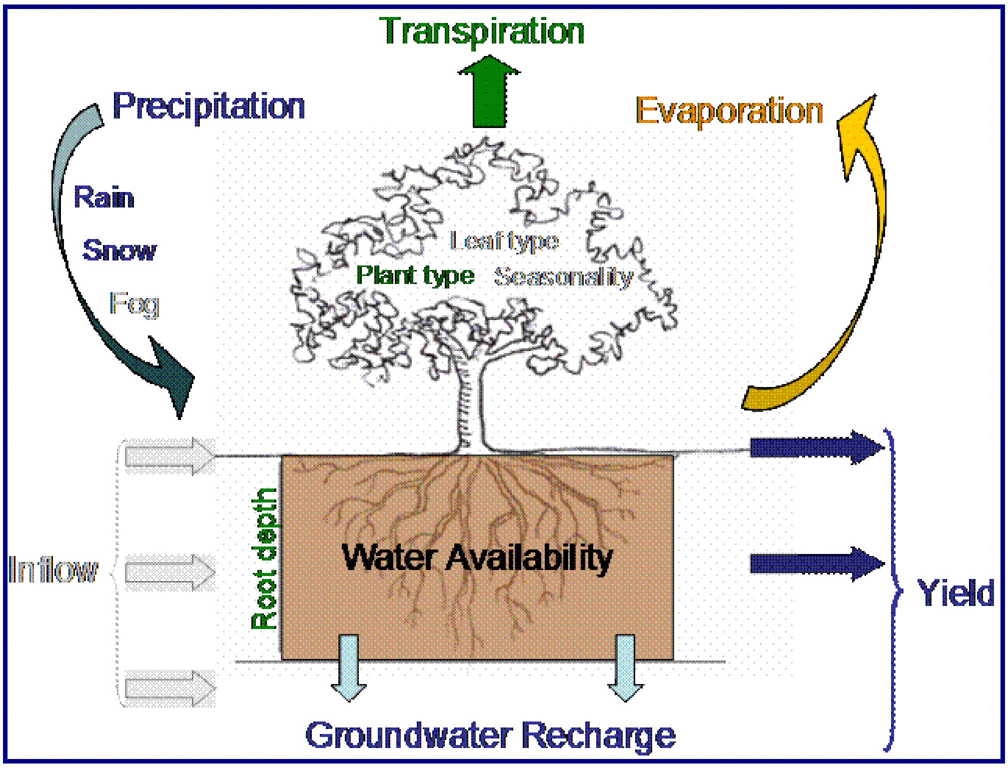

Figure 3: Conceptual diagram of the simplified water balance method used in the annual water yield model from the InVEST software (RICHARD SHARP et al., 2018)

As the model considers all LULC classes, it is needed to provide biophysical coefficients for each class. The respective coefficients are shown in Table 1. For vegetated LULC, root depth and plant evapotranspiration coefficient (Kc) for each class were obtained from studies with similar LULC classes (YANG et al., 2019).

Table 1: Biophysical table used for the baseline InVEST water yield model run, giving information about vegetation, plant evapotranspiration coefficient Kc and root

depth for each LULC class present in the study region. Adapted from Yang et al., 2019.

lucode	LULC_desc	LULC_veg	root_depth	Kc
0	unknown	0	0	0
3	Forest	1	8000	0.8
4	Savannnah	1	6000	0.7
11	Wetland	0	1000	1
12	Grassland	1	200	0.5
29	Rocky_outcrop	0	100	0.2
15	Pasture	1	200	0.45
36	Perenial_crops	1	7000	1
21	Mosaic_uses	1	2000	0.6
9	Silviculture	1	7000	1
25	Non_vegarea	0	0	0.2
24	Urban_area	0	0	0.3
30	Mining	0	0	0.2
33	Water_body	0	0	1

Where: *LUCODE* is the Land use/Land cover class code; *LULC_DESC* is the descriptive name of LULC; *LULC_VEG* is a binary value, 1 for vegetated LULC and 0 for all other LULC; *ROOT_DEPTH* is the maximum root depth for plants in the LULC class (unit: mm); *KC* is the crop coefficient.

Monthly total precipitation for 2022 from a total of 104 meteorological stations around the two studied watersheds was obtained from the *Portal HidroWeb* provided by the *Agência Nacional de Águas* (AGÊNCIA NACIONAL DE ÁGUAS, 2019). The watersheds were also obtained from the *Agência Nacional de Águas*. The average annual precipitation was then calculated and a value for each cell in the raster was generated using the Inverse Distance Weighting (IDW) interpolation method in QGIS 3.16 (QGIS DEVELOPMENT TEAM, 2024). For the evapotranspiration, we used data from the MOD16A2 Version 6.1. The product is an 8-day composite produced at 500-meter pixel resolution and needed to be converted to mm/year in the Google Earth Engine platform. For root restricting layer depth, we used the absolute depth to bedrock from ISRIC – SoilGrids 2017 and converted it to millimeters (HENGL et al., 2017). Similarly, plant available water content (PAWC) was calculated from 7 soil depth intervals provided by ISRIC, as suggested in the model’s user guidelines (RICHARD SHARP et al., 2018). Z parameter is a seasonality factor and represents seasonal distribution of precipitation. The value is obtained as a product of a constant value of 0.2 and the number of days with rain events.

Habitat quality

Habitat quality is addressed as the conditions which the ecosystem presents for the viability of different species to thrive regarding disturbance levels and potential anthropogenic threats (GOMES et al., 2020; YAN et al., 2018). Alternatively, we assessed the conditions of the native vegetation ecosystems by considering them as the most viable habitat for all native vegetation species from the Cerrado and the biome itself to thrive. In contrast to the work of Duarte et al. (2016), four threats: were considered: agriculture, silviculture areas (mainly Eucalyptus sp.), urban areas and paved roads (Table 2). The location and structure of the road network was obtained through the IBGE website (IBGE, 2019), while the LULC map was obtained from MapBiomas collection 8 (MAPBIOMAS PROJECT, 2023).

Table 2: Attributes of threat data with different land use. Adapted from Zhang et al., 2022.

Threat	Max distance (km)	Weight	Decay
Agriculture	8	0.8	linear
Paved roads	10	0.7	linear
Urban areas	11	0.9	exponential
Silviculture areas	8	1	linear

The habitat quality was mapped and estimated through the InVEST software (RICHARD SHARP et al., 2018). The analysis bases itself on the relative impact of threats, the distance between habitats and threat location, and the vulnerability of the habitat to threats, as shown in Table 3.

Table 3: Habitat suitability of different landscape types and sensitivity of LULC types to each threat. Adapted from Yan et al., 2018; Zhang et al., 2022.

LULC class	Habitat Suitability	Sensitivity to Threat Factors			
		Agriculture	Paved Road	Urban Area	Eucaliptus
unknown	0	0	0	0	0
Forest	1	0.75	1	0.6	0.85
Savannnah	1	0.75	1	0.85	0.85
Wetland	1	0.75	0.5	0.7	1
Grassland	1	0.75	1	0.6	0.85
Rock_outcrop	0	0	0	0	0
Pasture	0	0	0	0	0
Perenial_crops	0	0	0	0	0
Mosaic_uses	0	0	0	0	0
Eucaliptus plantation	0	0	0	0	0
Non_vegarea	0	0	0	0	0
Urban_area	0	0	0	0	0
Mining	0	0	0	0	0
Water_body	0	0	0	0	0

We expect that as the distance from the location of the threat increases there is a decreasing impact of that threat on the habitat. Subsequently an impact map is generated through the integration of the impact zones and the land use types considered as threats. The output map represents habitat quality with a relative metric ranging between 0 and 1, with low values for high impact zones and high values for low impact zones.

3.3. Data analysis

Mapping ecosystem services for PCU classification

In this study, three ecosystem services were considered: carbon storage, water yield, and habitat quality. These ecosystem services were selected due to relevant availability of data sources (GOMES et al., 2020) as well as being identified as the main ecosystem services perceived by farmers in Brazilian regions (TEIXEIRA et al., 2018). Habitat quality will be included as a proxy for biodiversity, by estimating how degraded or threatened the specific land cover is, while carbon storage and water yield are genuine indicators of ecosystem services. Carbon storage (Mg.ha-1) was estimated through the LUEmax approach, while annual water yield (mm.year-1) and habitat quality (index from 0 to 1) were assessed using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model. We used LULC maps from the MapBiomas Collection 8 and associated information of the land use types as model input, as specified on the previous topics.

Furthermore, to compute the PCU, a script based on the methodology developed by Costa et al. (2017) was implemented in Google Earth Engine (available at https://code.earthengine.google.com/76a7d9abc9109a6de575fe155ac7dee9). Differently from the original script, the PCU was calculated from six variables: soil class, terrain slope, distance to natural conservation areas, annual water yield, habitat quality and carbon stock. Each layer was associated with a score related to the aptitude for agricultural/livestock activities ranging from 0 to 5. Low scores (close to 0) represent the low potential, and the high scores (close to 5) describe the high potential

Soil classes with drainage balance, clayey texture, depth and fertile values had scores closer to five (COSTA et al., 2019; MUCIDA et al., 2023) (Table 4). The slope ranges according to the degree of inclination of the relief (Table 5). Flattest reliefs received higher scores, since these areas are more suitable for developing agricultural activities, and the bumpiest reliefs have smaller scores (COSTA et al., 2017).

Table 4: Soil classes present in the region and the respective PCU scores. Adapted from Costa et al., 2017.

Soil Class	PCU score
Gleysols	1
Leptsols	1
Rocky outcrop	1
Fluvisols	2
Arenosols	2
Cambisols	3
Dystrophic Regosol	3
Red-yellow Ferralsols	4
Red-yellow Acrisols	4
Yellow Ferralsols	4
Planosols	4
Red Ferralsols	5

Table 5: Slope classes and score on the PCU indicator.

Slope (%)	Relief classes	PCU Score
0 a 3	Flat	5
3 a 8	Gently sloping	4
8 a 20	Moderately sloping to Sloping	3
20 a 45	Strongly sloping	2
> 45	Mountainous to Steep	1

To aggregate individual indicators in different unit scales, each layer needs to be normalized to fit into the range of the PCU indicator. In this case, the min-max scaling method was applied to the quantitative environmental variables (distance to natural conservation areas, annual water yield, habitat quality, carbon storage). Min-max scaling is a data preprocessing technique that transforms numerical features into a specific range, in this study, 0 to 5 (MAZZIOTTA; PARETO, 2022).

The distance to natural conservation areas acts as proxy for the reminiscent native forest patches acting as matrices. Areas close to the natural conservation sites are expected to have high conservation values, since they provide greater amounts of biodiversity and more opportunities for successful reforestation (GOMES et al., 2020). Therefore, establishing an agricultural productive system would pose as a threat to the integrity of the conservation unit. In that sense, areas closer to natural conservation units received notes closer to 0. Carbon storage indicates the biomass density and its ability to assimilate carbon. Areas with higher carbon storage are generally areas with a higher biomass and tree density. Annual water yield relates to the availability of water on the land for the farmers. Lands with higher rates of annual water yield are perceived as lands with the most agricultural or grazing aptitude and hence influence farmers' decision making. Habitat quality is a proxy for biodiversity and land sensibility. It indicates if there are restrictions on land use and relevant interest to conservation and biodiversity. Areas that presented high habitat quality (close to 1) received notes closer to 0 since it presents greater interest for conservation practices. In contrast, areas with low habitat quality received notes closer to 5, as those areas already present levels of degradation and could be partially used for sustainable productive activities.

After receiving their scores, the variables must be (re)calculated in the GIS environment through map algebra and multicriteria evaluation, in this case, Analytic Hierarchy Process (AHP). In the AHP method, the variables are arranged in a paired sequence and are placed in comparison depending on the degree of importance (SAATY, 2008). This method involves constructing a pairwise comparison matrix, where each variable is compared to every other variable to generate relative weights based on their importance. In this study, the AHP helped indexing potential for conservationist use in the area for further analysis on priority zones for autochthonous SPS, based on the region's environmental and land use/cover attributes All six variables had their layers combined taking into consideration their weights assessed by the AHP, as shown in the following equation:

$$PCU = \sum_{n=1}^{i} (n * w_i) \quad (7)$$

where *PCU* = Potential for Conservation Use; *n* = environmental variables (Soil class, slope, distance to natural conservation areas, carbon storage, annual water yield and habitat quality); w_i = weights obtained in the AHP operation.

PCU classification

The thresholds for PCU classification were defined based on data distribution rather than arbitrary decisions, ensuring the variability of the data was taken into account. Percentile values were used to classify the data into three different classes (Table 6). This allowed the inclusion of autochthonous SPS's as an intermediate class between conservation practices and conventional agricultural/livestock practices. Managing land in autochthonous silvopastoral systems offers not only economic stability and income diversity but can also foster the provision of regulating ecosystem services. Therefore, SPS with native tree species are considered as a suitable land use to a certain degree, while maintaining productive factors (BRUZIGUESSI et al., 2021; PRABHU et al., 2015; RÖHRIG; HASSLER; ROESLER, 2020).

Table 6: PCU classification thresholds and description considering the percentile values.

Percentile (%)	PCU score	Class	Land Description
0 - 40	0 - 2.38	Conservation	Zones with high resilience potential and balance
40 - 60	2.38 - 2.53	SPS	Moderate restrictions on the use of natural resources
60 - 100	2.53 - 5	Conventional Ag./Livestock	Unstable areas with relative interest for conservation

Priority zones for SPS expansion

To address the priority zones for SPS expansion, the PCU map product was overlapped with the municipality boundaries map (IBGE, 2019). The municipalities included in the region of interest were those which had an area of more than 30% belonging to the watersheds of Rio Pardo and São João do Paraíso. Additionally, the 2022 LULC classification map was crossed with the PCU map to obtain the land use assessment. Similarly, for LULC classes, the main zones were defined based on their area size and compatibility for the adoption of autochthonous SPS's (KALOUDIS et al., 2021).

4. RESULTS

4.1. Biophysical paramaters of the landscape in the study area

The soil order has a high potential for autochthonous SPS's use since Ferralsols and Acrisols dominate it. The north and east portion of the region presented high scores related to those soil classes (Figure 4a). Low scores are often associated with Arenosols and Rocky outcrops, predominantly found in the western portion of the region. Conversely, the flattest reliefs are concentrated in the eastern portion (Figure 4b), indicating similar topographical and soil characteristics within these areas. The matching scores suggest that the region presents adequate geomorphological features for agricultural/livestock practices and that it may have appropriate productive conditions.

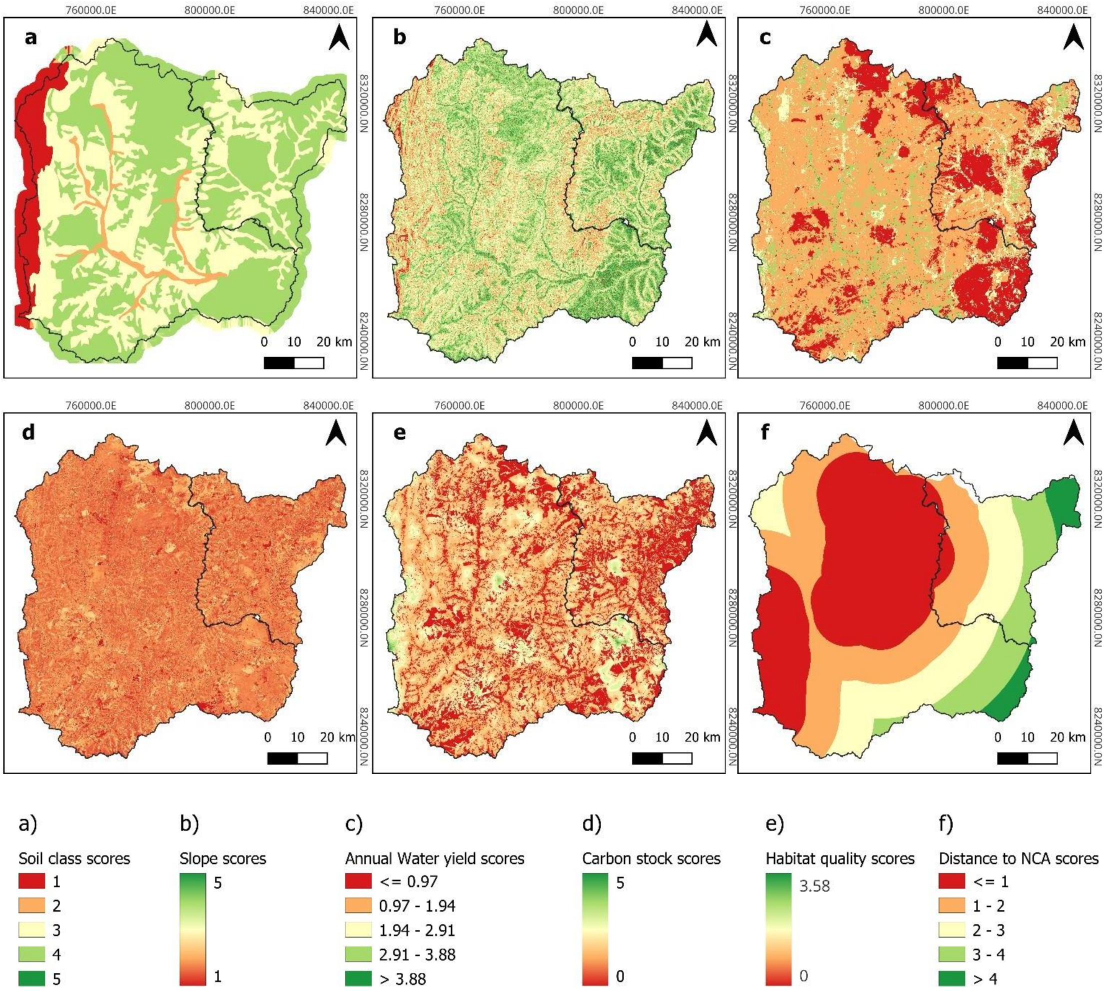

Figure 4: Score values for the six variable layers used in the study region: a) soil classes, b) terrain slope, c) annual water yield, d) carbon stock, e) habitat quality, f) distance to natural conservation areas.

On the other hand, the eastern and northern portions of the region showed low annual water production, which is the main layer in the PCU spatial distribution, while high annual water production areas are mainly along the streamlines and riparian forests (Figure 4c). The carbon stock map did not point out specific high stock regions and presented sparse land plots with the lowest carbon stock values (Figure 4d), translating to high PCU values. Similarly, for habitat quality (max value: 3.58), the eastern portion of the region presents good opportunities for agricultural or livestock activities and leaves the central-west area for SPS (Figure 4e). Natural conservation areas are present in the central, northern, and western regions of the map. The areas close to them were classified with low scores, while the eastern area exhibited the best PCU scores in this context (Figure 4f).

4.2. PCU in the Rio Pardo and São João do Paraíso watersheds

In the present study, the AHP was used to evaluate the criteria by assessing the effect of the parameters in proportion to their agricultural and livestock production potential. The pairwise comparison matrix, presented in Table 7, shows the values according to the relevance one parameter has over the other, followed by its individual weight generated through the AHP.

Table 7: Pair-wise comparison matrix and weights in AHP for PCU indicator

Attribute	**Attribute**						**Weight (%)**
	Annual water yield	Slope	Soil class	Habitat quality	Distance to NCA	Carbon stock	
Annual water yield	1	3	4	6	7	8	**45.3**
Slope	1/3	1	2	4	6	7	**24.1**
Soil class	1/4	1/2	1	3	4	5	**15.4**
Habitat quality	1/6	1/4	1/3	1	2	3	**7.3**
Distance to NCA	1/7	1/6	1/4	1/2	1	2	**4.7**
Carbon stock	1/8	1/7	1/5	1/3	1/2	1	**3.3**

Where *NCA*: Natural Conservation Areas.

After combining the slope, soil class, habitat quality, annual water yield, carbon stock, and distance to natural conservation areas (Figure 5) to create the PCU map, the region showed an average PCU score of 2.52, ranging from 1.00 to 4.28 (Figure 6).

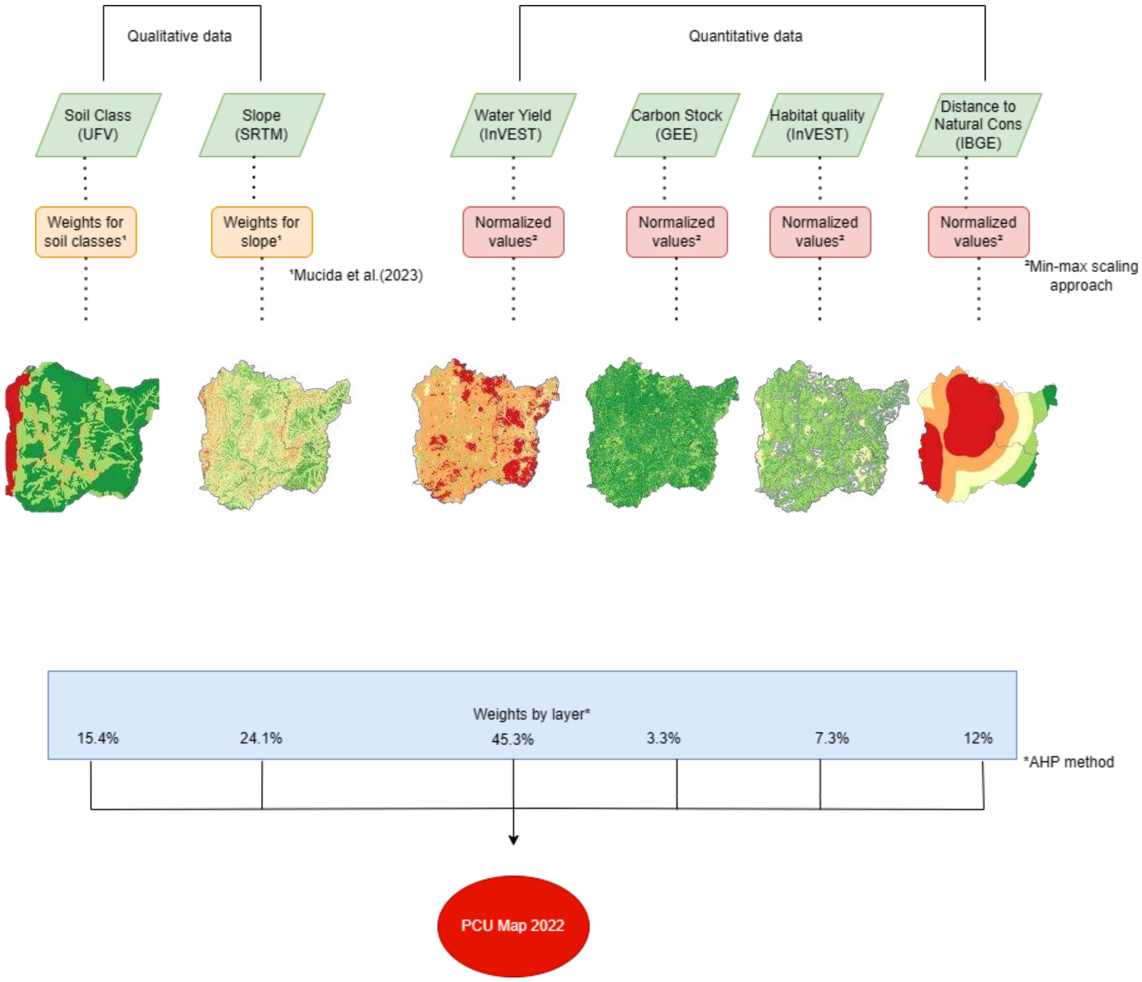

Figure 5: Flowchart of the methodological procedures adapted from Mucida et al., 2023.

The highest PCU score (> 4.2) was recorded in small regions to the south, heavily affected by the annual water yield distribution. The annual water yield is the main layer considered in the PCU spatial distribution, followed by slope (45.3 and 24.1% respectively). High PCU values were also indicated in the eastern portion of the map, where favorable slope conditions are present. In contrast, the lowest PCU score (≤ 1.8) was observed mainly in the extreme western region and between the two watersheds. Those regions are characterized by steep slope conditions and rocky outcrops due to mountain formations. Additionally, the region also presents a natural conservation unit following the mountain formation and it further affects the PCU score.

4.3. Municipal divisions – PCU and autochthonous SPS land use

Considering the 7 municipalities of the Rio Pardo and São João do Paraíso watersheds (Figure 6), the results of PCU showed approximately 20.92% (~170,000.00 ha) of land with adequate potential for autochthonous SPS land use.

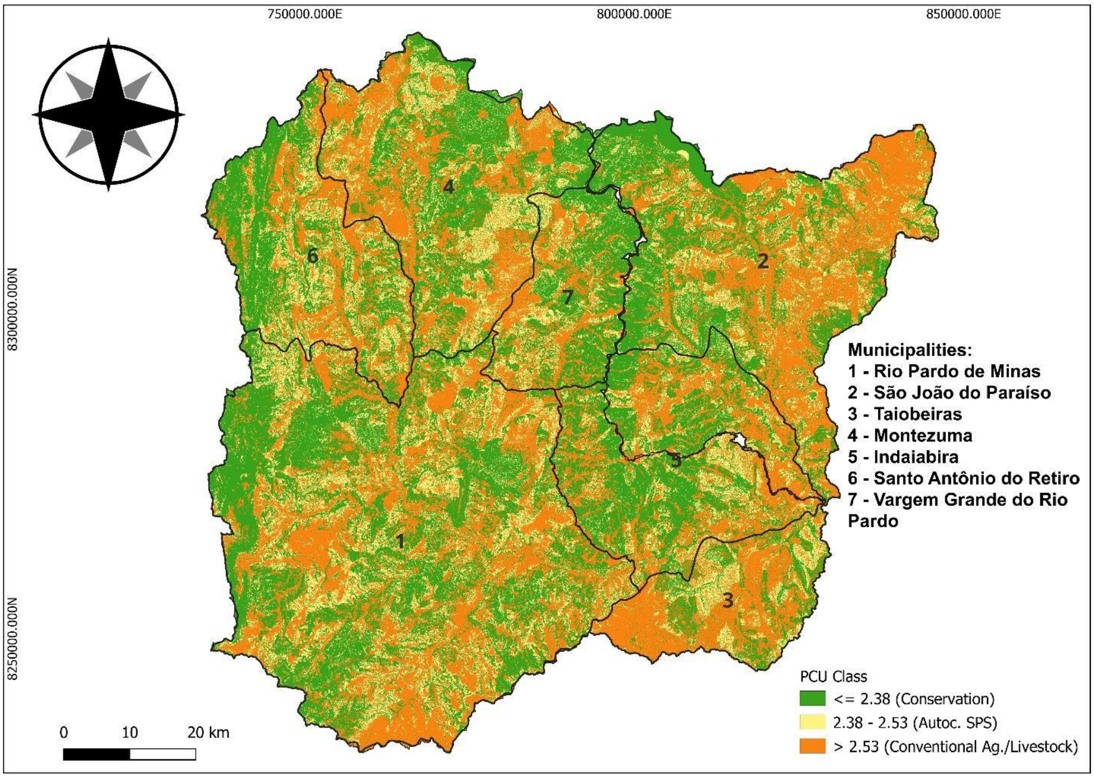

Figure 6: PCU generated from the combined layers: soil classes, terrain slope, annual water yield, carbon stock, habitat quality, distance to natural conservation areas with municipality divisions. Where *Autoc.SPS*: Autochthonous silvopastoral system; *Conventional Ag./Livestock*: Conventional Agriculture and livestock production systems.

The percentage for each class on the PCU classification is presented in Table 8. The highest potential for silvopastoral systems is in Santo Antônio do Retiro, with 22.53% of the area with PCU between 2.37 and 2.54, followed by Montezuma (22.18 % SPS) and Rio Pardo de Minas (21.82% SPS). Taiobeiras presented the highest PCU average (2.65), while Santo Antônio do Retiro had the lowest PCU average (2.45).

Table 8: Average PCU scores and classification of land potential for three different uses for each municipality.

Municipality	PCU average score	Conservation (%)	SPS (%)	Conventional Ag/Livestock (%)
Montezuma	2.53	37.76	22.18	40.05
Rio Pardo de Minas	2.50	40.32	21.82	37.86
Santo Antônio do Retiro	2.45	44.17	22.53	33.29
Taiobeiras	2.65	24.15	21.30	54.54
Vargem Grande do Rio Pardo	2.47	46.27	20.83	32.90
São João do Paraíso	2.59	36.11	18.55	45.33
Indaiabira	2.51	44.03	19.00	36.97

Where *SPS*: Silvopastoral systems; *Conventional Ag/Livestock*: Conventional agriculture and livestock production systems.

4.4. LULC and priority zones for autochthonous SPS land use

Land use data from Mapbiomas (2022) overlapped with the PCU map indicates that Savanna Formation (26.29%), Perennial Crop areas (25.17%) and Forest Plantations (20.96%) have higher potential for autochthonous SPS land use (Table 9). With over 500,00.00 ha, Savanna Formations are the most present and extensive LULC class in the region (Figure 2). This vast area presents a significant opportunity for sustainable practices and can have an impact on the overall land use strategy, thus a high priority for autochthonous SPS.

Table 9: Average PCU scores and classification of land potential for three different uses for each LULC class in the study region.

LULC class	LULC area (ha)	PCU average score	Conservation (%)	Autoc. SPS (%)	Conventional Ag/Livestock (%)
Forest Formation	37192.80	2.15	80.21	12.74	6.98
Savanna Formation	508679.36	2.42	42.09	26.29	31.47
Forest Plantation	96703.71	2.29	64.81	20.96	13.67
Wetland	1026.49	2.21	69.27	9.14	21.44
Grassland	17258.57	2.67	27.15	11.05	61.55
Pasture	102892.64	3.19	3.39	3.59	92.84
Mosaic of Uses	41107.95	2.77	12.31	12.74	74.64
Urban Area	1703.97	3.53	1.57	0.38	97.82
Other non Vegetated areas	7477.25	3.48	3.06	2.73	94.03
Rocky outcrop	229.37	3.34	5.06	4.62	90.27
Mining	18.56	3.46	3.36	0.78	95.86
River, Lake and Ocean	793.55	2.14	75.80	11.74	12.44
Perennial Crop	1166.52	2.45	41.19	25.17	33.58

Where *LULC:* Land use/land cover; *PCU:* Potential for conservationist use; *Autoc. SPS:* Autochthonous silvopastoral system; *Conventional Ag/Livestock*: Conventional agriculture and livestock production systems.

Savanna formation, Perennial Crops and Forest Plantations combined represent approximately 154,000.00 ha of potential land for autochthonous SPS practices. Forest formations showed moderate potential for further autochthonous SPS implementation, with 12.74% of its 37,192.80 ha classified under SPS. Adversely, pastures and grasslands presented high inclination towards conventional agriculture/livestock (92.84% and 61.55% respectively). While only 3.59% of pasture land is classified under autochthonous SPS, grasslands show a moderate potential for more sustainable systems with 11.05% classified under autochthonous SPS

5. DISCUSSION

5.1. Biophysical paramaters of the landscape in the study area

Concerning the environmental factors, the region’s soil classes underscore high potential for SPS with a predominance of Ferralsols and Acrisols. These soil orders are known for their fertility and structural stability, making them conducive to conventional and sustainable agrossilvopastoral practices (MOTERLE et al., 2019). In contrast, Arenosols and Rocky outcrops, are less suitable for SPS due to their poor nutrient content and challenging physical conditions, which withhold endemic species with relative interest for conservation (FITZSIMONS; MICHAEL, 2017). The flattest reliefs present ideal conditions for conventional agricultural and livestock activities (CHATTERJEE; MURALI KRISHNA, 2019). The homogeneous landscape of the region facilitates mechanized farming and efficient land management practices, which are crucial for both conventional agriculture/livestock and SPS (YANG et al., 2022).

Considered as a critical factor in the PCU spatial distribution, the annual water production varies across the region. The low water yield throughout the scenery shows a challenge for the rural production systems in the region. As water is deemed as one of the most important things in an environmental system (PEREIRA, 2017), improving its quantity, quality and distribution through SPS use may improve the overall productivity of those systems (MARTINKOSKI et al., 2017). Addressing those issues through SPS implementation could foster their adoption in the region, where farmers perceive water as the main source of high or low yields (SILVA et al., 2021).

For carbon stocks, the map highlights areas where land use practices could be optimized for carbon sequestration. Implementing SPS in these low carbon stock areas presents a vast potential which could improve soil health, and increase carbon sequestration, contributing to climate mitigation efforts while safeguarding food security (FORNARA et al., 2018). The habitat quality offers significant opportunities for agricultural and livestock activities. These areas, characterized by intermediate habitat quality values, are less constrained by conservation practices and can be developed for sustainable production systems, such as SPS (KUMAR et al., 2022). Enhancing habitat quality through integrated land management practices can further support biodiversity while promoting socioeconomical advantages.

Natural conservation areas play a major role in the region, where there are local communities that already conduct autochthonous SPS. The central-north and western regions exhibit extensive areas that have stringent conservation regulations due to the presence of conservation units (BRASIL, 2000). However, these areas have strong potential for strategic land use planning that balances conservation with low input livestock practices, such as the autochthonous SPS developed by the local communities (PIGNATARO et al., 2016).

The region presents a mosaic of opportunities and challenges for SPS implementation. By leveraging areas with favorable soil and topographical conditions and addressing annual water yield and carbon stock constraints, it is possible to develop sustainable and productive SPS's that enhance both agricultural output and environmental health (PÉREZ-LOMBARDINI et al., 2021).

5.2. PCU in the Rio Pardo and São João do Paraíso watersheds

The region's average PCU score (2.52) and range (1.00 – 4.28) reflects a diverse landscape with varying suitability for conservationist use and agricultural activities. The multi-layered approach provides a comprehensive assessment of the potential for sustainable land management. Low PCU regions emphasize the need for studies to understand the ecosystem's fragilities and to develop sustainable management plans for the landscape (FRANÇA et al., 2022). Strategies based on methods like the PCU classification are expected to encourage and promote appropriate agricultural practices in areas with high aptitude (MÉNDEZ-VÁZQUEZ et al., 2019). Furthermore, areas with medium PCU scores can support the development of public policies and strategies for sustainable land uses, including autochthonous SPS.

Regarding the environmental factors, annual water yield is expected to be a driver of farmers' decisions in a water-scarce region such as the Cerrado (D'ODORICO et al., 2020; SILVA et al., 2021) and has a significant impact of 45.3% on the PCU classification in this study. The region's annual water yield distribution shows a predominance of low scores and represents a major challenge in the tropical savanna environment for conventional agricultural/livestock systems. Regions with higher scores are often associated with riparian forests and water bodies, which reflect in medium PCU scores when combined with the other environmental factors, such as habitat quality and carbon stock. Those medium score regions present moderate restrictions on the use of natural resources and were classified as potential sites for autochthonous SPS. On the other hand, areas with low water yield in the region were often found near urban centers which also present low carbon stock values. It is expected that intense deforestation reduces water production by disrupting the balance between evapotranspiration and infiltration (PEÑA-ARANCIBIA et al., 2019).

Slope, which has a weight of 24.1% in the PCU classification, plays a crucial role in determining land suitability for various uses (CHATTERJEE; MURALI KRISHNA, 2019). The slope scores in the region are generally high, particularly on the expansive flat plateaus, which are highly favorable for agricultural/livestock and SPS activities. In the other hand, lower slope scores are often associated with the *vereda's* structures and mountain ranges. These areas present significant challenges for implementing conventional agricultural/livestock techniques due to their steep and uneven terrain. Thus, these areas receive lower PCU scores, indicating reduced suitability for intensive land use (FITZSIMONS; MICHAEL, 2017), yet they may still hold potential for alternative land management practices like conservation projects or diverse autochthonous SPS that can adapt to challenging topographies (PINHEIRO; NAIR, 2018).

Soil classes and the distance to natural conservation areas also played an important role in the PCU classification (15.4% and 12% respectively). Mainly affected by the negative features of those layers, the lowest PCU scores were more present in the rocky outcrop zones, which were also zones of natural conservation areas to the west portion of the map (Figure 5). These areas had low scores individually and PCU scores, since it is expected that endemic animal and plant species can thrive in such conditions. Therefore, it is more likely that those regions of the map are considered for biodiversity conservation practices to avoid further losses in the watersheds and in the Cerrado biome (FITZSIMONS; MICHAEL, 2017).

Finally, both carbon stock and habitat quality were classified as the least important for the PCU classification, with weights of 3.3% and 7.3%, respectively. High carbon stock areas had low PCU scores, as it is expected that these highly vegetated areas could become emission sources if converted to different land covers (LAL et al., 2018). Conversely, they can also represent monoculture areas, such as Eucaliptus plantations or short duration crop plantations with high biomass stock that do not provide as many ES as expected, which explains their low impact on the PCU score (HUA et al., 2022). Monocultures of Eucalyptus not only reduces biodiversity, similar to other monocultures, but also severely decreases water yield, which may endanger water security in the Cerrado (BUSTAMANTE, et al.,

2019) The biome in the north of Minas Gerais State is experiencing a critical water shortage due to historical low precipitation and large-scale afforestation on tablelands in the last decades (LEITE; FUJACO, 2010). Habitat quality, with a maximum weighted value of only 3.58 in this study, reflected in a medium PCU score range of 2.38 – 2.53. This relatively low value helped identify areas most suitable for autochthonous SPS, as these systems are expected to prioritize land rehabilitation while maintaining productivity and income for local communities (KUMAR et al., 2022).

5.3. Municipal divisions – PCU and autochthonous SPS land use

Municipal divisions in the region showed high agricultural and livestock aptitude overall, in addition to SPS aptitude. These results emphasize the need to improve land use programs at the municipality level for further successful adoption of autochthonous SPS (MUCIDA et al., 2023). Santo Antônio do Retiro, Montezuma and Rio Pardo de Minas show great potential for autochthonous SPS adoption or expansion. With better road conditions and road network logistics to bigger cities, the north-western portion of the region is expected to have better product trading capacity and strategies are most likely to succeed there (LUPINETTI-CUNHA et al., 2022).

Areas that presented low to medium PCU values should primarily be carefully used, either through conservation practices or autochthonous SPS that are more suitable to provide ecosystem services (MAURICIO et al., 2019; RÖHRIG; HASSLER; ROESLER, 2020b; SALES-BAPTISTA; FERRAZ-DE-OLIVEIRA, 2021). When a low PCU region shows potential for autochthonous SPS, it is essential to adopt appropriate soil conservation practices and management practices that may provide improved rates of ecosystem services in a municipal and landscape level (IOANNIDOU et al., 2022; XIONG; SUN; CHEN, 2018). Since those areas are expected to be more fragile and susceptible to degradation when subjected to inadequate management practices, understanding each municipality's potential and regulatory opportunities for conservation or autochthonous SPS activities is necessary for a successful management plan.

The region studied shows a strong economic dependence on agricultural, livestock and forestry activities (IBGE, 2023). With approximately 40% of the land presenting a high PCU score (2.53 – 5), encouraging adequate soil and water management techniques are even more critical for maintaining the sustainability of conventional agricultural and livestock activities. The practices adopted in this type of land cover reflect directly on the soil’s overall properties, water regime and quality, as well as on biodiversity conservation indicators (SHAH; WU, 2019; XIONG; SUN; CHEN, 2018). Initiatives that seek to organize the landscape heavily rely on solid imagery with the best possible resolution to develop spatially explicit environmental data (JUEL et al., 2015). The PCU approach makes it possible to identify potential areas for, in this study, autochthonous SPS from a conservationist perspective. Depending on the variables used to assess the potential for a specific land use, this compatibility can help open new markets and evaluate the distribution of possible new and environmentally friendly systems, allowing a scalable, replicable, and auditable methodology (COSTA et al., 2022; KEESSTRA et al., 2018).

5.4. LULC and priority zones for autochthonous SPS land use

The PCU score showed a good agreement with the current LULC map from Mapbiomas for the region (MAPBIOMAS PROJECT, 2023). Determining the PCU’s spatial distribution within a region is essential for appropriate management and development of public policies for soil conservation, water conservation, biodiversity, land use regulation, and ecosystem services supply in general, according to the layers used (GRÊT-REGAMEY et al., 2017). Crossing data on current LULC and potential for conservationist use made it possible to identify conflict points and define priorities for maintaining a balanced natural ecosystem through autochthonous SPS. With over 150 thousand hectares available, savanna formation, perennial crop and forest plantation areas have shown high potential for autochthonous SPS use. These land cover types present only moderate restrictions on the use of natural resources, and sustainable systems such as the studied SPS are legally allowed to be taken place even in legal reserves (BRASIL, 2012). Because of these environmental attributes and regulatory restrictions, these areas are considered as the primary priority zones with high potential for the adoption or expansion of the local SPS.

Despite of the advance of environmental zoning methods to enhance the territorial planning, the adoption or expansion of autochthonous SPS remains low (CHITAKIRA; TORQUEBIAU, 2010; LEE et al., 2020). Addressing socioeconomic variables can further improve the adoption through the environmental zoning method to be more aligned to farmer's realities. Payment for environmental services is a great alternative to increase the environmental performance of agriculture, livestock and forestry activities, thus making it more attractive for farmers to use different productive systems (HAYES, 2012; ZAPATA; ROBALINO; SOLARTE, 2015). Farmers that currently undergo autochthonous SPS have no encouragement to keep their trees on the land from an economic point of view. This study also enabled the identification of regions where farmers can have success with SPS and support the development of public policies and municipal strategies which can improve their system's ecological sustainability and profitability (PANCHOLI et al., 2023)

6. CONCLUSION

The identification of priority zones for autochthonous silvopastoral system (SPS) expansion provides a strategic framework for targeted implementation, revealing that adopting SPS in high-suitability areas can optimize land use and enhance sustainable management practices. Our findings suggest that the region has great potential for autochthonous SPS that were similarly distributed between the municipalities. Our assessment of current land use in relation to these priority zones shows that those high-suitability areas, particularly in land cover types such as savanna formations, perennial crops, and forest plantations, are prime locations for autochthonous SPS adoption. This integrative approach is essential for improving water management, enhancing carbon sequestration, and aligning conservation goals with agricultural and livestock productivity, ultimately supporting environmental sustainability and offering socioeconomic benefits. By promoting sustainable land use in the Cerrado, it is possible to enhance ecosystem services, support biodiversity conservation, and contribute to the overall resilience and health of the ecosystem.

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GENERAL CONCLUSION

The research highlights the significant role that autochthonous SPS can play in addressing the pressing environmental challenges faced by the Brazilian Cerrado. The bibliometric analysis reveals a growing global interest in SPS, driven by the need for sustainable agricultural practices that mitigate land degradation and support biodiversity. This analysis identifies key factors influencing SPS adoption, encompassing encompassing socio-economic elements such as implementation costs, lack of knowledge, and labor intensity; environmental aspects like the presence of springs; and technical factors including government subsidies and access to extension services. These findings are crucial for understanding the barriers and motivations behind farmers' decisions, providing a foundation for targeted interventions and policy development.

The study provides a detailed assessment of the region’s suitability for autochthonous SPS implementation and expansion. The findings indicate that there are substantial areas within the Cerrado that are highly suitable for SPS, particularly in municipalities like Santo Antônio do Retiro, Montezuma, and Rio Pardo de Minas. These areas exhibit favorable soil and slope conditions, although challenges such as low annual water yield must be addressed. The mapping of ecosystem services and the identification of priority zones for SPS implementation underscore the potential of these systems to enhance ecosystem services, promote sustainable land use, and support biodiversity conservation.

The thesis also emphasizes the importance of public policies, such as payments for environmental services, in promoting and facilitating the adoption of SPS. These policies can provide the necessary incentives and support for farmers to transition to more sustainable land use practices. The insights gained from this research can inform policymakers, researchers, and practitioners in their efforts to promote sustainable agricultural practices that conserve the rich biodiversity of the Cerrado and enhance the resilience of rural communities. By integrating scientific research with practical solutions, this thesis lays the groundwork for future initiatives aimed at achieving environmental sustainability and socio-economic development in the Brazilian Cerrado and beyond.