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Silvopastoral systems with native trees: The economic, productive and social potential in the cerrado mineiro

Felipe Corrêa Ribeiro
Doctor Scientiae

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

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Co-advisers: Dietrich Darr
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Assent:

Felipe Corrêa Ribeiro
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Carlos Moreira Miquelino Eleto Torres
Adviser

By observing the past, understanding the present, and envisioning the future, we trace the path toward a sustainable development of land uses.

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“*Sou assim...*
Do mato, cerrado, da mata, do brejo.
Gosto do cheiro, do pé descalço,
Do vento na cara
Até do sol queimando a pele.
Gosto de olhar, de sentir...
Assim me conecto com o criador
É na natureza que Deus está
Na beleza de tudo que Ele me permite admirar!
Não sou poeta, nem sei escrever direito.
Mas com o coração puro tudo se torna perfeito.
Obrigado Senhor por eu ser desse jeito!.”
(Rogerio Helmer)

ABSTRACT

RIBEIRO, Felipe Corrêa, D.Sc., Universidade Federal de Viçosa, September, 2025. **Silvopastoral systems with native trees: The economic, productive and social potential in the cerrado mineiro**. Adviser: Carlos Moreira Miquelino Eleto Torres. Co-advisers: Dietrich Darr and Eleydiane Maria Gomes Vale.

The Cerrado is the most biodiverse savanna in the world, with a high rate of endemism and the provision of essential ecosystem services. Currently, the Cerrado presents a wide range of land uses and is constantly affected by land-use conversion due to its high agricultural productive potential. Among these uses, silvopastoral systems (SPS) with native trees stand out as an alternative model that integrates local biodiversity with economic practices of natural resource use. This research aims to clarify the current status of these systems and assess their economic, productive, and social potential in the Cerrado of northern Minas Gerais. In Chapter 1, we assessed the economic performance and sensitivity of the three main land uses in the region: agriculture, silvopastoral systems with native trees, and Eucalyptus plantations, with different sample sizes. For each system, we calculated gross margin and profitability indicators, considering income and both fixed and variable costs. Sensitivity analysis was conducted using a Monte Carlo simulation and a Random Forest model. The results revealed statistically significant differences in cost structure, income composition, and profitability across systems. Eucalyptus plantations showed the highest average profitability and the lowest economic risk, although they are highly dependent on external inputs (hired labor, market access, and infrastructure). SPS presented intermediate performance, with lower variable costs and potential ecological co-benefits, although their productive and commercial remains underutilized. Agriculture, primarily family-based and subsistence-oriented, showed the lowest profitability due to high fixed costs and limited market integration. Family labor was the main fixed cost component in both agriculture and SPS, strongly influencing the economic results. Despite the differences, low-risk farms were identified across all land uses, suggesting that profitability is achievable under supportive conditions. These findings underscore the importance of specific public policies that promote financial planning, technical assistance, and diversification of income sources in each land use. In Chapter 2, we investigated which productive, environmental, socioeconomic, technical, and farm-related factors influence the adoption and intensification of SPS with native trees. Based on interviews conducted with over 100 farmers, we used the Seemingly Unrelated Regressions (SUR) model, estimated through the Full

Information Maximum Likelihood (FIML) method. Three equations were developed to assess the adoption of SPS, the intensification of its use through the generation of products, and the commercialization of these products. We found that 12 variables, distributed across the five groups of factors, influence the adoption and intensification of SPS differently. Water availability for production and the presence of family labor are key factors for intensification, although they do not directly affect adoption. In contrast, the age of farmers and their environmental awareness impact adoption but not intensification, often associated with older and more environmentally conscious farmers. Variables such as the total number of land uses and currently productive land uses positively affect all equations, while the distance between the farmer's residence and the productive area has a negative effect. Based on these findings, we propose public policies targeting two groups, adopters and non-adopters, so that efforts to promote SPS with native trees focus not only on increasing adoption but also on intensifying its use. In Chapter 3, we investigated the NTFP market through interviews with traders located in the study region and major urban centers of the Cerrado in Minas Gerais. Using K-means clustering, we identified three market segments: small-scaled, medium-scaled, and large-scaled. The small-scaled market is characterized by low product diversity, predominantly unprocessed goods, and is found in municipalities with smaller populations, resulting in a more limited market. The medium-scaled market has the highest proportion of processed products and is present in the main municipalities of the study region but still has limited product diversity and volume. The large-scaled market includes traders located in large urban centers and the most populous municipality of the region, with higher commercialization levels, diverse suppliers, and a broad variety of products and species. Despite these differences, certain products such as pequi (Caryocar brasiliense) are found across all market segments, highlighting their commercial relevance. At the same time, each segment includes exclusive products, indicating a specialization in supply. The NTFP market context reveals a high economic and productive potential, particularly relevant for farmers who adopt SPS with native trees, given the variety of market scales and products identified.

Keywords: land use; rural sustainability; non-timber forest products; economic analysis; farmers' decision-making ; family farming; value chains; agroforestry systems; climate adaptation; productive diversification

RESUMO

RIBEIRO, Felipe Corrêa, D.Sc., Universidade Federal de Viçosa, setembro de 2025. **Sistemas silvipastoris com árvores nativas: O potencial econômico, produtivo e social no cerrado mineiro**. Orientador: Carlos Moreira Miquelino Eleto Torres. Coorientadores: Dietrich Darr e Eleydiane Maria Gomes Vale.

O Cerrado é a savana com maior biodiversidade no mundo, com alta taxa de endemismo e a provisão de serviços ecossistêmicos essenciais. Atualmente, o Cerrado apresenta uma ampla gama de usos da terra e é constantemente afetado pela conversão do uso da terra devido ao seu alto potencial produtivo agrícola. Entre esses usos, os sistemas silvipastoris (SSP) com árvores nativas se destacam como um modelo alternativo que integra a biodiversidade local com as práticas econômicas de uso de recursos naturais. Esta pesquisa visa esclarecer o status atual desses sistemas e avaliar seu potencial econômico, produtivo e social no Cerrado do norte de Minas Gerais. No Capítulo 1, avaliamos o desempenho econômico e a sensibilidade dos três principais usos da terra na região: agricultura, sistemas silvipastoris com árvores nativas e plantações de Eucalipto, com diferentes tamanhos de amostra. Para cada amostra, calculamos a margem bruta e os indicadores de lucratividade, considerando a receita e os custos fixos e variáveis. A análise de sensibilidade foi conduzida usando uma simulação de Monte Carlo e um modelo de Random Forest. Os resultados revelaram diferenças estatisticamente significativas na estrutura de custos, composição da receita e lucratividade entre os sistemas. As plantações de Eucalipto mostraram a maior lucratividade média e o menor risco econômico, embora sejam altamente dependentes de insumos externos (mão de obra contratada, acesso ao mercado e infraestrutura). Os SSPs apresentaram desempenho intermediário, com menores custos variáveis e potenciais co-benefícios ecológicos, embora sua produtividade e comercialização permaneçam subutilizadas. A agricultura, principalmente familiar e de subsistência, mostrou a menor lucratividade devido aos altos custos fixos e à limitada integração ao mercado. A mão de obra familiar foi o principal componente de custo fixo tanto na agricultura quanto nos SSPs, influenciando fortemente os resultados econômicos. Apesar das diferenças, foram identificadas fazendas de baixo risco em todos os usos da terra, sugerindo que a lucratividade é alcançável sob condições favoráveis. Esses achados ressaltam a importância de políticas públicas específicas que promovam o planejamento financeiro, assistência técnica e diversificação das fontes de renda em cada uso da terra. No Capítulo 2, investigamos quais fatores produtivos, ambientais, socioeconômicos,

técnicos e relacionados à fazenda influenciam a adoção e intensificação de SSPs com árvores nativas. Com base em entrevistas conduzidas com mais de 100 produtores rurais, usamos o modelo de Regressões Aparentemente Não Relacionadas (SUR), estimado através do método de Máxima Verossimilhança de Informação Completa (FIML). Três equações foram desenvolvidas para avaliar a adoção de SSPs, a intensificação de seu uso através da geração de produtos e a comercialização desses produtos. Descobrimos que 12 variáveis, distribuídas entre os cinco grupos de fatores, influenciam a adoção e a intensificação dos SSPs de forma diferente. A disponibilidade de água para produção e a presença de mão de obra familiar são fatores-chave para a intensificação, embora não afetem diretamente a adoção. Em contraste, a idade dos produtores e sua consciência ambiental impactam a adoção, mas não a intensificação, sendo frequentemente associados a produtores mais velhos e com maior consciência ambiental. Variáveis como o número total de usos da terra e os usos da terra atualmente produtivos afetam positivamente todas as equações, enquanto a distância entre a residência do produtor e a área produtiva tem um efeito negativo. Com base nesses achados, propomos políticas públicas que visem a dois grupos, adotantes e não adotantes, para que os esforços para promover os SSPs com árvores nativas se concentrem não apenas em aumentar a adoção, mas também em intensificar seu uso. No Capítulo 3, investigamos o mercado de PFNM através de entrevistas com comerciantes localizados na região de estudo e nos principais centros urbanos do Cerrado em Minas Gerais. Usando a clusterização K-means, identificamos três segmentos de mercado: pequena escala, média escala e grande escala. O mercado de pequena escala é caracterizado pela baixa diversidade de produtos, predominância de produtos não processados e é encontrado em municípios com populações menores, resultando em um mercado mais limitado. O mercado de média escala tem a maior proporção de produtos processados e está presente nos principais municípios da região de estudo, mas ainda possui diversidade e volume de produtos limitados. O mercado de grande escala inclui comerciantes localizados em grandes centros urbanos e no município mais populoso da região, com maiores níveis de comercialização, fornecedores diversificados e uma ampla variedade de produtos e espécies. Apesar dessas diferenças, certos produtos como o pequi (Caryocar brasiliense) são encontrados em todos os segmentos de mercado, destacando sua relevância comercial. Ao mesmo tempo, cada segmento inclui produtos exclusivos, indicando uma especialização no fornecimento. O contexto do mercado de PFNM revela um alto potencial econômico e produtivo, particularmente relevante para os agricultores que adotam SPS com árvores nativas, dada a variedade de escalas de mercado e produtos identificados.

Palavras-chave: uso da terra; sustentabilidade rural; produtos florestais não madeireiros; análise econômica; tomada de decisão agrícola; agricultura familiar; cadeias de valor; sistemas agroflorestais; adaptação climática; diversificação produtiva.

SUMMARY

GENERAL INTRODUCTION

Land-use changes over recent decades have triggered profound transformations in tropical ecosystems (Obidike-Ugwu et al., 2023; Sharma et al., 2019; Zhao et al., 2024). The increasing demand for food, minerals, energy, and agricultural commodities has driven the expansion of production frontiers into natural areas, intensifying the conversion of native landscapes into monocultures, pastures, and other forms of intensive land use (Li, 2025; Silva & Silva, 2022). This reality is particularly evident in regions such as the Brazilian Cerrado, which, despite its enormous ecological, social, and hydrological relevance, has been systematically degraded by anthropogenic pressures, compromising the provision of ecosystem services (Coelho et al., 2020; Ferreira et al., 2021). This accelerated habitat loss, driven by agricultural expansion, extensive livestock grazing, frequent wildfires, and the lack of effective protection policies, has made the Cerrado an epicenter of environmental degradation (Alencar et al., 2020; Coelho et al., 2020; Dick et al., 2021).

The Cerrado is the second-largest biome in Brazil, covering approximately 2 million km² (24% of the national territory) (MapBiomas, 2023). Recognized as the most biodiverse savanna in the world, it harbors around 12,000 plant species, 35% of which are endemic (Zappi et al., 2015). This biological richness, combined with its vast geographic distribution and ongoing pressures, places the Cerrado among the world's 35 biodiversity hotspots (Myers et al., 2000).

Functionally, the Cerrado plays a strategic role in Brazil's climate and hydrological regulation. With approximately 5.5 billion tons of carbon stored, much of it in belowground biomass, the biome significantly contributes to carbon sequestration and climate change mitigation (D. R. P. Gonçalves et al., 2024; Morais et al., 2020). Moreover, it supplies water to eight of the twelve major hydrographic regions in Brazil, regulating the water flow of key basins such as the São Francisco, Tocantins, Araguaia, and Paraná rivers, among others (Althoff et al., 2021; Rodrigues et al., 2022a). The Cerrado also provides essential ecosystem services such as pollination, erosion control, biodiversity support, and soil fertility, all of which are fundamental for the ecological and productive resilience of the territory (Ferreira et al., 2021; Lambers et al., 2020; Schüler & Bustamante, 2022).

Beyond its ecological importance, the Cerrado sustains diverse forms of life and local cultures. It is home to Indigenous peoples, traditional communities, family farmers, and rural settlers who have developed adaptive environmental management practices based on extractivism, agroecology, and the diversification of productive systems (de Mello et al., 2020, 2023a). One of the central elements of this interaction between society and nature is the use of non-timber forest products (NTFPs), such as fruits, seeds, leaves, roots, and resins used for food, medicine, cosmetics, and cultural purposes (de Mello et al., 2020, 2023a). Species like *pequi* (*Caryocar brasiliense*), *baru* (*Dipteryx alata*), *jatobá* (*Hymenaea stigonocarpa*), and *araticum* (*Annona crassiflora*) are widely harvested by local populations and are essential sources of food and income for many communities (Guéneau et al., 2017, 2020; Walverde et al., 2021).

Despite their cultural significance and economic potential, the NTFP supply chain still faces major challenges: seasonal availability, low value addition, logistical constraints, and low quality of the products to their integration into broader and more stable markets (Mondo et al., 2024; Nabaloum et al., 2025). Nonetheless, research highlights the economic and productive potential of NTFPs, which can be enhanced by collective initiatives or targeted public policies (Berte et al., 2023; Orioli et al., 2025).

In this context, there is a growing need for productive models that combine environmental conservation, income generation, and socioeconomic resilience. Silvopastoral systems (SPS), which integrate trees, pastures, and livestock in the same productive area, are widely recognized as sustainable alternatives capable of improving land use, increasing productivity, and conserving natural resources (Nair, 2011, 1993). These systems promote permanent vegetation cover, reduce soil erosion, improve animal thermal comfort, and encourage product diversification on farms (Jose et al., 2019; Nair, 2011; Picasso & Pizarro, 2024). In many cases, they allow for the inclusion of native tree species, whose products align with the NTFP market logic (Lima et al., 2017, 2022).

In the Cerrado, silvopastoral systems with native species have been implemented for some years by family farmers and medium-sized producers, especially in contexts where there is greater familiarity with native vegetation and an interest in maintaining a portion of native tree species (Lima et al., 2017). These systems offer multiple benefits: they enhance local biodiversity, strengthen carbon stocks, increase farm-level climate resilience, and provide opportunities to market both animal products and NTFPs (Lima et al., 2022; Teixeira et al., 2022). Additionally, although the labor-intensive nature of SPS makes them potentially valuable tools for employment generation and productive inclusion, this potential is often challenged by the declining availability and high opportunity cost of rural labor, which can limit the viability and expansion of these systems (Lima et al., 2022; Pinheiro et al., 2021).

Indeed, the adoption of these systems remains limited by several factors. The market for NTFPs is still incipient and fragmented (Diniz et al., 2021; Walverde et al., 2021), and public incentives are scarce (de Mello et al., 2020, 2023a). Furthermore, there is a lack of technical knowledge regarding the costs, revenues, and risks of these production models. Finally, conventional production systems, such as mechanized agriculture and extensive livestock farming, continue to dominate land-use decisions, often due to their more immediate and predictable economic returns (Aragão et al., 2022; dos Reis et al., 2023).

Studies that integrate the ecological, productive, economic, and social dimensions of silvopastoral systems with native species are essential for informing sustainable rural development strategies and guiding more inclusive and effective public policies. Therefore, this research was structured into three chapters to address the proposed objectives. Chapter I conducts an economic and sensitivity analysis comparing the main land-use systems in the Cerrado, including silvopastoral systems with native trees. Chapter II aims to identify the socioeconomic, environmental, technical, farm-related, and productive factors that influence farmers' decisions to adopt and intensify the use of silvopastoral systems with native trees in the Cerrado. Chapter III seeks to segment the non-timber forest product (NTFP) markets in the Cerrado by analyzing the profiles of present traders and identifying the main species and products within each market segment.

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CHAPTER I:

ECONOMIC EVALUATION OF DIFFERENT LAND USES IN THE BRAZILIAN SAVANNA

To be submitted to the **Land Use Policy**

Economic evaluation of different Land Uses in the Brazilian Savanna

Abstract

The Cerrado is a biodiversity hotspot under increasing pressure from agricultural expansion, where balancing productivity and sustainability presents a complex challenge. Understanding the economic performance of land uses is crucial for supporting rural development policies that align with conservation goals. This study evaluates the economic performance and sensitivity of agriculture, silvopastoral systems (SPS) with native trees, and Eucalyptus plantations, in the northern Cerrado of Minas Gerais, Brazil. Data were collected from 80 farmers using a semi-structured questionnaire. For each unit, gross margin and profitability indicators were calculated, considering both cash and non-cash costs and income. A sensitivity analysis using Monte Carlo simulations quantified economic risk, while Random Forest models identified key cost and income variables. The different land uses had significant differences in cost structure, income composition, and profitability. Eucalyptus plantations showed the highest average profitability and the lowest economic risk, but also the highest dependence on external inputs (hired labor, market access, and infrastructure). SPS had intermediate performance, with lower costs and total income, while its productive and commercial potential remains underutilized. Agriculture, largely subsistence-oriented, exhibited the lowest profitability due to high fixed costs and limited market integration. Family labor dominated fixed costs in both SPS and agriculture. Despite these differences, farms with low risk were identified across all land uses, suggesting profitability is attainable under supportive conditions. These findings highlight the importance of public policies tailored to the specific challenges of each land use, fostering financial planning, technical assistance, and diversification to support sustainable rural development in the Cerrado.

Keywords: profitability, sensitivity, agriculture, silvopastoral systems, Eucalyptus plantation, economic analyses.

1. Introduction

The Brazilian Cerrado is the most biodiverse savanna on the planet (Myers et al., 2000) and provides essential ecosystem services, including water conservation and carbon storage (Arantes et al., 2016). This biome plays a strategic role in national food and energy production, but also faces mounting environmental and socio-economic pressures due to the expansion of conventional agriculture and forestry (de Mello et al., 2023; Salatino and Faria Salatino, 2023). These pressures have contributed to accelerated land conversion and deforestation in the Cerrado, driven by the growing global demand for food (Basso et al., 2024; Souza et al., 2020).

Spanning approximately a quarter of Brazil's territory, the Cerrado has undergone profound land-use changes and currently hosts the largest agricultural area among Brazilian biomes, with over 23 Million Hectares dominated by soybean and sugarcane cultivation. It also encompasses more than 51 Million Hectares of pastures, making it the second-largest Brazilian biome in terms of pasture area. In total, the Cerrado is one of the biomes most affected by agricultural expansion, with 47.2% of its territory dedicated to agro-pastoral activities (MapBiomas, 2023). With further increases in global food demand, this trend is likely to continue.

In large parts of the Cerrado landscape, farmers manage a variety of land-use systems, ranging from intensive agriculture, Eucalyptus plantations, and agroforestry (Ferraz-Almeida and da Mota, 2021; Lima et al., 2022; Teixeira and Rodrigues, 2021). A particularly common land use in the region is the Silvopastoral System (SPS), which allows traditional Brazilian cattle production integrated with trees, focusing on improving system performance (Lima et al., 2022, 2017).

SPS may incorporate either exotic or local tree and grass species (Nair, 1993). SPSs with native tree species are particularly relevant due to their combined ecological and economic benefits (Lima et al., 2022, 2017). These systems not only provide diversified products for the farm, such as timber, non-timber products, and fodder, but also enhance livestock welfare through shade, temperature regulation, and additional feed resources, ultimately contributing to higher overall land and animal productivity (Lima et al., 2022; Sandoval et al., 2023; Teixeira et al., 2022).

However, in the Cerrado, economic returns and social demand are often key considerations in land-use decisions, while environmental impacts may receive less attention (Aragão et al., 2022). In this context, the limited research comparing the economic performance of alternative land uses hampers the development of targeted public policies that promote economic efficiency for sustainable practices, including SPS (Ferraz-Almeida and da Mota, 2021; Polizel et al., 2021). In other Latin American contexts, SPS have frequently been associated with positive economic outcomes (Junca Paredes et al., 2025; Sandoval et al., 2023), which underscores the relevance of expanding such assessments in the Cerrado.

This study assesses the economic viability of main land uses in the Cerrado. We analyze statistical differences across land-use types by categorizing production, costs, revenues, and economic indicators. Additionally, the economic indicators are examined using the Monte Carlo method to identify the sensitivity of the main productive and economic variables associated with each land use.

2. Conceptual framework

Economic returns vary significantly across land-use types. Agriculture is recognized for its high productivity and the ability to produce multiple crops annually (Garbelini et al., 2022; Volsi et al., 2021), while eucalyptus plantations involve long investment cycles and delayed financial returns (Elli et al., 2020). Both systems are economically relevant in the Brazilian context, each with distinct cost structures and income dynamics. In contrast, SPS, especially those based on native species, introduce greater complexity due to their multi-component structure and multifunctional role in landscapes. Studies have indicated that these systems can generate relevant economic, productive, and environmental benefits (Cunha et al., 2025; Lima et al., 2022). However, despite growing interest, economic comparisons between SPS and conventional systems remain limited, often relying on localized case studies that fail to capture broader regional variability (Cunha et al., 2025; Ferreira et al., 2022).

Farm economic evaluation typically relies on profitability indicators that account for revenue generation and cost structure. Among these, gross margin and profitability are widely used to evaluate economic viability, with the advantage of being applicable across different land uses (FAO, 1995). Gross margin reflects the difference between total revenue and variable costs, providing insight into the short-term financial sustainability of production systems. Profitability, in turn, extends this analysis by incorporating fixed costs, offering a broader perspective on long-term economic performance. By assessing each land use individually, this study explores how these indicators behave under different production realities, contributing to a better understanding of their role in supporting long-term financial sustainability.

By using a larger and more diverse sample of land-use types, this study characterizes and explores economic variability both between and within land uses. This approach not only enhances the generalizability of findings but also provides critical insights for policymakers and land managers seeking to promote sustainable rural development. Furthermore, the analysis integrates a sensitivity component using the Monte Carlo method, which is widely employed to identify the most influential variables and conditions under which economic returns become negative (Senova et al., 2023). This dual analysis, comparative and sensitivity, offers a robust understanding of the economic performance of different land-use strategies in the Cerrado.

3. Material and Methods

3.1. Study area

The study area is in the northern mesoregion of Minas Gerais, Brazil, covering 809,848 hectares across various municipalities, defined by the watersheds of the Rio Pardo and São João do Paraíso (figure 1). The region is covered mostly by Cerrado plant physiognomies, with smaller areas of Caatinga vegetation and transitional zones. The plant physiognomies include Cerrado field, montane deciduous forest, Vereda (palm swamps), and submontane deciduous forest (Carvalho et al., 2009).

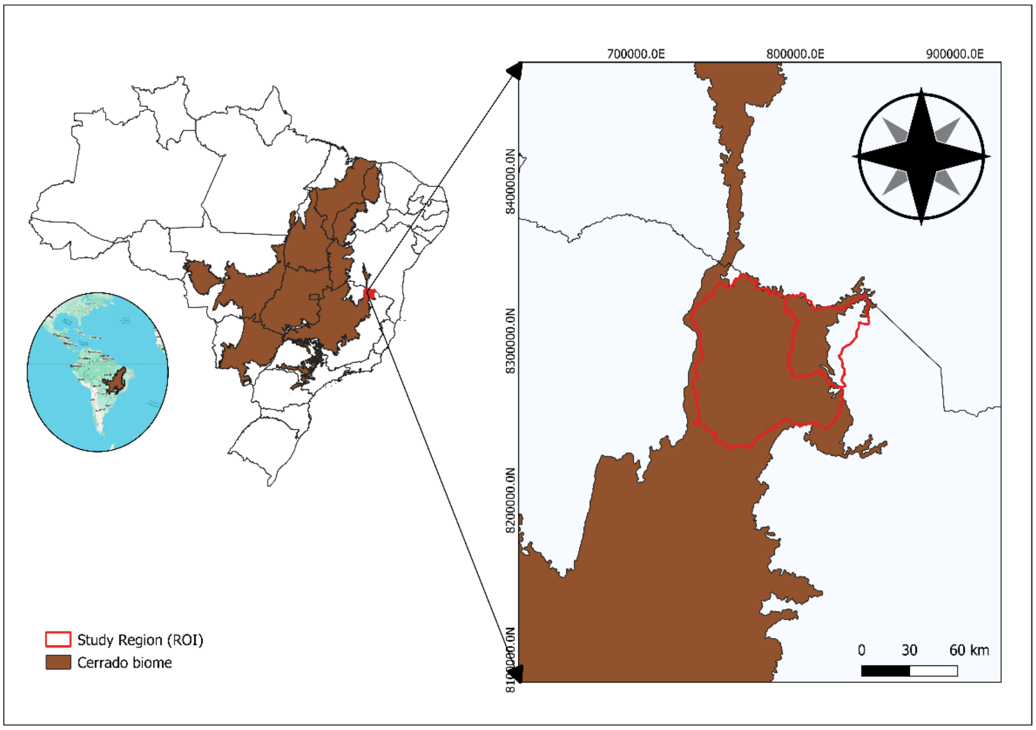

Figure 1. Map of the study region that includes the basins of Rio Pardo and São João do Paraíso, state of Minas Gerais, Brazil. Source: Elaborated by the authors based on geospatial data from the Brazilian Institute of Geography and Statistics (IBGE, 2024).
Source: Elaborated by the authors.

The climate is tropical (Aw) with warmer summers and dry winters (Martins et al., 2018). In 2024, annual precipitation was 940 mm, concentrated in a few months, leaving a prolonged dry season that challenges most land uses, though the severity of its impact varies across systems (INMET, 2024).

The municipalities of Vargem Grande do Rio Pardo, Santo Antônio do Retiro, Montezuma, Indaiabira, Rio Pardo de Minas, São João do Paraíso, and Taiobeiras account for 99.8% of the basin. The sampling frame consisted of all farms registered in the Brazilian Rural Environmental Registry (SICAR, 2022), with a total of 19,225 eligible farms. They were stratified by size using so-called fiscal modules (65 ha in all municipalities), resulting in four categories: Class I (≤65 ha), Class II (65-<130 ha), Class III (130-<260 ha), and Class IV (>260 ha).

3.2. Data collection

3.2.1. Farm selection

Sampled farms were selected based on their size, municipality, and proportional representation across land use types. Due to logistical and financial constraints, a sample of 160 farms was chosen (table S1). Farms were randomly selected from the four farm size strata, with the same proportion in each stratum. Additional farms were drawn to account for possible non-responses. Data collection occurred from November 2023 to March 2024.

3.2.2. Questionnaire application

The questionnaire was pretested using two local farmers. Necessary adjustments were applied in the questionnaire, the data were discarded, and a revised version was used for the final survey. Of the 160 selected, 106 farmers agreed to participate. The semi-structured questionnaire covered economic data, land use details, socioeconomic characteristics, technical practices, and additional activities. Prior informed consent was obtained from all participants, and the study was approved by the Human Research Ethics Committee of the Federal University of Viçosa (Protocol CAAE no. 72996223.0.0000.5153).

3.3. Land use classification and appraisal

The study focused on farms with commercial production and cost data, of which 80 met the inclusion criteria. Since many farms had more than one type of land use, the analysis considered a total of 129 land-use units. The most frequent land uses were Agriculture (57 units), Silvopastoral Systems with native trees (52), and Eucalyptus plantations (20). Indirect costs not attributable to specific land use were allocated according to the income generated by each unit. For consistency, both costs and incomes were standardized per hectare based on the area allocated to each land-use unit and adjusted to reflect 2023 values. All monetary values were then converted from Brazilian Reais (R$) to US Dollars (US$) using the 2023 average exchange rate (1 US$ = 4.99 R$).

3.4. Economic Variables

3.4.1. Variable cost

3.4.1.1. Production

This category includes expenses directly related to production for each land use. Variable costs in production consist of input costs, such as fertilizers and limestone, seed and seedling costs, pesticides, and fuel. In cases of land use with animals, veterinary and feeding services are also included. These costs were determined and analyzed individually.

3.4.1.2. Hired labor

Costs associated with contracted employees were based on their wages, payment frequency (daily, monthly, or annually), and the duration of employment (days or months), generating labor costs on an annual basis. This cost was considered variable, as it is directly related to production and represents a financial expense for the farm. As with other general costs for the farm, hired labor costs were subdivided proportionally according to the revenue generated from each land use on the farm.

3.4.1.3. Marketing

Marketing costs refer to expenses directly associated with product sales, including packaging and transportation to buyers. This cost was considered alongside production costs, as it is directly linked to the quantity of products marketed and subdivided by land use type. These costs are considered variable due to their direct relationship with production.

3.4.2. Fixed cost

3.4.2.1. Production

Fixed costs related to production include electricity, water, fences, administration, insurance, and maintenance/repair, which were accounted for individually but considered together due to their low prevalence across the farms (fixed cost of production).

3.4.2.2. Machinery costs

Machinery costs include both the annual contracting of equipment and machinery services and the depreciation of machinery and equipment owned by the farm. For contracted services, the total annual cost was reported directly by the interviewees and treated as a fixed yearly expense. For owned assets, depreciation was calculated using the straight-line method, based on the initial value of each item, as reported by the interviewees, and its estimated useful life. A residual (salvage) value of zero was assumed.

We treated machinery costs as fixed costs because they represent farm-level investments and service contracts that are incurred independently of short-term fluctuations in production levels, as long as the equipment or service remains available to the farm. This classification indicates that these costs cannot be readily adjusted in the short run in response to changes in output, unlike variable costs that scale directly with production. Because these costs are incurred at the farm level, they were allocated proportionally across land uses based on the income generated by each unit. This approach allows inclusion of machinery costs in the analysis while acknowledging that actual usage may vary between land-use types.

3.4.2.3. Family labor

The opportunity cost of family labor was based on the time spent annually by each family member assisting with production. For family members working more than 8 hours per day, the full day's wage was considered, while shorter shifts were proportionally calculated. This process was carried out for each family member working on the farm. The wage considered was based on the average rate for "General Agricultural/Livestock Labor" as reported by the interviewees, since much of the family work aligns with this role and the service is commonly available in rural areas. In total, there were 64 instances of hiring this type of labor among the interviewees, with an average wage of US$15.50 per day (standard deviation US$3.80; range US$10.40–30.10). We treated the opportunity cost of family labor as a fixed cost because it is borne by the farm regardless of the production level or output fluctuations, rather than as a cost that varies directly with production quantity. As with other general costs, we subdivided it proportionally to the total income from each land use on the farm.

3.4.2.4. Land opportunity

The opportunity cost of land refers to the potential returns a farmer foregoes by using their land for a specific purpose instead of alternative uses. To estimate this cost, we used the average price of bare land in the macro-regions of Minas Gerais, based on data from the Land Market Analysis Report (RAMT) Minas Gerais, published by the Regional Superintendency of Minas Gerais (Minas Gerais, 2023). The average value was US$609.50 per hectare, which was multiplied by Brazil's 2023 benchmark interest rate (SELIC), set at 11.75% per year. The final cost was calculated according to the total area allocated to each land use on the farm.

3.4.2.5. Capital opportunity

The opportunity cost of capital refers to the foregone returns from not investing the resources elsewhere. It was estimated based on the total value of equipment, infrastructure, and machinery reported by each farmer, applying the Brazilian reference interest rate (SELIC) of 11.75% for 2023. As this value was reported at the farm level, we allocated it proportionally according to the income generated by each land use.

3.4.3. Income

Cash income per land use type was determined based on the products produced and marketed. Each interviewee provided information on production volume, quantity sold, and selling price. This data enabled the calculation of cash income for each product sold and for each land use type.

Since some farmers retain part of their production for on-farm consumption (FAO, 1995), the non-cash income was also estimated, which accounts for the total annual production consumed by the farmers. For these cases, when products consumed on-farm did not have specific transportation costs or market prices within the sample, the average market price and transportation costs observed across all sampled land uses were considered. In this way, an additional marketing cost was created and included in the variable costs, which generated the potential variable cost. If the raw product was transformed into a processed product for consumption or commercialization, only the income equivalent to the processed product's market value was considered. Ultimately, the total income comprised both cash income and non-cash income for each land use type.

3.4.4. Gross margin

Gross margin was calculated as the difference between cash income generated from product sales and the corresponding variable costs (production, hired labor, and marketing costs) for each land use, standardized per hectare. Additionally, we computed the potential gross margin, which includes the total income, both cash and non-cash, for each land use type, following the same procedure.

3.4.5. Profitability

Profitability was assessed by incorporating both variable and fixed costs. Fixed costs included machinery, family labor, fixed production costs, land opportunity costs, and opportunity cost of capital. We also estimated the potential profitability by considering total income alongside these costs, following the same procedure per land use type.

Furthermore, we calculated potential profitability under three distinct scenarios:

(1) excluding the opportunity costs of land;
(2) excluding the opportunity costs of land and capital;
(3) excluding the opportunity costs of land, capital, and labor family.

3.5. Data Analysis

3.5.1. Statistical inference by groups

In the descriptive analysis, 24 variables were evaluated across the three land uses. These included specific and aggregated costs, various income types, economic indicators, and farm characteristics (table 1). Some cost components, such as land and animal-related costs, were excluded from this comparative step due to standardization issues or absence in specific systems, although they were included in profitability calculations.

Table 1. Variables included in the descriptive analysis by land use

Category	Variables
Specific Costs	Inputs, Seeds/Seedlings, Pesticides, Fuel, Fixed Production, Machinery, Hired Labor, Family Labor, Capital, Marketing
Aggregated Costs	Variable Costs, Fixed Costs, Potential Variable Costs (within Non-Cash Income)
Incomes	Cash Income, Non-Cash Income, Total Income

Category	Variables
Economic Indicators	Gross Margin, Profitability, Potential Gross Margin (within Non-Cash Income), Potential Profitability (within Non-Cash Income), Potential Profitability 1, 2, and 3 (distinct scenarios)
Excluded Costs	Land Cost (fixed per hectare), Animal-related Costs (feed, veterinary)
Farm Characteristics	Size Class, Productive Area, Number of Products, Number of Land Uses

Source: Elaborated by the authors.

The Shapiro-Wilk test indicated that the data had non-normal distributions (table S2), thus non-parametric methods were applied throughout the analysis. Consequently, the descriptive statistics for each land use, presented in Table 2, rely on robust measures: the median for central tendency and the Median Absolute Deviation (MAD) for dispersion. To better characterize the intermittent nature of costs and revenues, the table also includes the percentage of zero occurrences, a more informative metric than the minimum value in this context. General differences among land uses were tested using the Kruskal-Wallis test, with significance levels indicated by asterisks in the results table. Where significant differences were found, Dunn's post hoc test was used for pairwise comparisons, with p-values adjusted using the Bonferroni correction for multiple comparisons. Detailed Dunn test results are provided in Supplementary Material (table S3), and statistical differences in pairwise comparisons are indicated by letters in the main results table.

As a complementary analysis, descriptive statistics were compiled for each land use, disaggregated by farm size class (tables S4, S5, and S6). Given the limited sample size in some classes, this summary is intended to provide exploratory insights into within-category variability.

Table 2. Descriptive statistics (median, Median Absolute Deviation (MAD), % of value 0, and maximum) at the land level for the different land uses. Agriculture (Agri), Eucalyptus plantation (Eucal), and Silvopastil System (SPS)

Economic Variables	Median			MAD			% of 0			Maximum		
	Agri (n=57)	SPS (n=52)	Eucal (n=20)	Agri (n=57)	SPS (n=52)	Eucal (n=20)	Agri (n=57)	SPS (n=52)	Eucal (n=20)	Agri (n=57)	SPS (n=52)	Eucal (n=20)
Num_Land_Use	2.0	2.0	2.0	0.0	0.0	1.5	0.0	0.0	0.0	3	3	3
Productive area (ha)	3.0	10.0	105.0	3.0	11.9	126.0	0.0	0.0	0.0	700	200	800
Class	1.0	2.0	3.0	0.0	1.5	1.5	0.0	0.0	0.0	4	4	4
Input_Cost (US$/ha)	50.8	0.0	1.6	68.1	0.0	2.4	19.3	84.6	50.0	3351.8	232.5	1269.2
Seed_Cost (US$/ha)	0.0	0.0	0.0	0.0	0.0	0.0	54.4	63.5	85.0	601.2	112.2	288.6
Pesticide_Cost (US$/ha)	0.0	0.0	2.5	0.0	0.0	3.6	78.9	88.5	40.0	801.6	8.0	32.8
Fuel_Cost (US$/ha)	0.0	0.0	7.5	0.0	0.0	11.1	57.9	65.4	50.0	961.9	961.9	685.4
Prod_Fixed_Cost (US$/ha)	42.8	40.1	19.7	63.4	58.1	29.3	24.6	19.2	25.0	2144.3	701.4	521.0
Depreciation_Cost (US$/ha)	79.6	29.4	40.0	118.0	42.7	59.4	26.3	17.3	25.0	6778.3	1287.4	302.3
Hired_Cost (US$/ha)	0.0	17.5	63.2	0.0	36.5	69.2	50.9	36.5	20.0	4584.2	1208.7	583.0
LaborFamily_Cost (US$/ha)	372.6	74.3	9.1	552.5	110.1	13.6	33.3	23.1	35.0	29065.7	2341.2	549.6
Capital_Cost (US$/ha)	46.0	14.7	42.1	68.2	21.6	62.3	33.3	23.1	25.0	3727.2	1841.9	645.2
Marketing_Cost (US$/ha)	0.0	0.0	6.0	0.0	0.0	8.9	71.9	73.1	50.0	250.1	170.2	721.4
Variable_Cost (US$/ha)	157.5	88.0	242.8	199.1	108.8	339.5	0.0	3.8	5.0	4844.7	1285.3	1775.4
Pot_Variable_Cost (US$/ha)	161.1	89.1	242.8	195.7	112.6	339.5	0.0	3.8	5.0	4872.7	1285.3	1775.4
Fixed_Cost (US$/ha)	1121.2	365.8	326.7	1543.2	338.6	301.9	0.0	0.0	0.0	30673.0	5600.9	1496.0
Num_Products (US$/ha)	1.0	1.0	1.0	1.5	0.0	0.0	26.3	17.3	20.0	4	3	3
Cash_Income (US$/ha)	288.6	69.4	532.1	427.8	102.9	543.2	26.3	17.3	20.0	6412.8	3503.0	3847.7
Non_cash_Income (US$/ha)	60.1	7.5	0.0	89.1	11.1	0.0	38.6	21.2	100.0	6651.5	787.3	0.0
Total_Income (US$/ha)	454.2	110.9	532.1	673.5	164.3	543.3	21.1	5.8	20.0	6939.4	3503.0	3847.7
Gross_Margin (US$/ha)	6.9	-11.5	213.0	415.7	172.6	558.5	0.0	1.9	5.0	3718.6	3323.7	2072.3
Profit (US$/ha)	-975.9	-317.6	80.5	1311.0	436.9	526.4	0.0	0.0	0.0	649.1	3161.7	1242.4
Pot_Gross_Margin (US$/ha)	131.3	11.0	213.0	498.3	152.3	558.5	0.0	1.9	5.0	6262.1	3323.7	2072.3
Pot_Profit (US$/ha)	-881.9	-249.9	80.5	1220.1	342.4	526.4	0.0	0.0	0.0	6133.0	3161.7	1242.4
Pot_Profit_1 (US$/ha)	-801.6	169.6	160.8	1220.1	342.4	526.4	0.0	0.0	0.0	6213.3	3242.0	1322.7

Economic Variables	Median			MAD			% of 0			Maximum		
	Agri (n=57)	SPS (n=52)	Eucal (n=20)	Agri (n=57)	SPS (n=52)	Eucal (n=20)	Agri (n=57)	SPS (n=52)	Eucal (n=20)	Agri (n=57)	SPS (n=52)	Eucal (n=20)
Pot_Profit_2 (US$/ha)	-619.9	-59.0	253.3	1073.0	267.7	565.8	0.0	0.0	0.0	6340.0	3348.0	1439.9
Pot_Profit_3 (US$/ha)	40.3	12.1	278.5	396.6	225.6	510.3	0.0	0.0	0.0	6399.6	3348.0	1491.1

Where: Agri = agriculture; Eucal = Eucalyptus plantation; and SPS = silvopastoral systems with native trees; between parentheses is the number of samples for each group, and SD = standard deviation. Num_Land_Use - Number of different land uses present on the farm; Productive area (ha) - Total area in hectares used for productive purposes; Class - Farm size classification based on fiscal modules (I to IV); Input_Cost (US$/ha) - Cost of inputs (e.g., fertilizers, lime), per hectare; Seed_Cost (US$/ha) - Cost of seeds or seedlings used, per hectare; Pesticide_Cost (US$/ha) - Cost of pesticides per hectare; Fuel_Cost (US$/ha) - Fuel expenses related to production, per hectare; Prod_Fixed_Cost (US$/ha) - Fixed production costs (e.g., electricity, water, maintenance), per hectare; Machinery_Cost (US$/ha) - Annual depreciation of machinery and equipment, per hectare; Hired_Cost (US$/ha) - Cost of hired labor, per hectare; LaborFamily_Cost (US$/ha) - Cost of family labor, per hectare; Capital_Cost (US$/ha) - Opportunity cost of capital invested in infrastructure and equipment, per hectare; Marketing_Cost (US$/ha) - Marketing-related costs (e.g., transportation, packaging), per hectare; Variable_Cost (US$/ha) - Total variable cost (production, hired labor, marketing), per hectare; Pot_Variable_Cost (US$/ha) - Potential variable cost including non-marketed (on-farm consumed) production, per hectare; Fixed_Cost (US$/ha) - Total fixed costs (machinery, family labor, production, capital, land), per hectare; Num_Products (US$/ha) - Number of products marketed per land-use type; Cash_Income (US$/ha) - Revenue from product sales, per hectare; Non_cash_Income (US$/ha) - Estimated value of on-farm consumed production, per hectare; Total_Income (US$/ha) - Sum of cash and non-cash income, per hectare; Gross_Margin (US$/ha) - Cash income minus variable costs, per hectare; Profit (US$/ha) - Cash income minus variable and fixed costs, per hectare; Pot_Gross_Margin (US$/ha) - Total income minus potential variable costs, per hectare; Pot_Profit (US$/ha) - Total income minus all fixed and variable costs, per hectare; Pot_Profit_1 (US$/ha) - Potential profit excluding land opportunity cost; Pot_Profit_2 (US$/ha) - Potential profit excluding land and capital opportunity costs; Pot_Profit_3 (US$/ha) - Potential profit excluding land, capital, and family labor costs.

Source: Elaborated by the authors.

3.5.2 Empirical models

A Monte Carlo framework was used to evaluate the effect of cost and revenue variability on Potential Gross Margin and Potential Profitability (Senova et al., 2023). Triangular distributions were selected because they require only a minimum, maximum, and most-likely value, making them suitable for representing empirical ranges when sample sizes are limited or the underlying distribution is unknown (Vose, 2008). riangular distributions were defined for each variable, using observed values for each sample as the mode and applying variability bounds estimated from the coefficient of variation derived from the confidence intervals of economic data, stratified by land use and farm size. As a constraint on overdispersion, variability was capped at 100%, except for Land_Cost, which was set at a fixed 30% due to uniformity in the dataset. Full details by variable and class are provided in Supplementary Material (Table S7).

Each sample of land use was subjected to 1,000 independent simulations, assuming no correlation among variables (Heijungs, 2020). Outputs were filtered to exclude the extremes of both economic indicator values outside the 5th–95th percentile range. Economic risk was defined as the share of negative outcomes for each indicator and sample, then categorized as very low (<10%), low (10–25%), medium (25–50%), high (50–75%), or very high (>75%). Risk classification results were presented by land use in the main text and further disaggregated by farm size class and land use in the supplementary material (table S8).

A Random Forest model was independently fitted for each sample and economic indicator to identify the key drivers of economic variation. All simulated cost and revenue components were used as predictors, and the simulated values of Potential Gross Margin and Potential Profitability served as response variables. All observations were used to train each Random Forest model; model performance and variable importance were assessed internally via the algorithm's out-of-bag (OOB) samples. Variable importance was evaluated using the standard permutation-based measure, the percentage increase in mean squared error (%IncMSE) (Genuer et al., 2010).

Resulting %IncMSE scores were aggregated by land use, computing the mean importance per variable for each indicator. This approach enabled the ranking of cost and revenue factors according to their influence on economic performance. Separate rankings for Potential Gross Margin and Potential Profitability were generated and depicted as comparative bar plots.

By integrating this Random Forest–based analysis with the preceding Monte Carlo–based risk assessment, we obtained a comprehensive understanding of both the magnitude and variance of economic outcomes. This dual approach not only identifies the primary sources of financial instability but also highlights actionable leverage points for each land-use system. All analysis was conducted in R (v. 4.4.1) using the random Forest package.

4. Results

4.1 Inferencial and descriptive statistic

Among the 27 economic and productive variables tested across the land use types, 15 showed statistically significant differences. The productive median area varied substantially: agriculture had the smallest (3 ha), Eucalyptus plantations had the largest (105 ha), and SPS had an intermediate value (105.0 ha). These patterns are reflected in the distribution of land uses across farm size classes: agriculture and SPS were predominantly found in smaller farms (Class I, 56% of agricultural units and 40% of SPS units), while Eucalyptus plantations were concentrated in the largest farms (Class IV, 40% of Eucalyptus units) (table 3).

Table 3. Annual variables tested pairwise by the Dunn test with letters indicating statistical differences and their mean value for each land use type in the study area

Economic Variables	Agriculture		SPS		Eucalyptus Plantation	
	Median	DT	Median	DT	Median	DT
Productive area (ha) **	3.0	a	10.0	b	105.0	c
Class **	1.0	a	2.0	a	3.0	b
Num_Land_Use	2.0	a	2.0	a	2.0	a
Num_Products (US$/ha)	1.0	a	1.0	a	1.0	a
Input_Cost (US$/ha) **	50.8	a	0.0	b	1.6	a
Seed_Cost (US$/ha)	0.0	a	0.0	a	0.0	a
Pesticide_Cost (US$/ha) **	0.0	a	0.0	a	2.5	b
Fuel_Cost (US$/ha)	0.0	a	0.0	a	7.5	a
Hired_Cost (US$/ha)	0.0	a	17.5	a	63.2	a
Marketing_Cost (US$/ha) **	0.0	a	0.0	a	6.0	b
Variable_Cost (US$/ha) **	157.5	a	88.0	b	242.8	a
Pot_Variable_Cost (US$/ha) **	161.1	a	89.1	b	242.8	a
Prod_Fixed_Cost (US$/ha)	42.8	a	40.1	a	19.7	a
Machinery_Cost (US$/ha)	79.6	a	29.4	a	40.0	a
LaborFamily_Cost (US$/ha) *	372.6	a	74.3	ab	9.1	b
Capital_Cost (US$/ha)	46.0	a	14.7	a	42.1	a
Fixed_Cost (US$/ha) **	1121.2	a	365.8	b	326.7	b
Cash_Income (US$/ha) *	288.6	ab	69.4	b	532.1	a
Non_Cash_Income (US$/ha) **	60.1	a	7.5	a	0.0	b
Total_Income (US$/ha)	454.2	a	110.9	a	532.1	a
Gross_Margin (US$/ha)	6.9	a	-11.5	a	213.0	a
Pot_Gross_Margin (US$/ha)	-975.9	a	-317.6	a	80.5	a
Profit (US$/ha) **	131.3	a	11.0	b	213.0	c
Pot_Profit (US$/ha) **	-881.9	a	-249.9	b	80.5	c
Pot_Profit_1 (US$/ha) **	-801.6	a	169.6	b	160.8	c
Pot_Profit_2 (US$/ha) **	-619.9	a	-59.0	b	253.3	c
Pot_Profit_3 (US$/ha)	40.3	a	12.1	a	278.5	a

Where: Significance levels from the Kruskal-Wallis test indicate overall differences among the three land uses: ** $p < 0.01$, * $p < 0.05$. Medians in the same row followed by different letters are significantly different according to Dunn's post-hoc test with Bonferroni correction ($p < 0.05$)
Source: Elaborated by the authors.

Five variable cost components exhibited significant differences. Input costs were notably lower in SPS compared to agriculture and Eucalyptus. Pesticide use in Eucalyptus was associated primarily with ant control, showing a pest management reliance on the farmers. Marketing costs were highest in Eucalyptus, reinforcing its intensive management model. Overall, agriculture and Eucalyptus showed higher observed and potential variable costs than SPS.

For fixed costs, family labor and total fixed costs differed significantly. Agriculture, largely based on family farming, showed the highest values, especially for family labor, which represented 41.5% of its fixed costs. In SPS, family labor was also substantial (32.7%), while in Eucalyptus, it was less relevant. Eucalyptus, conversely, showed greater dependence on hired labor.

Cash income was highest in Eucalyptus, significantly surpassing SPS. However, it had no non-cash income, unlike agriculture and SPS, which had non-cash values. Agriculture led in total income due to its high non-cash component. No significant differences were found in total income across land uses.

The median gross margin values did not differ statistically, despite the low values associated with SPS and Agriculture. Profitability differed significantly between land uses, with Eucalyptus showing the highest median profitability, followed by SPS and then agriculture. Positive median profitability occurred only in Eucalyptus and in potential scenarios where some fixed costs were excluded.

4.2. Sensitivity among land uses

The simulations for agriculture, SPS, and Eucalyptus plantation revealed differences in sensitivity depending on the economic indicators analyzed. Gross Margin showed lower overall economic risk, with over 42% of negative returns across all land uses. Eucalyptus plantations performed best, with 60% of farms classified under very low risk. However, the high share of farms (≥30%) in the very high-risk class for all land uses reflects short-term economic challenges for a part of farmers (table 4).

Table 4. Percentage of negative returns and corresponding risk levels by economic indicator and across land uses

Degree of risk	Gross Margin					
	Agriculture	%	SPS	%	Eucalyptus	%
Very high	18	31.6%	16	30.8%	6	30.0%
High	3	5.3%	5	9.6%	0	0.0%
Medium	3	5.3%	4	7.7%	0	0.0%
Low	1	1.8%	4	7.7%	2	10.0%
Very low	32	56.1%	23	44.2%	12	60.0%
% of negative return	36.05%		41.07%		30.83%	
Degree of risk	Profitability					
	Agriculture	%	SPS	%	Eucalyptus	%
Very high	51	89.5%	45	86.5%	9	45.0%
High	0	0.0%	1	1.9%	0	0.0%
Medium	1	1.8%	2	3.8%	4	20.0%
Low	1	1.8%	2	3.8%	1	5.0%
Very low	4	7.0%	2	3.8%	6	30.0%
% of negative return	89.70%		88.83%		54.02%	

Source: Elaborated by the authors.

In contrast, profitability exhibited consistently higher risk, with most farms in agriculture (89.7%) and SPS (88.8%) experiencing negative returns. Eucalyptus showed a better performance, though 54% of its farms still registered losses. Notably, each land use had at least some farms classified under very low risk, suggesting that economic success is attainable depending on context.

The sensitivity analysis also assessed the relative importance of cost and revenue components for each indicator. For the gross margin, cash income was the most influential factor across all land uses. Non-cash income was also important for SPS and agriculture, but irrelevant for Eucalyptus, where it was not generated. Among variable costs, hired labor dominated in SPS and agriculture, while input costs were slightly more important in Eucalyptus. Fuel costs were relevant in all land uses, especially Eucalyptus (18.6%) and SPS (15.9%), as were marketing costs (notably Eucalyptus at 14.6%) and animal feed (notably for SPS at 15.2%) (figure 2).

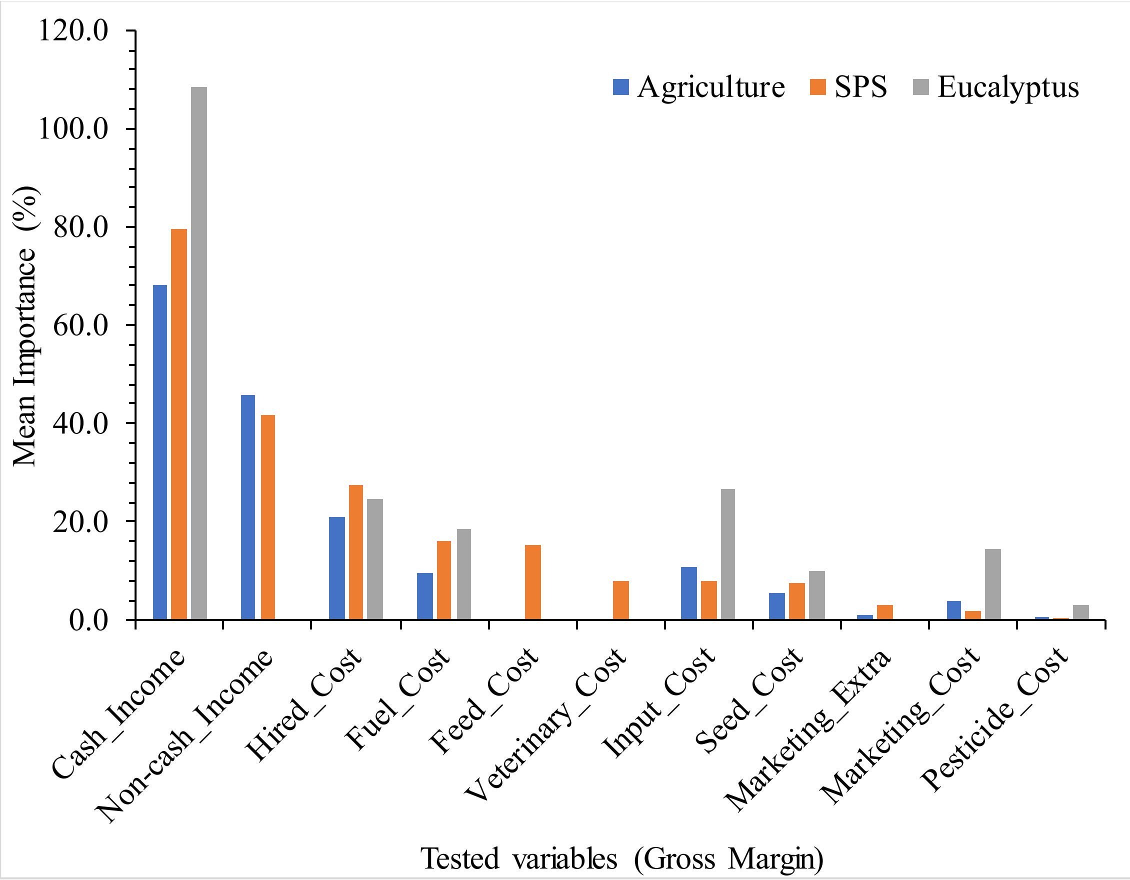

Figure 2. Average importance of input variables for Gross Margin across land uses. Values represent mean %IncMSE obtained from Random Forest models fitted to the outputs of 1,000 Monte Carlo simulations per land use type.
Source: Elaborated by the authors.

For profitability, which encompasses both fixed and variable costs, the importance of variables has shifted. Family labor was the most critical cost for agriculture and SPS, surpassing income components. For Eucalyptus, cash income, hired labor, and input costs were more influential. Machinery and fixed production costs also had a significant impact on profitability for all uses, especially SPS. Capital costs approached 10% importance across uses, while land costs exceeded this threshold only for SPS (12.5%). Only in the case of Eucalyptus did fuel, input, and marketing costs exceed the 10% threshold, reinforcing its higher dependency on a broader set of cost components. (figure 3).

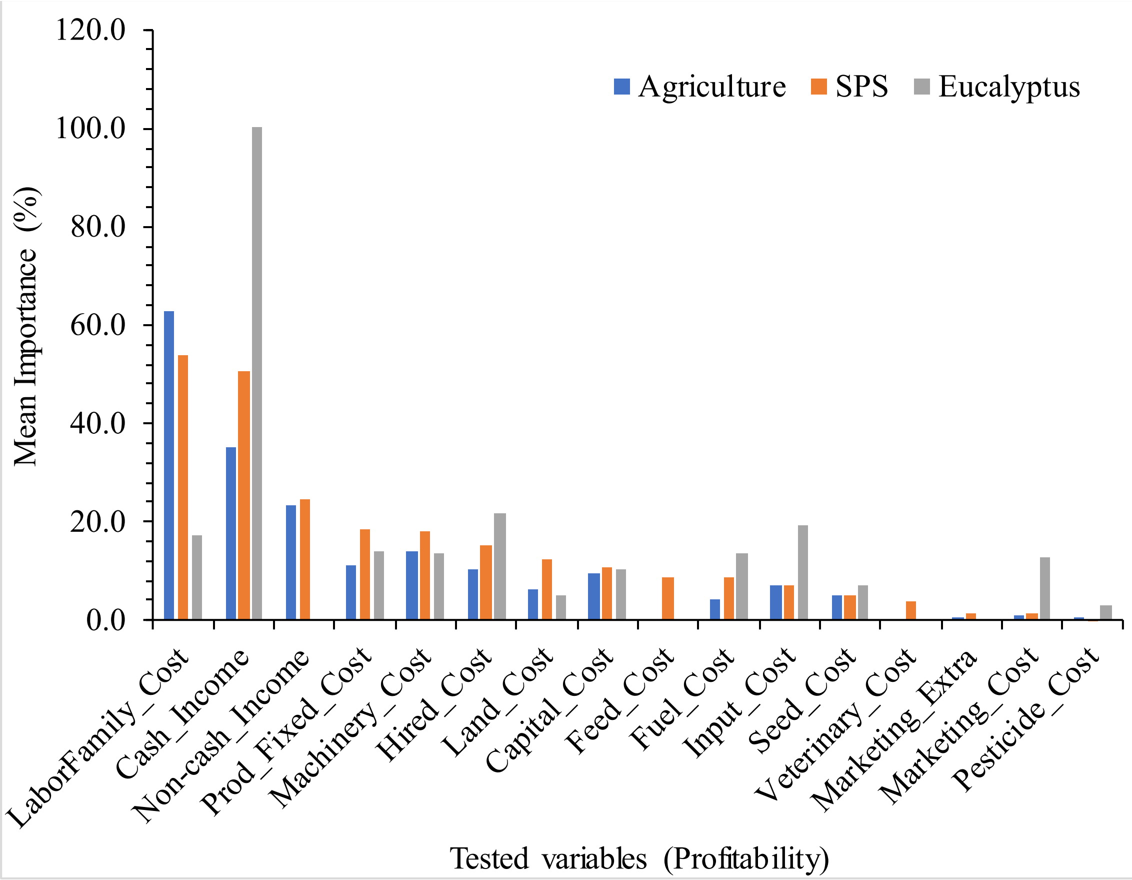

Figure 3. Average importance of input variables for Profitability across land uses. Values represent mean %IncMSE obtained from Random Forest models fitted to the outputs of 1,000 Monte Carlo simulations per land use type.
Source: Elaborated by the authors.

5. Discussion

5.1 Inferential and descriptive statistics among land uses

Land use systems in the Cerrado differ widely in their economic and ecological characteristics, reflecting distinct production strategies and historical pathways (Siqueira-Neto et al., 2021; Souza et al., 2020). This diversity is evident in the significant variation in costs, revenues, and resource allocation across agriculture, silvopastoral systems (SPS) with native trees, and Eucalyptus plantations in northern Minas Gerais.

Agriculture, primarily practiced by smallholder family farms, occupies the smallest cultivated areas yet generates the highest non-cash income, highlighting its key role in subsistence and food security (Ayaz and Mughal, 2024; Tanure et al., 2024). SPS, a traditional land use in the region, covers moderately larger areas and is present across all farm sizes (Lima et al., 2022, 2017). Various studies demonstrate the ecological benefits linked to SPS, such as biodiversity conservation and ecosystem service provision (Cunha et al., 2025; Lima et al., 2017; Teixeira et al., 2022). Eucalyptus is more commonly associated with large-scale farms due to its historical introduction via state concessions for charcoal production (Lima et al., 2022; Teixeira and Rodrigues, 2021). Though it contributes to local economic development (Afonso and Miller, 2021), it also leads to environmental degradation in the Cerrado. Studies document reductions in the ecosystem services associated with forest monoculture, underscoring the ecological risks posed by the expansion of Eucalyptus in this sensitive biome (Bellink and Verburg, 2023; Ferraz et al., 2024).

The differences in variable costs underscore operational specificities. Eucalyptus incurs higher pesticide and transportation costs, primarily due to intensive pest control (Vinha et al., 2020) and long delivery distances, a challenge to small farmers (Silva et al., 2024). SPS has the lowest input use and variable costs, highlighting both its extensive management style, justifying the lower total income, and indicating the need for public policies that encourage greater management, diversification, and productivity of SPS with native trees (Lima et al., 2022; Urruth et al., 2022).

Family labor is the main fixed cost in agriculture and SPS. In agriculture, this reflects a reliance on internal labor for staple crops like cassava and beans, but the productive inefficiency and low financial returns associated with family farming indicate the need for social assistance policies (Ayaz and Mughal, 2024; Vilpoux et al., 2021). Although SPS is recognized as being more labor-intensive (Varela et al., 2022), the regional SPS with native species does not appear to be very intensive in production and commercialization, given the lower cost values compared to other land uses. In contrast, Eucalyptus depends more on outsourced labor, which may require training programs and public policies to promote sustainable practices associated with forest plantations (Afonso and Miller, 2021; Lewark, 2022). These differences may also reflect the distinct profiles of producers engaged in eucalyptus plantation compared with those in agriculture and SPS, as discussed in the following section.

Eucalyptus generates the highest cash income, but the lack of non-cash income suggests a model focused on market sales, reinforcing the barriers experienced to develop more sustainable models associated with mixed sustainable Eucalyptus plantations in Brazil (Bellink and Verburg, 2023). Agriculture and SPS, in contrast, support family livelihoods, which in contexts of uncertain, unreliable, or imperfect markets can be a rational risk-minimization strategy for smallholder farmers (Ayaz and Mughal, 2024; Tanure et al., 2024). SPS shows the lowest total income but is recognized for diversifying production, improving family nutrition, and enhancing economic profitability, in addition to contributing to biodiversity conservation, soil protection, and climate change mitigation (Cunha et al., 2025; Lima et al., 2022, 2017; Sandoval et al., 2023; Teixeira et al., 2022). However, this potential currently remains underutilized.

Profitability analysis shows Eucalyptus is the most profitable land use, with statistically higher returns across most scenarios (table 3). This performance is driven by its scale, market integration, and technological development (Afonso and Miller, 2021; Teixeira and Rodrigues, 2021). However, profitability remains sensitive to context (figures 2 and 3). Returns can fluctuate between cutting cycles, and financial viability may diminish in the absence of strong market demand due to the high costs of operations, such as harvesting and transportation (Lewark, 2022; Munis et al., 2022).

Despite its ecological and cultural value (Lima et al., 2022, 2017), SPS presents intermediate profitability. The land use's economic potential in the region is constrained by factors such as low costs, productivity, and limited diversification (table 3). These systems can have high profitability, especially through the inclusion of the production of timber and NTFPs (Berte et al., 2023; dos Reis et al., 2021), although such models are not frequently implemented locally due to the required investments, which are often unfeasible in the absence of accessible credit (Cunha et al., 2025).

Agriculture is the least profitable land use and is heavily impacted by high fixed costs and reduced scalability. In the study region, it is generally confined to smaller, more fertile areas that represent only a limited share of each farm. This spatial restriction, combined with the region’s predominantly dry conditions, constrains economic returns, as production is often subsistence-oriented, with surplus sold only occasionally (Zilli et al., 2020). The reliance on family labor further limits technological innovation and broader market integration (Achmad et al., 2022). Even promising strategies like crop diversification face adoption challenges due to cultural preferences and limited market access (Achmad et al., 2022; Garbelini et al., 2022).

Despite the statistical differences, all uses show lower median profitability under traditional calculations, a reflection of the vulnerabilities in Brazilian rural systems. Reported droughts and production losses highlight the need for a complementary sensitivity analysis to explore the robustness of each land use under variable conditions (dos Reis et al., 2021; Zilli et al., 2020).

5.2. Sensitivity among land uses

Across all land uses, the lower risk associated with gross margin suggests that variable costs are more manageable and that returns can be positive when fixed costs are excluded. Brazilian farmers often exert tighter control over variable costs (Lizot et al., 2021; Vieira Filho and Furtado, 2024), especially through collective purchasing and local associations (Silva et al., 2020), reducing economic vulnerability.

However, the high sensitivity of profitability illustrates structural weaknesses in long-term planning, exposure to climatic variability, and inconsistent financial control (Elli et al., 2020; Vilpoux et al., 2021; Zilli et al., 2020). While some agribusinesses adopt advanced software for economic planning (Lizot et al., 2021), most farms are small-scale, family-run, and resistant to management changes (Fuller et al., 2021). Financial literacy and training correlate with better farm performance in Minas Gerais (Silva & Malaquias, 2020), indicating that policies fostering these skills could enhance rural resilience.

The presence of low-risk farms under SPS and agriculture indicates that economic stability is attainable with supportive strategies like rural credit, technical assistance, and new products (Cunha et al., 2025; Ferreira et al., 2022). Despite literature highlighting the productive and economic potential of these systems (Peri et al., 2024; Volsi et al., 2021), the local SPS remains low in diversity, poorly commercialized, and underutilized. Agriculture also suffers from low prices and high family labor input (Ayaz and Mughal, 2024; Fuller et al., 2021).

Eucalyptus plantations show the lowest sensitivity and highest profitability, attributed to production cycles that allow delaying sales to seek better prices (Munis et al., 2022). However, high initial investments deter adoption (Elli et al., 2020; Lewark, 2022), highlighting the need for long-term financial analyses and the presence of unused land on the farm.

Cash income is the main driver of gross margin across land uses (figure 3). Improving marketing conditions, via product differentiation or processing, can raise income and reduce vulnerability (Cunha et al., 2025; dos Reis et al., 2023; Volsi et al., 2021). SPS has untapped potential through incorporating revenue streams from NTFPs and ecosystem services, such as carbon credits, which could significantly enhance profitability (Berte et al., 2023; de Mello et al., 2023; Sandoval et al., 2023).

The importance of non-cash income generated from SPS and agriculture underlines the contribution of these land uses to reducing household cash food expenses (Moreira et al., 2023). Alternatively, many smallholders can share surplus production via cooperatives or public procurement programs, such as the National School Feeding Program (Programa Nacional de Alimentação Escolar – PNAE), and the Food Acquisition Program (Programa de Aquisição de Alimentos – PAA) (Moreira et al., 2023). Additionally, selling organic baskets directly to urban consumers can increase cash income and represents an opportunity for these farmers (Ferreira et al., 2022).

Hired labor remained crucial across land uses, particularly in Eucalyptus, given its scale (Lewark, 2022). According to interviewees, hired labor in SPS and agriculture is typically employed for planting and harvesting in agriculture and for milking in SPS (Malanski et al., 2021; Varela et al., 2022). Declining rural labor availability may constrain future expansion, especially for intensive systems (Cunha, 2025; Malanski et al., 2021).

The gross margin for Eucalyptus was heavily influenced by costs for inputs, fuel, and marketing, indicative of an intensive model relying on machinery and external inputs (Florentino et al., 2021; Lewark, 2022). Transport costs further elevated marketing expenses, especially due to long distances to markets (Castro et al., 2019; Ferraz et al., 2024).

Agriculture also had significant fuel and input costs, although lower than those of eucalyptus (figure 2). Fertilization and liming are common, particularly in the Cerrado, due to soil acidity (Moreira et al., 2025). Fuel use is associated with mechanization, but its reduced importance may reflect lower levels of intensification (Smaniotto et al., 2024).

In SPS, key variable costs are fuel and animal feed, though not used by all farms (table S5). Feed supplementation can improve animal performance (Naves et al., 2024). While native SPS enhances animal welfare and productivity (Sandoval et al., 2023; Teixeira et al., 2022), the irregular spatial distribution of trees, typical of conserved Cerrado vegetation, can increase fuel consumption due to less efficient machinery movement, warranting further investigation (Lima et al., 2022; Smith et al., 2022).

Profitability in SPS and agriculture is strongly shaped by family labor, often tied to traditional systems (Fuller et al., 2021). NTFP harvesting frequently involves women and children (Gumucio et al., 2018), further emphasizing labor dependency. Accounting for family labor at its full economic cost can yield negative profitability, showing that the returns from household labor are low and may lead producers to seek income outside their land uses, limiting their future interest in intensifying these activities (Ayaz and Mughal, 2024; Cunha, 2025; Malanski et al., 2021).

The profitability of Eucalyptus was more influenced by cash income, hired labor, and input costs (figures 2 and 3), consistent with its larger scale and market orientation, different from the agriculture and SPS, which is more focused on family subsistence (Lewark, 2022; Silva et al., 2024). Nonetheless, income remains a crucial factor for profitability across all uses, reinforcing the need for better prices and productivity, or for targeting higher-value markets (Tanure et al., 2024; Volsi et al., 2021). The SPS, with its greater number of productive components, is particularly well-positioned to explore these higher-value opportunities, including ecosystem services, such as carbon credits, which could substantially enhance economic returns (Sandoval et al., 2023).

Among fixed costs, machinery, capital, and fixed production costs significantly impacted the profitability of all land uses (figure 3). Shared machinery and labor exchanges among cooperatives can mitigate these burdens, mainly for small farmers (Cornée et al., 2025; Futemma et al., 2020).

Eucalyptus maintained the widest range of relevant cost components, making it more vulnerable to market or labor disruptions (Cunha, 2025; Lewark, 2022). Despite these sensitivities, its high profitability and low-cost land in the region have driven your expansion, following the broader trend in Minas Gerais, the Brazilian state with the largest planted forest area (Afonso and Miller, 2021; Teixeira and Rodrigues, 2021). Historically concentrated in the south of the state, Eucalyptus cultivation has progressively advanced to northern areas, where land prices are lower and mechanization is more feasible, potentially stimulating adoption even among smallholders, despite structural constraints that may limit its long-term viability in this group (Teixeira and Rodrigues, 2021).

Overall, this study illustrates the complex economic, social, and ecological dynamics of land uses in the Cerrado of northern Minas Gerais. In this context, public policies should be tailored to address the specific challenges identified for each land use, fostering sustainable development that combines productivity, diversification, and permanence of these systems in the region. Although based on a single production year, these findings highlight important drivers of the financial and economic performance of main land uses in the region, and the associated risk profiles. The cross-sectional nature of the data, however, presents a key limitation. It allows for the identification of strong correlations but prevents the establishment of causality and the analysis of long-term investment cycles or responses to shocks like droughts. Future research using panel data, which tracks the same farms over multiple years, would be crucial to control for unobserved farm-specific characteristics and to model the dynamic evolution of these systems' performance. Building on such methodological advances, future studies should also expand their thematic scope to explore NTFP valorization, public policy roles, and financial tools such as carbon credits and Payments for Ecosystem Services (PES), to foster sustainable agroecological transitions. Additionally, it would be valuable to investigate whether institutional procurement programs, such as PNAE and PAA, are effectively reaching family farmers engaged with Cerrado-based NTFPs, and whether these markets can offer price premiums or stable demand. These advances can increase the understanding of how to promote sustainable agroecological transitions in the region, opening pathways to integrate profitability and conservation more effectively.

6. Conclusions

This study demonstrates that different land uses in the Cerrado region exhibit distinct productive and economic characteristics, directly influencing farm profitability and economic stability. Eucalyptus plantations stand out for their higher profitability and stronger market integration but rely heavily on hired labor, external inputs, and infrastructure, which may limit adoption by smallholders. Agriculture, aligned with family subsistence, involves intensive production, but most output is consumed by the family and has low market value, reducing financial returns. In contrast, native species-based silvopastoral systems (SPS) also play role in family subsistence and environmental conservation but lack productive diversification and sustainable intensification to ensure economic viability.

The sensitivity analysis reinforces the importance of public policies that strengthen financial management, expand access to differentiated markets, and promote diversified and sustainable production, particularly through non-timber forest products (NTFPs) and ecosystem services in SPS. Overall, this study contributes to a deeper understanding of the limitations and opportunities of local production systems and underscores the need for integrated strategies specifically designed to support sustainable rural development for all uses in the Cerrado region of Minas Gerais.

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Supplementary Materials

Table S1. Selected municipalities in the study area, with their total area, percentage of coverage within the study basin, and number of sampled farms for the four land size classes

Municipality	Area (km²)	Percentual within basins	Class I	Class II	Class III	Class IV	Total
Vargem Grande do Rio Pardo	491.51	100.00%	2	2	2	2	8
Santo Antônio do Retiro	796.3	99.71%	4	4	4	4	16
Montezuma	1130.41	99.64%	6	6	6	6	24
Indaiabira	1004.14	99.62%	5	5	5	5	20
Rio Pardo de Minas	3,117.68	89.41%	14	14	14	14	56
São João do Paraíso	1,925.58	74.13%	7	7	7	7	28
Taiobeiras	1,220.05	39.68%	2	2	2	2	8
Total	9,685.66	99.8%	40	40	40	40	160

Source: Data from the Brazilian Rural Environmental Registry System (Sicar) (SICAR, 2022), and the Brazilian Institute of Geography and Statistics (IBGE, 2024); Elaborated by the authors.

Table S2. Shapiro-Wilk and Kruskal-Wallis test at land use level for the different land uses present at the study area

Economic Variables	Shapiro-Wilk Test by different land use			Kruskal-Walis Test	Significance
	Agri (57n)	Eucal (20n)	SPS (52n)		
Num_Land_Use	1.29E-07	4.04E-05	2.58E-07	0.6562	
Productive area (ha)	8.29E-16	2.16E-04	1.71E-09	1.05E-09	*
Class	2.92E-09	3.17E-03	4.08E-07	2.89E-04	*
Input_Cost (US$.ha)	8.43E-16	2.34E-07	1.51E-14	7.44E-10	*
Seed_Cost (US$.ha)	6.08E-15	9.48E-08	4.27E-11	0.1495	
Pesticide_Cost (US$.ha)	1.40E-16	3.17E-05	1.67E-14	3.12E-05	*
Fuel_Cost (US$.ha)	1.47E-13	2.92E-06	5.72E-14	0.2520	
Prod_Fixed_Cost (US$.ha)	5.84E-12	2.31E-05	9.73E-11	0.3918	
Machinary_Cost (US$.ha)	1.80E-14	1.06E-03	1.21E-12	0.1781	
Hired_Cost (US$.ha)	3.07E-14	5.26E-05	2.73E-13	0.0674	
LaborFamily_Cost (US$.ha)	4.75E-13	1.05E-06	4.76E-10	0.0114	*
Capital_Cost (US$.ha)	2.51E-13	7.16E-06	7.48E-15	0.2438	
Marketing_Cost (US$.ha)	1.33E-14	2.02E-05	1.63E-14	0.0152	*
Variable_Cost (US$.ha)	1.39E-12	5.35E-03	1.46E-10	2.98E-03	*
Pot_Variable_Cost (US$.ha)	1.37E-12	5.35E-03	2.60E-10	4.86E-03	*
Fixed_Cost (US$.ha)	1.06E-11	1.73E-03	3.83E-10	0.0073	*
Num_Products (US$.ha)	9.49E-06	2.05E-05	3.52E-06	0.6494	
Cash_Income (US$.ha)	2.76E-12	9.87E-04	1.88E-11	0.0273	*
Non_Cash_Income (US$.ha)	6.19E-14	0	2.88E-11	1.51E-06	*
Total_Income (US$.ha)	1.87E-11	9.87E-04	8.59E-11	0.0582	
Gross_Margin (US$.ha)	1.13E-07	3.85E-01	1.38E-09	0.1074	
Profit (US$.ha)	9.15E-12	3.43E-02	9.30E-07	1.87E-06	*
Pot_Gross_Margin (US$.ha)	1.43E-08	0.3852	7.04E-10	0.3324	
Pot_Profit (US$.ha)	3.40E-11	0.0343	7.38E-07	3.28E-05	*
Pot_Profit_1 (US$.ha)	3.40E-11	0.0343	7.38E-07	3.28E-05	*
Pot_Profit_2 (US$.ha)	1.58E-11	0.0782	7.72E-07	4.14E-05	*
Pot_Profit_3 (US$.ha)	1.83E-08	0.2536	6.89E-09	0.1484	

Where: Agri = agriculture; Eucal = Eucalyptus plantation; and SPS = native silvopastoral systems; between parentheses is the number of samples for each group, * = significance indicates by the Kruskal-Walis test for the variable.

Source: Elaborated by the authors.

Table S3. Results of Dunn's post hoc test comparing economic variables across land uses

Variable	Comparison	Z-Value	P.unadj	P.adj	Sign
Num_Land_Use	Agriculture - Eucalyptus	0.21	0.84	1	
	Agriculture - SPS	-0.77	0.44	1	
	Eucalyptus - SPS	-0.76	0.45	1	
Productive_Area	Agriculture - Eucalyptus	-6.01	1.8E-09	5.4E-09	*
	Agriculture - SPS	-4.25	2.2E-05	6.5E-05	*
	Eucalyptus - SPS	2.85	4.4E-03	0.01	*
Class	Agriculture - Eucalyptus	-4.03	5.5E-05	1.7E-04	*

Variable	Comparison	Z-Value	P.unadj	P.adj	Sign
	Agriculture - SPS	-1.59	0.11	0.34	
	Eucalyptus - SPS	2.83	4.7E-03	0.01	*
Num_Products	Agriculture - Eucalyptus	0.69	0.49	1.00	
	Agriculture - SPS	-0.33	0.74	1.00	
	Eucalyptus - SPS	-0.93	0.35	1.00	
Input_Cost	Agriculture - Eucalyptus	1.53	0.13	0.38	
	Agriculture - SPS	6.44	1.2E-10	3.7E-10	*
	Eucalyptus - SPS	3.18	1.5E-03	4.4E-03	*
Seed_Cost	Agriculture - Eucalyptus	1.93	0.05	0.16	
	Agriculture - SPS	0.96	0.34	1.00	
	Eucalyptus - SPS	-1.20	0.23	0.69	
Pesticide_Cost	Agriculture - Eucalyptus	-3.62	3.0E-04	9.0E-04	*
	Agriculture - SPS	1.32	0.19	0.56	
	Eucalyptus - SPS	4.53	5.8E-06	1.7E-05	*
Fuel_Cost	Agriculture - Eucalyptus	-0.85	0.40	1.00	
	Agriculture - SPS	1.04	0.30	0.90	
	Eucalyptus - SPS	1.59	0.11	0.33	
Hired_Cost	Agriculture - Eucalyptus	-2.21	0.03	0.08	
	Agriculture - SPS	-0.12	0.90	1.00	
	Eucalyptus - SPS	2.10	0.04	0.11	
Marketing_Cost	Agriculture - Eucalyptus	-2.54	0.01	0.03	*
	Agriculture - SPS	0.40	0.69	1.00	
	Eucalyptus - SPS	2.80	5.1E-03	0.02	*
Variable_Cost	Agriculture - Eucalyptus	-0.95	0.34	1.00	
	Agriculture - SPS	2.73	0.01	0.02	*
	Eucalyptus - SPS	2.93	3.4E-03	0.01	*
Pot_Variable_Cost	Agriculture - Eucalyptus	-0.91	0.36	1.00	
	Agriculture - SPS	2.62	0.01	0.03	*
	Eucalyptus - SPS	2.80	0.01	0.02	*
Prod_Fixed_Cost	Agriculture - Eucalyptus	1.32	0.19	0.56	
	Agriculture - SPS	0.80	0.43	1.00	
	Eucalyptus - SPS	-0.72	0.47	1.00	
Machinary_Cost	Agriculture - Eucalyptus	1.09	0.28	0.83	
	Agriculture - SPS	1.79	0.07	0.22	
	Eucalyptus - SPS	0.23	0.82	1.00	
LaborFamily_Cost	Agriculture - Eucalyptus	2.94	0.00	0.01	*
	Agriculture - SPS	1.54	0.12	0.37	
	Eucalyptus - SPS	-1.79	0.07	0.22	
Capital_Cost	Agriculture - Eucalyptus	-0.16	0.87	1.00	
	Agriculture - SPS	1.51	0.13	0.39	
	Eucalyptus - SPS	1.26	0.21	0.62	
Fixed_Cost	Agriculture - Eucalyptus	2.69	0.01	0.02	*
	Agriculture - SPS	2.45	0.01	0.04	*
	Eucalyptus - SPS	-0.87	0.38	1.00	
Cash_Income	Agriculture - Eucalyptus	-1.59	0.11	0.34	

Variable	Comparison	Z-Value	P.unadj	P.adj	Sign
	Agriculture - SPS	1.47	0.14	0.43	
	Eucalyptus - SPS	2.64	0.01	0.03	*
Non_Cash_Income	Agriculture - Eucalyptus	5.05	4.33E-07	1.30E-06	*
	Agriculture - SPS	0.73	0.47	1.00	
	Eucalyptus - SPS	-4.46	8.10E-06	2.43E-05	*
Pot_Income	Agriculture - Eucalyptus	-0.44	0.66	1.00	
	Agriculture - SPS	2.04	0.04	0.12	
	Eucalyptus - SPS	1.92	0.05	0.16	
Gross_Margin	Agriculture - Eucalyptus	-1.85	0.06	0.19	
	Agriculture - SPS	0.29	0.77	1.00	
	Eucalyptus - SPS	2.05	0.04	0.12	
Pot_Gross_Margin	Agriculture - Eucalyptus	0.88	0.38	1.00	
	Agriculture - SPS	0.81	0.42	1.00	
	Eucalyptus - SPS	1.46	0.14	0.43	
Profit	Agriculture - Eucalyptus	-4.98	6.2E-07	1.9E-06	*
	Agriculture - SPS	-2.91	3.6E-03	0.01	*
	Eucalyptus - SPS	2.80	0.01	0.02	*
Pot_Profit	Agriculture - Eucalyptus	-4.40	1.1E-05	3.2E-05	*
	Agriculture - SPS	-2.91	0.01	0.03	*
	Eucalyptus - SPS	2.46	0.01	0.04	*
Pot_Profit_1	Agriculture - Eucalyptus	-4.40	1.1E-05	3.2E-05	*
	Agriculture - SPS	-2.60	0.01	0.03	*
	Eucalyptus - SPS	2.46	0.01	0.04	*
Pot_Profit_2	Agriculture - Eucalyptus	-4.37	1.3E-05	3.8E-05	*
	Agriculture - SPS	-2.53	0.01	0.03	*
	Eucalyptus - SPS	2.47	0.01	0.04	*
Pot_Profit_3	Agriculture - Eucalyptus	-1.88	0.06	0.18	
	Agriculture - SPS	-0.17	0.86	1.00	
	Eucalyptus - SPS	1.73	0.08	0.25	

Where: Agri = agriculture; Eucal = Eucalyptus plantation; and SPS = silvopastoral systems with native trees; between parentheses is the number of samples for each group, and SD = standard deviation. Num_Land_Use - Number of different land uses present on the farm; Productive area (ha) - Total area in hectares used for productive purposes; Class - Farm size classification based on fiscal modules (I to IV); Input_Cost (US$/ha) - Cost of inputs (e.g., fertilizers, lime), per hectare; Seed_Cost (US$/ha) - Cost of seeds or seedlings used, per hectare; Pesticide_Cost (US$/ha) - Cost of pesticides per hectare; Fuel_Cost (US$/ha) - Fuel expenses related to production, per hectare; Prod_Fixed_Cost (US$/ha) - Fixed production costs (e.g., electricity, water, maintenance), per hectare; Machinery_Cost (US$/ha) - Annual depreciation of machinery and equipment, per hectare; Hired_Cost (US$/ha) - Cost of hired labor, per hectare; LaborFamily_Cost (US$/ha) - Cost of family labor, per hectare; Capital_Cost (US$/ha) - Opportunity cost of capital invested in infrastructure and equipment, per hectare; Marketing_Cost (US$/ha) - Marketing-related costs (e.g., transportation, packaging), per hectare; Variable_Cost (US$/ha) - Total variable cost (production, hired labor, marketing), per hectare; Pot_Variable_Cost (US$/ha) - Potential variable cost including non-marketed (on-farm consumed) production, per hectare; Fixed_Cost (US$/ha) - Total fixed costs (machinery, family labor, production, capital, land), per hectare; Num_Products (US$/ha) - Number of products marketed per land-use type; Cash_Income (US$/ha) - Revenue from product sales, per hectare; Non_cash_Income (US$/ha) - Estimated value of on-farm consumed production, per hectare; Total_Income (US$/ha) - Sum of cash and non-cash income, per hectare; Gross_Margin (US$/ha) - Cash income minus variable costs, per hectare; Profit (US$/ha) - Cash income minus variable and fixed costs, per hectare; Pot_Gross_Margin (US$/ha) - Total income minus potential variable costs, per hectare; Pot_Profit (US$/ha) - Total income minus all fixed and variable costs, per hectare; Pot_Profit_1 (US$/ha) - Potential profit excluding land opportunity cost; Pot_Profit_2 (US$/ha) - Potential profit excluding land and capital opportunity costs; Pot_Profit_3 (US$/ha) - Potential profit excluding land, capital, and family labor costs.

Table S4. Descriptive statistics (mean, standard deviation (SD), % of value 0, and maximum) for agriculture for different size class farms

Economic Variables	Mean				SD				% of 0				Maximum			
	Class1	Class2	Class3	Class4	Class1	Class2	Class3	Class4	Class1	Class2	Class3	Class4	Class1	Class2	Class3	Class4
Num_Land_Use	1.9	2.4	1.8	2.4	0.6	0.7	0.5	0.7	0.0	0.0	0.0	0.0	3.0	3.0	2.0	3.0
Productive area (ha)	2.5	7.2	13.0	113.7	2.0	5.3	18.5	232.5	0.0	0.0	0.0	0.0	10.0	20.0	40.0	700.0
Input_Cost (US$.ha)	79.2	53.3	53.0	377.1	79.3	63.3	36.2	1046.8	15.6	27.3	25.0	20.0	288.6	209.4	77.5	3351.8
Seed_Cost (US$.ha)	34.7	8.4	14.0	17.0	108.5	19.0	16.5	43.9	46.9	72.7	50.0	60.0	601.2	57.3	32.1	140.3
Pesticide_Cost (US$.ha)	1.9	1.2	3.5	83.4	6.4	4.1	7.0	252.6	81.3	81.8	75.0	70.0	32.1	13.5	14.0	801.6
Fuel_Cost (US$.ha)	64.0	16.4	75.0	182.7	187.3	32.0	150.1	323.0	59.4	54.5	75.0	50.0	961.9	106.9	300.1	961.9
Prod_Fixed_Cost (US$.ha)	215.1	66.0	141.2	225.6	282.6	80.4	140.8	674.5	25.0	9.1	0.0	50.0	1149.0	274.8	312.6	2144.3
Machinery_Cost (US$.ha)	441.9	200.0	82.3	269.3	1214.2	167.2	68.2	747.0	28.1	9.1	0.0	50.0	6778.3	469.3	180.4	2389.0
Hired_Cost (US$.ha)	275.9	117.8	482.0	165.8	913.6	145.9	890.8	329.3	71.9	9.1	0.0	50.0	4584.2	424.9	1817.8	1022.1
LaborFamily_Cost (US$.ha)	3131.5	556.4	1126.0	102.7	5555.3	438.6	2068.0	219.1	34.4	9.1	25.0	60.0	29065.7	1550.5	4225.3	667.9
Capital_Cost (US$.ha)	227.7	188.9	75.5	397.6	425.9	229.8	74.9	1171.3	37.5	18.2	0.0	50.0	1756.3	647.5	183.7	3727.2
Marketing_Cost (US$.ha)	13.5	23.8	4.2	19.8	44.9	75.1	8.4	61.6	68.8	81.8	75.0	70.0	240.5	250.1	16.7	195.2
Variable_Cost (US$.ha)	469.3	220.9	631.8	845.8	970.4	175.1	1032.5	1378.7	0.0	0.0	0.0	0.0	4844.7	534.6	2178.1	4569.1
Pot_Variable_Cost (US$.ha)	474.7	222.1	633.8	846.0	974.1	174.1	1036.5	1378.7	0.0	0.0	0.0	0.0	4872.7	534.6	2186.1	4569.1
Fixed_Cost (US$.ha)	4096.4	1091.7	1505.4	1075.4	6027.4	669.8	2157.9	2047.2	0.0	0.0	0.0	0.0	30673.0	2261.1	4738.4	6196.4
Num_Products (US$.ha)	1.3	1.1	1.3	0.7	1.2	0.5	0.5	0.9	28.1	9.1	0.0	50.0	4.0	2.0	2.0	3.0
Cash_Income (US$.ha)	588.6	638.6	285.5	305.9	1130.2	676.3	145.1	606.6	28.1	9.1	0.0	50.0	6412.8	2004.0	417.5	1734.9
Non_cash_Income (US$.ha)	345.8	227.7	148.2	1250.5	1025.7	269.4	204.0	2263.9	34.4	36.4	50.0	50.0	5811.6	774.7	432.4	6651.5
Total_Income (US$.ha)	934.4	866.4	433.7	1556.4	1631.1	823.7	239.8	2517.4	21.9	9.1	0.0	40.0	6939.4	2492.4	776.1	6722.4
Gross_Margin (US$.ha)	119.3	417.7	-346.3	-540.0	1121.1	685.3	995.9	845.2	0.0	0.0	0.0	0.0	3718.6	1710.9	226.7	14.0
Profit (US$.ha)	-3975.4	-674.0	-1851.6	-1280.2	5956.1	776.3	3152.1	1851.6	0.0	0.0	0.0	0.0	-84.2	649.1	-91.1	-80.0
Pot_Gross_Margin (US$.ha)	420.6	544.4	-200.1	233.4	1548.7	718.0	806.8	1482.8	0.0	0.0	0.0	0.0	6262.1	1733.9	226.7	4392.1
Pot_Profit (US$.ha)	-3636.7	-447.4	-1705.4	-364.9	5681.8	800.0	2963.8	2891.8	0.0	0.0	0.0	0.0	476.5	963.1	-91.1	6133.0
Pot_Profit_1 (US$.ha)	-3556.4	-367.1	-1625.1	-284.6	5681.8	800.0	2963.8	2891.8	0.0	0.0	0.0	0.0	556.8	1043.4	-10.8	6213.3
Pot_Profit_2 (US$.ha)	-3248.4	-97.8	-1469.3	193.2	5496.9	884.0	2985.7	2390.6	0.0	0.0	0.0	0.0	744.9	1670.4	130.7	6340.0
Pot_Profit_3 (US$.ha)	-116.9	458.6	-343.3	295.9	1510.1	729.3	918.8	2314.2	0.0	0.0	0.0	0.0	4948.4	2003.1	200.6	6399.6

Table S5. Descriptive statistics (mean, standard deviation (SD), % of value 0, and maximum) for SPS for different size class farms

Economic Variables	Mean				SD				% of 0				Maximum			
	Class1	Class2	Class3	Class4	Class1	Class2	Class3	Class4	Class1	Class2	Class3	Class4	Class1	Class2	Class3	Class4
Num_Land_Use	2.0	2.3	2.3	2.2	0.6	0.8	0.5	0.7	0.0	0.0	0.0	0.0	3.0	3.0	3.0	3.0
Productive area (ha)	7.1	20.5	68.2	77.2	6.5	20.2	73.2	66.3	0.0	0.0	0.0	0.0	10.0	20.0	40.0	700.0
Input_Cost (US$.ha)	0.1	23.8	0.0	18.6	0.3	67.5	0.0	47.4	95.2	83.3	100.0	61.5	1.2	232.5	0.0	162.8
Seed_Cost (US$.ha)	16.5	3.2	11.2	8.4	29.3	6.2	21.9	15.1	66.7	66.7	66.7	53.8	112.2	20.0	54.7	50.1
Pesticide_Cost (US$.ha)	0.4	0.1	0.0	0.6	1.7	0.3	0.0	1.1	95.2	91.7	100.0	69.2	8.0	1.2	0.0	3.9
Fuel_Cost (US$.ha)	66.4	50.4	1.0	21.7	211.4	105.3	2.5	44.4	76.2	58.3	83.3	46.2	961.9	334.0	6.0	154.5
Prod_Fixed_Cost (US$.ha)	153.2	69.2	35.2	27.3	194.4	132.0	34.5	27.7	19.0	25.0	16.7	15.4	701.4	478.8	92.7	79.5
Depreciation_Cost (US$.ha)	54.3	205.8	20.4	71.6	72.1	366.6	23.2	87.6	23.8	16.7	16.7	7.7	256.5	1287.4	50.0	247.9
Hired_Cost (US$.ha)	19.4	219.6	15.5	130.4	45.2	400.3	12.4	311.5	61.9	25.0	16.7	15.4	193.2	1208.7	34.0	1154.3
LaborFamily_Cost (US$.ha)	608.6	526.0	81.4	78.0	736.4	850.2	140.1	128.3	28.6	16.7	16.7	23.1	2288.1	2341.2	365.7	445.2
Capital_Cost (US$.ha)	28.4	202.6	20.0	39.0	48.5	522.0	25.9	53.6	33.3	25.0	16.7	7.7	197.8	1841.9	69.6	180.1
Marketing_Cost (US$.ha)	1.8	19.5	0.2	6.1	6.5	49.7	0.5	20.7	85.7	58.3	66.7	69.2	29.3	170.2	1.1	75.1
Variable_Cost (US$.ha)	142.2	346.0	105.2	214.3	280.3	442.7	163.6	308.8	9.5	0.0	0.0	0.0	1285.3	1228.8	435.1	1183.3
Pot_Variable_Cost (US$.ha)	147.6	357.7	107.4	218.6	280.2	439.0	162.8	309.7	9.5	0.0	0.0	0.0	1285.3	1229.1	435.1	1183.3
Fixed_Cost (US$.ha)	924.9	1083.9	237.4	296.2	838.6	1616.1	159.2	255.2	0.0	0.0	0.0	0.0	2965.0	5600.9	556.4	942.9
Num_Products (US$.ha)	1.0	1.3	1.5	1.3	0.7	0.9	1.0	0.8	23.8	16.7	16.7	7.7	3.0	3.0	3.0	3.0
Cash_Income (US$.ha)	234.9	605.9	85.9	402.5	389.0	898.2	145.4	945.8	23.8	16.7	16.7	7.7	1683.4	2382.4	360.7	3503.0
Non_cash_Income (US$.ha)	103.5	93.3	111.4	59.6	190.8	233.9	239.1	89.1	28.6	16.7	0.0	23.1	601.2	787.3	597.4	244.2
Total_Income (US$.ha)	338.4	699.2	197.3	462.1	540.1	1037.3	298.3	927.3	9.5	8.3	0.0	0.0	2284.6	3101.9	737.8	3503.0
Gross_Margin (US$.ha)	92.7	259.9	-19.3	188.2	452.2	792.2	185.6	988.1	4.8	0.0	0.0	0.0	1633.3	2367.5	287.3	3323.7
Profit (US$.ha)	-832.2	-824.0	-256.7	-108.0	782.6	1691.2	319.1	1073.7	0.0	0.0	0.0	0.0	24.7	2156.6	122.3	3161.7
Pot_Gross_Margin (US$.ha)	190.8	341.6	90.0	243.5	533.2	886.5	160.4	971.9	4.8	0.0	0.0	0.0	2234.5	2368.9	302.7	3323.7
Pot_Profit (US$.ha)	-734.1	-742.4	-147.4	-52.7	660.9	1546.3	136.2	1062.4	0.0	0.0	0.0	0.0	24.7	2158.0	122.4	3161.7
Pot_Profit_1 (US$.ha)	-653.8	-662.1	-67.1	27.6	660.9	1546.3	136.2	1062.4	0.0	0.0	0.0	0.0	105.0	2238.3	202.7	3242.0
Pot_Profit_2 (US$.ha)	-545.0	-379.2	33.2	147.0	661.1	1301.8	136.1	1039.3	0.0	0.0	0.0	0.0	198.4	2331.8	301.3	3348.0
Pot_Profit_3 (US$.ha)	63.6	146.9	114.7	224.9	509.7	819.3	161.3	995.1	0.0	0.0	0.0	0.0	1718.2	2388.6	341.5	3348.0

Table S6. Descriptive statistics (mean, standard deviation (SD), % of value 0, and maximum) for Eucalyptus for different size class farms

Economic Variables	Mean			SD			% of 0			Maximum		
	Class2	Class3	Class4	Class2	Class3	Class4	Class2	Class3	Class4	Class2	Class3	Class4
Num_Land_Use	2.5	1.9	1.8	1.0	0.9	1.0	0.0	0.0	0.0	3.0	3.0	3.0
Productive area (ha)	31.5	114.6	284.4	52.4	119.2	257.2	0.0	0.0	0.0	110.0	350.0	800.0
Input_Cost (US$.ha)	0.0	279.0	72.2	0.0	452.5	88.4	100.0	28.6	37.5	0.0	1269.2	200.4
Seed_Cost (US$.ha)	0.0	19.1	51.7	0.0	50.5	105.3	100.0	85.7	75.0	0.0	133.6	288.6
Pesticide_Cost (US$.ha)	9.1	6.2	4.4	15.9	8.5	5.8	50.0	28.6	37.5	32.8	24.0	17.0
Fuel_Cost (US$.ha)	3.8	119.9	87.7	7.5	251.1	128.0	75.0	42.9	50.0	15.0	685.4	300.6
Prod_Fixed_Cost (US$.ha)	76.0	103.3	82.8	117.0	194.1	98.6	25.0	42.9	12.5	250.5	521.0	212.7
Depreciation_Cost (US$.ha)	28.6	76.9	99.0	55.2	85.5	119.7	50.0	28.6	12.5	111.5	234.1	302.3
Hired_Cost (US$.ha)	171.9	55.3	101.0	278.5	57.8	123.7	50.0	28.6	0.0	583.0	160.3	392.7
LaborFamily_Cost (US$.ha)	50.7	94.3	33.0	101.4	200.0	60.4	75.0	42.9	12.5	202.7	543.4	177.2
Capital_Cost (US$.ha)	41.1	152.3	65.3	79.0	230.7	82.9	50.0	28.6	12.5	159.5	645.2	263.3
Marketing_Cost (US$.ha)	60.1	176.1	97.0	120.2	284.6	99.5	75.0	57.1	25.0	240.5	721.4	294.5
Variable_Cost (US$.ha)	244.9	655.6	414.1	390.5	729.5	269.2	25.0	0.0	0.0	827.1	1775.4	827.4
Pot_Variable_Cost (US$.ha)	244.9	655.6	414.1	390.5	729.5	269.2	25.0	0.0	0.0	827.1	1775.4	827.4
Fixed_Cost (US$.ha)	276.7	507.0	360.3	211.9	567.9	212.0	0.0	0.0	0.0	553.9	1496.0	661.5
Num_Products (US$.ha)	0.5	0.7	1.3	0.6	0.5	0.7	50.0	28.6	0.0	1.0	1.0	3.0
Cash_Income (US$.ha)	596.6	1134.8	667.4	1063.9	1461.7	410.2	50.0	28.6	0.0	2186.2	3847.7	1570.5
Non_cash_Income (US$.ha)	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0	0.0	0.0	0.0
Total_Income (US$.ha)	596.6	1134.8	667.4	1063.9	1461.7	410.2	50.0	28.6	0.0	2186.2	3847.7	1570.5
Gross_Margin (US$.ha)	351.8	479.2	253.3	674.2	1122.4	392.9	25.0	0.0	0.0	1359.1	2072.3	845.8
Profit (US$.ha)	75.1	-27.8	-107.0	788.2	1166.0	471.6	0.0	0.0	0.0	1242.4	1149.0	414.0
Pot_Gross_Margin (US$.ha)	351.8	479.2	253.3	674.2	1122.4	392.9	25.0	0.0	0.0	1359.1	2072.3	845.8
Pot_Profit (US$.ha)	75.1	-27.8	-107.0	788.2	1166.0	471.6	0.0	0.0	0.0	1242.4	1149.0	414.0
Pot_Profit_1 (US$.ha)	155.4	52.5	-26.7	788.2	1166.0	471.6	0.0	0.0	0.0	1322.7	1229.3	494.3
Pot_Profit_2 (US$.ha)	276.7	285.1	118.9	758.0	1197.1	484.1	0.0	0.0	0.0	1407.8	1439.9	616.7
Pot_Profit_3 (US$.ha)	327.4	379.4	151.9	727.2	1032.6	479.7	0.0	0.0	0.0	1407.8	1462.7	617.9

Table S7. Relative variation of tested economic variables across farm size classes within each land use

Tested variables	Applyed variation - Class 1			Applyed variation - Class 2			Applyed variation - Class 3			Applyed variation - Class 4		
	Agriculture	SPS	Eucalyptus	Agriculture	SPS	Eucalyptus	Agriculture	SPS	Eucalyptus	Agriculture	SPS	Eucalyptus
Capital_Cost	0.67	0.78	0.00	0.82	1.00	1.00	1.00	1.00	1.00	1.00	0.83	1.00
Depreciation_Cost	0.99	0.60	0.00	0.56	1.00	1.00	1.00	1.00	1.00	1.00	0.74	1.00
Extra_Income	1.00	0.84	0.00	0.79	1.00	0.00	1.00	1.00	0.00	1.00	0.90	0.00
Feed_Cost	0.00	0.84	0.00	0.00	0.91	0.00	0.00	1.00	0.00	0.00	0.86	0.00
Fuel_Cost	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hired_Cost	1.00	1.00	0.00	0.83	1.00	1.00	1.00	0.84	0.97	1.00	1.00	1.00
Income	0.69	0.75	0.00	0.71	0.94	1.00	0.81	1.00	1.00	1.00	1.00	0.51
Input_Cost	0.36	1.00	0.00	0.80	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00
LaborFamily_Cost	0.64	0.55	0.00	0.53	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00
Land_Cost	0.30	0.30	0.00	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Marketing_Cost	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.86
Marketing_Extra	0.84	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00
Pesticide_Cost	1.00	1.00	0.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00
Prod_Fixed_Cost	0.47	0.58	0.00	0.82	1.00	1.00	1.00	1.00	1.00	1.00	0.61	1.00
Seed_Cost	1.00	0.81	0.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
Veterinary_Cost	0.00	1.00	0.00	0.00	0.92	0.00	0.00	1.00	0.00	0.00	1.00	0.00

Table S8. Risk classification by economic indicator, land use, and farm size class

Agriculture

Degree of risk	Gross Margin							
	Class 1	%	Class 2	%	Class 3	%	Class 4	%
Very high	10	31.3%	3	27.27%	1	25.00%	4	40.00%
High	2	6.3%	0	0.00%	0	0.00%	1	10.00%
Medium	1	3.1%	1	9.09%	0	0.00%	1	10.00%
Low	0	0.0%	0	0.00%	0	0.00%	1	10.00%
Very low	19	59.4%	7	63.64%	3	75.00%	3	30.00%
% of negative return	35.20%		29.52%		25.33%		50.24%	

Degree of risk	Profitability							
	Class 1	%	Class 2	%	Class 3	%	Class 4	%
Very high	31	96.9%	8	72.7%	4	100.0%	8	80.0%
High	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Medium	0	0.0%	1	9.1%	0	0.0%	0	0.0%
Low	0	0.0%	1	9.1%	0	0.0%	0	0.0%
Very low	1	3.1%	1	9.1%	0	0.0%	2	20.0%
% of negative return	96.10%		77.60%		94.30%		80.70%	

SPS

Degree of risk	Gross Margin							
	Class 1	%	Class 2	%	Class 3	%	Class 4	%
Very high	6	28.6%	4	33.3%	1	16.7%	5	38.5%
High	2	9.5%	1	8.3%	0	0.0%	2	15.4%
Medium	1	4.8%	1	8.3%	2	33.3%	0	0.0%
Low	0	0.0%	2	16.7%	2	33.3%	0	0.0%
Very low	12	57.1%	4	33.3%	1	16.7%	6	46.2%
% of negative return	35.85%		46.94%		36.56%		46.15%	

Degree of risk	Profitability							
	Class 1	%	Class 2	%	Class 3	%	Class 4	%
Very high	20	95.2%	10	83.3%	5	83.3%	10	76.9%
High	0	0.0%	0	0.0%	0	0.0%	1	7.7%
Medium	1	4.8%	1	8.3%	0	0.0%	0	0.0%
Low	0	0.0%	0	0.0%	1	16.7%	1	7.7%
Very low	0	0.0%	1	8.3%	0	0.0%	1	7.7%
% of negative return	96.48%		86.87%		82.44%		81.22%	

Eucalyptus plantation

Degree of risk	Gross Margin							
	Class 1	%	Class 2	%	Class 3	%	Class 4	%
Very high			1	20.00%	3	42.86%	2	25.00%
High			0	0.00%	0	0.00%	0	0.00%

Medium			0	0.00%	0	0.00%	0	0.00%
Low			1	20.00%	0	0.00%	1	12.50%
Very low			3	60.00%	4	57.14%	5	62.50%
% of negative return			23.73%		44.08%		23.67%	

Degree of risk	**Profitability**							
	Class 1	**%**	**Class 2**	**%**	**Class 3**	**%**	**Class 4**	**%**
Very high			3	60.0%	3	42.9%	3	37.5%
High			0	0.0%	0	0.0%	0	0.0%
Medium			0	0.0%	1	14.3%	3	37.5%
Low			1	20.0%	0	0.0%	0	0.0%
Very low			1	20.0%	3	42.9%	2	25.0%
% of negative return			66.29%		50.76%		49.21%	

CHAPTER II:

UNDERSTANDING FACTORS IMPACTING ADOPTION AND USE OF SILVOPASTORAL SYSTEMS WITH NATIVE TREES IN THE CERRADO: EVIDENCE FROM THE NORTHERN OF MINAS GERAIS, BRAZIL

Submitted to the **Trees, Forests and People**

Understanding Factors Impacting Adoption and Use of Silvopastoral Systems with Native Trees in the Cerrado: Evidence from the Northern of Minas Gerais, Brazil

Abstract

The Brazilian Cerrado faces increasing pressure for land cover change from expanding livestock farming and monoculture agriculture practices. In this context, silvopastoral systems (SPS) using native trees present a promising alternative for sustainable land use. However, the adoption and intensification of these systems depend on various influencing factors. This study, conducted in the northern mesoregion of Minas Gerais State, Brazil, seeks to understand the impact of production, environmental, technical, socioeconomic, and farm-related variables on the use of SPS. Using the Seemingly Unrelated Regressions (SUR) model, estimated through the Full Information Maximum Likelihood (FIML) method, we developed three equations to assess the adoption of SPS and the intensification of their use, assessed by the intensity of production and commercialization efforts. We found that 12 variables of five impacting factors influence the adoption and intensification of SPS. Water resources are one of the most important variables that impact the intensification of SPS, but not the adoption of them. In contrast, the farmer's age positively influences adoption but not their intensification. While farm size and number of productive land uses impact all equations positively, the distance from the farmer's house to the production area shows an inverse effect. Based on our findings, we suggest differentiated policies and support measures addressing “Adopters” and "Not-yet-adopters" to successfully promote silvopastoral systems with native trees in the region.

Keywords: adoption of silvopastoral systems; agroforestry; sustainable land use; Brazilian Savanna; Seemingly Unrelated Regressions (SUR).

1. Introduction

The Cerrado is an important global biodiversity hotspot, harboring more than 13,000 plant species and a rich fauna, with high endemism (BRASIL, 2025; Marris, 2005). This biome provides essential ecosystem services, such as carbon storage, nutrient cycling, water supply, and climate regulation (Rodrigues et al., 2022b; Salmona et al., 2023), which safeguards the productive basis for the country's main agricultural production area (Klink et al., 2020; Rajão et al., 2020). Despite its importance, the biome continually suffers from deforestation and land use change (Alencar et al., 2020; Sano et al., 2019), in which 50% of its native vegetation has been converted mainly into croplands and pastures (Leite-Filho et al., 2024).

In these pasture areas in the Cerrado, 32 Mha shows some level of degradation as a direct consequence of poor pasture management practices (C. O. dos Santos et al., 2024). While degradation severely compromises pasture productivity, land users often find it more profitable to establish new pastures on prime land than to manage the existing pastureland sustainably. The current land use accelerates biodiversity loss, reduces ecosystem services, and intensifies pressure on the remaining areas (Pereira et al., 2018; Vieira et al., 2022).

Conventional grazing practices are widely associated with increased greenhouse gas emissions, degraded water quality, soil erosion, and land use changes (Fleming et al., 2019; Wang et al., 2020). A promising alternative to the conventional grazing is silvopastoral systems (SPS), i.e., systems combining trees and woody, perennial plants with pasture (livestock) (Nair, 1993). These systems can enhance ecosystem services, improve forage production, and promote animal welfare (Bermeo et al., 2022; Hernández-Salmerón & Holmgren, 2022). SPS are also linked to the pursuit of greater economic resilience by adding incomes from marketable tree products while mitigating the impacts of climate change, such as extreme drought events and climate variability (Maia et al., 2021). Additionally, these systems contribute significantly to food security and restoring soil health (Duffy et al., 2021; Silva-Olaya et al., 2021), and animal welfare.

By integrating native tree and shrub species rather than exotic ones into SPS, such systems can present an even more sustainable alternative to pasture management. In the Brazilian Cerrado, traditional "Geraizeiros" communities in the northeastern region of the Cerrado already incorporate locally adapted native species into their livestock pastures (Lima et al., 2017, 2022). Studies demonstrate the potential of these systems to enhance agricultural productivity, increase resilience to climate change, and expand ecosystem services, including biodiversity conservation (Lima et al., 2017, 2022; Teixeira et al., 2022). A diversity of native tree products from the SPS, such as timber and firewood, wild fruits and nuts, honey, animal fodder, and medicinal resources, contribute to family subsistence and income generation for these communities (Duffy et al., 2021; Lima et al., 2017).

However, farmers outside the traditional communities are less enthusiastic to adopt such native SPS due to the prevailing belief that modern monoculture pastures are more productive or that native SPS require an increased labor demand (Sandino et al., 2023; Mukhlis et al., 2022). Such widespread misconceptions highlight the pressing need for studies that scrutinize the factors influencing the adoption and implementation of native silvopastoral systems, as such research can provide critical insights for shaping more effective public policies and fostering broader acceptance and development of these systems (Foguesatto & Machado, 2022; Solorio et al., 2017).

This study aims to identify the key production, environmental, technical, socioeconomic, and farm-related factors influencing the adoption of silvopastoral systems

(SPS) with native trees in the Cerrado region, as well as their intensification through the production and commercialization of products. Specifically, it seeks to determine and analyze the factors influencing SPS adoption, the factors that explain the productive use of SPS, and those shaping the commercialization of SPS products.

2. Conceptual framework

Previous research indicates factors linked to adopting or intensifying SPS (Sandino et al., 2023; Tschopp et al., 2020, 2022). The factors investigated depended on the specific context, data availability, the chosen model, and knowledge from previous research. In this study, based on a thorough literature review, we allocated factors into five groups: production, environmental, technical, socioeconomic, and farm-related factors, comprising 31 variables (table S1), as done in other studies (Jara-Rojas et al., 2020; Sandino et al., 2023). A summary of the conceptual framework and the expected hypotheses for the variables is presented in Figure 1.

Productive elements, such as the availability of labor, either family or hired, are positively associated with SPS adoption due to the system's higher labor requirements (Sandino et al., 2023). Technical assistance and irrigation also contribute positively (Jara-Rojas et al., 2020).

Environmental aspects, including the presence of water sources and fire prevention strategies, enhance SPS adoption by encouraging conservation practices (Tarbox et al., 2020). Farmers with greater environmental awareness, access to environmental support, and knowledge of laws are more likely to adopt SPS (Sandino et al., 2023).

Technical factors like farmer training and familiarity with SPS are crucial to intensification (Sandino et al., 2023). The number of cattle, livestock system type, and use of adapted breeds also matter, along with management techniques such as pruning (Opdenbosch & Hansson, 2023).

Socioeconomic characteristics are recognized as key drivers of adoption. Age, in particular, is often hypothesized to have a negative relationship with the adoption of new technologies. This is theoretically grounded in two main assumptions: first, that older farmers tend to have shorter planning horizons, which discourages investment in systems with long-term returns like SPS; and second, that they may exhibit higher levels of risk aversion, prioritizing traditional and predictable production models over innovative, albeit more sustainable, alternatives. For these reasons, younger farmers are often considered more inclined to adopt SPS (Cancino et al., 2016; Sandino et al., 2023). Other characteristics, such as better education and being a male farmer, are also associated with a higher likelihood of adoption, typically due to greater access to resources and information. However, off-farm income activities may limit adoption due to competing time (Mukhlis et al., 2022). Access to credit and fewer financial constraints positively influence SPS use (Jara-Rojas et al., 2020; Tschopp et al., 2020). Household size and the collection of non-timber forest products (NTFPs) also contribute positively, supporting family subsistence (Lima et al., 2017, 2022).

Farm-level conditions, including land size, diversified production, community infrastructure, and proximity of farmer house to the SPS area, significantly shape adoption dynamics. Farms with multiple income sources and better access to resources tend to show greater interest in sustainable practices (Jara-Rojas et al., 2020; Sandino et al., 2023).

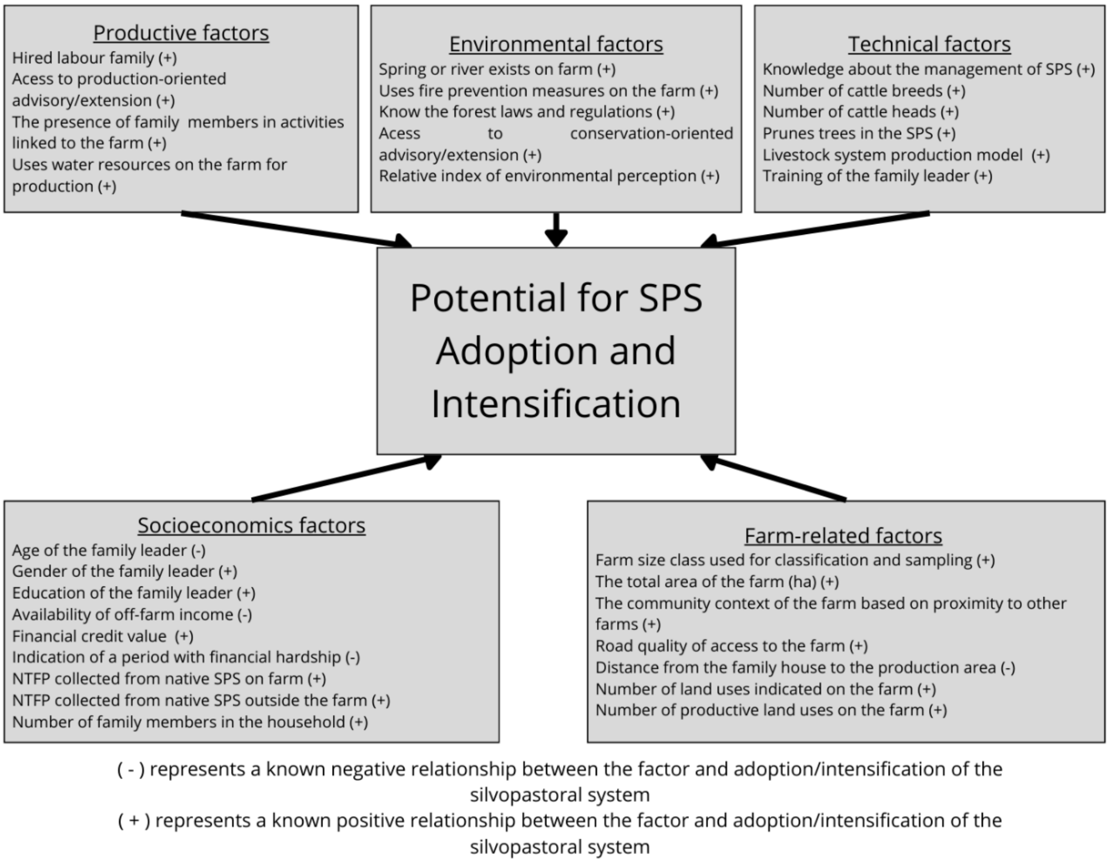

Figure 1. Conceptual framework showing the factors influencing the adoption and intensification of SPS.
Source: Elaborated by the authors.

3. Material and Methods

3.1. Study area

The study area is located within the northern mesoregion of Minas Gerais state, Brazil, defined by the water basins of the Rio Pardo and São João do Paraíso (Figure 2), encompassing 809,848 hectares in several municipalities. The regional vegetation consists of the plant physiognomies of the Cerrado, and minor areas covered by Caatinga biome vegetation and transition zones. The main plant physiognomies are Cerrado field, montane deciduous seasonal forest, *Vereda* (palm swamps), and submontane deciduous seasonal forest (Carvalho et al., 2009).

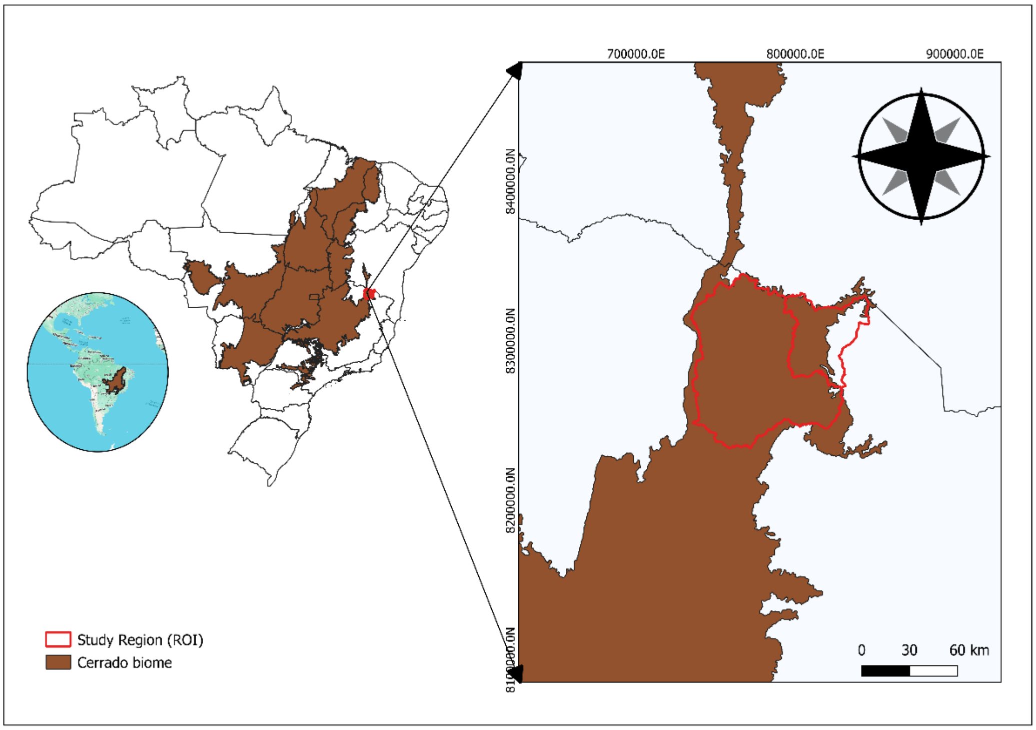

Figure 2. Map of the region of interest (ROI), including the Rio Pardo and São João do Paraíso basins in Minas Gerais, Brazil.
Source: Elaborated by the authors based on geospatial data from the Brazilian Institute of Geography and Statistics (IBGE, 2024).

The tropical highland climate predominates, featuring warmer or milder summers and dry winters (Aw). Tropical climates, characterized by high temperatures throughout the year and drier summers, also occur (Martins et al., 2018). The predominant soil types are Cambisols, Ferralsols, and Arenosols, with Acrisols and Plinthosols occurring to a lesser extent (H. G. dos Santos et al., 2011).

The regional relief is diverse, characterized by a combination of mountainous areas and flat plains. Notable relief features include plateaus, valleys, and hills, with altitudes ranging from 500 to 1,000 meters asl, in most parts of the basin, but can reach values above 140 meters asl (Brito Neto et al., 2020). Heterogeneous landscapes are associated with higher levels of species endemism and various land uses in the region, influencing the generation of ecosystem services and highlighting the need for sustainable production practices, such as SPS with native species (Lima et al., 2022; Matias et al., 2024).

3.2. Data collection

The municipalities Vargem Grande do Rio Pardo, Santo Antônio do Retiro, Montezuma, Indaiabira, Rio Pardo de Minas, São João do Paraíso, and Taiobeiras represent 99.8% of the total study are, and were selected for analysis.

We randomly selected farms for sampling based on farm area size and the proportion of the municipality area within the two basins. For this, we classified farms into four size classes based on Brazil's official classification of fiscal modules, a land measurement unit used to classify rural properties based on their economic viability: Class I ($\leq 65\ ha$), Class II ($> 65\ to\ 130\ ha$), Class III ($> 130\ to\ 260\ ha$), and Class IV

($> 260\ ha$). The distribution of sampled farms across municipalities considered the four farm size groups, the municipality's area within the basins, and its area proportional representation within the basins (table S2).

We relied on the data from the Brazilian Rural Environmental Registry System (Sicar, accessed in November 2022) to identify farm area size and its geographical location. Farms smaller than 1 hectare or those extending into municipalities outside the seven selected municipalities were excluded from the study. The total number of farms by municipality and by size class is shown in supplementary material (table S3).

The random selection of farms was done with the R 4.2.2 software version. From a total of 19,225 eligible rural farms, this work could complete 106 questionnaires. This fieldwork was from November 2023 to March 2024. A pre-test of the questionnaire was conducted in the area involving two local farmers. Necessary corrections were made, leading to a revised questionnaire version. Data collected during the pre-test were discarded. Each participant answered a semi-structured questionnaire focusing on socioeconomic aspects of the family, technical practices, productive and economic data related to the farm, additional economic activities, and environmental perceptions. The questionnaire was applied primarily to the family leader of the farm. This study received approval from the Human Research Ethics Committee of the Federal University of Viçosa, under protocol CAAE no. 72996223.0.0000.5153, and is registered with the National System for Management of Genetic Heritage and Associated Traditional Knowledge (SisGen) under registration no. A88AFC2.

3.3. Descriptive statistics

The descriptive statistical analysis includes 31 independent variables, and three dependent variables used in the initial model (table 1). Dummy variables represent the percentage of affirmative responses.

The environmental perception index was constructed based on 14 affirmative questions addressing environmental issues related to the farm and the conservation of natural resources. For each question, a 3-point Likert scale is used. Depending on the content of the statement, responses were assigned a value of 1 (indicating a positive environmental perception), -1 (indicating a negative perception), or 0 (if the respondent was indifferent). The values from the 14 statements are summed up to generate a composite score for each respondent. This composite score is then normalized to a scale ranging from 0 to 1 by adjusting each value proportionately to the dataset's minimum and maximum scores.

The livestock system is classified into four categories: dairy cattle (1), beef cattle (2), mixed system (beef and milk) (3), and absence of a production system (0), which applied when neither native SPS nor livestock were present. The mixed system is assigned the highest value due to its capacity to support diversified production and marketing activities, representing a more significant land-use intensification. Conversely, the absence of a production system is assigned to be the lowest value for this variable.

Table 1. Variable Description

	Variable	Type	Description	Yes (%)	Median	Min	Max	Mean	Standard deviation
Dependents	y_{1s}	Dummy	Adoption of native SPS on the farm	70.6					
	y_{2s}	Dummy	Animal or plant-based products harvested from native SPS	57.8					
	y_{3s}	Dummy	Commercialization of animal or plant-based products from native SPS	46.1					
Production Factors	emp_far	Dummy	Hired labor on the farm	72.5					
	ass_prod	Dummy	Access to production-oriented advisory/extension/ support services	28.4					
	fam_far *	Dummy	The presence of family members in activities linked to the farm	89.2					
	use_wat *	Dummy	Uses water resources on the farm for production	45.1					
Enviromental Factors	spring_river	Dummy	Spring or river exists on farm	78.4					
	prev_fire	Dummy	Use of fire prevention measures on the farm	52					
	law_m	Multinomial	Knowledge about forest laws and regulations		Not (60.8%)	Not (60.8%)	Yes (30.4%)		
	ass_env *	Dummy	Access to conservation-oriented advisory/ extension/ support services	26.5					
	per_env *	Index	Relative index of environmental perception (%)			0	1	0.84	0.1695
Technical Factors	kno_sps	Dummy	Knowledge about the management of SPS	37.3					
	n_bree_cat *	Discrete	Number of cattle breeds			0	4	1	0.9544
	head_cat	Discrete	Number of cattle heads			0	600	31.2	74.0133
	pru_sps	Dummy	Pruning of trees in the SPS	18.6					
	purp_live	Dummy	Livestock production model		Absence (34.3%)	Absence (34.3%)	Mixed (30.4%)		
	prof_trai	Dummy	Training of the family leader	29.4					
Socioeconomic Factors	age *	Discrete	Age of the family leader (years)			26	84	55.2	13.57
	gender	Dummy	Gender of the family leader	6.7 (Female)					
	education	Categoric	Education of the family leader		Incomplete elementary school - 40.2%	No instruction (14.7%)	Post-grad education (0.9%)		

	Variable	Type	Description	Yes (%)	Median	Min	Max	Mean	Standard deviation
	inc_out	Dummy	Availability of off-farm income	85.3					
	credit_num *	Continuous	Financial credit value (R$)			0	3,000,000.00	87,867.65	332,098.53
	less_inc	Dummy	Indication of a period with financial hardship	56.7					
	col_ntfp_on	Dummy	NTFP collected from native SPS on farm	63.3					
	col_ntfp_out	Dummy	NTFP collected from native SPS outside the farm	33.3					
	num_hou	Discrete	Number of family members in the household			1	6	3	1.3087
	clas_are *	Categoric	Farm size class used for classification and sampling		Class I (40.2%)	Class I (40.2%)	Class IV (25.5%)		
	area_ha	Continuous	Total farm area (ha)			1	5000	240.54	558.9706
	cont_far *	Dummy	Farm location in proximity to other farms of the community	78.4					
Farm-related Factors	aces_far	Categoric	Road quality of access to the farm		Good (76.5%)	Good (76.5%)	High (8.8%)		
	d_far_pro *	Continuous	Distance from the family house to the production area (km)			0	890	16.55	89.3613
	nland_use *	Discrete	Number of land uses indicated on the farm			1	6	3.3	1.2804
	ninc_land *	Discrete	Number of productive land uses on the farm			0	4	1.3	0.8058

Where: * = variables maintained in the final adjusted model. The answer options are presented in supplementary material (table S1).
Source: Elaborated by the authors

3.4. Econometric Model

Due to the exclusion of questionnaires with missing data, the final dataset for analysis (sample S) consists of 102 questionnaires. Variables were selected following the conceptual framework (Figure 1), which identified the factors hypothesized to influence the adoption and intensification of SPS. To evaluate these issues, three dependent variables are defined in a system of 3 equations: (1) Adoption of native SPS on the farm, (2) Harvesting of animal or plant-based products from native SPS, and (3) Commercialization of animal or plant-based products from native SPS. The seemingly unrelated regressions (SUR) model comprises 12 explanatory variables, with 11 variables common across all equations (Greene, 2012). Additionally, equation (1) includes a unique variable (environmental perception), while equations (2) and (3) share another specific variable (number of cattle breeds). The general form of each equation is presented below:

$$y_{1s} = x_{1s}\beta_1 + \varepsilon_{1s} \tag{1}$$

$$y_{2s} = x_{2s}\beta_2 + \varepsilon_{2s} \tag{2}$$

$$y_{3s} = x_{3s}\beta_3 + \varepsilon_{3s} \tag{3}$$

Where y_{is} represents the dependent variables, x_{is} represents the impacting factors, β_i are the estimated coefficients, and ε_{is} are the unobserved error term. With $i = 1, 2, 3$ and $s = 1, 2 \ldots, S$.

The Full Information Maximum Likelihood (FIML) method was employed to estimate the SUR model, as it provides more accurate and less biased estimates than the single-equation approach such as Generalized Method of Moments (GMM), or even more advanced techniques like Two-Stage Least Squares (2SLS) and Three-Stage Least Squares (3SLS) (Fair & Parke, 1980; Lindé, 2005). FIML is well regarded for its complexity and its ability to manage nonlinear modeling, resulting in lower errors in simultaneous equation systems. The EViews 12 software was employed for correlation analysis and modeling using the FIML method.

4. Results

Production factors were significant only for the intensification of SPS, primarily due to their direct influence on production processes and, consequently, on the products commercialization (table 2). Based on the odds rate calculated, the involvement of family labor in the activities had significantly increased the probability of harvesting animal or plant-based products from the native SPS by 35.6% and consequently of commercializing these products by 33.06%. Water use had a stronger relationship with production than commercialization, as its presence increased the probability of production by 27.35% and commercialization by 19.40%. This outcome highlights the critical importance of water resources in the SPS production process.

Environmental perception was significant and positively related to SPS adoption. The availability of conservation-oriented advisory services did not contribute to the adoption and production of SPS. The most frequently reported institutions include private consulting agencies and state public agencies (EMATER and IEF), with nine different institutions mentioned.

Table 2. Model Results

Factor	Variable	Description	Equation 1 Adoption of SPS	Equation 2 Production within SPS	Equation 3 Commercialization within SPS
			Estimated Coefficients		
Production	use_wat	Uses water resources on the farm for production	0.0647 *(0.062)*	0.2418 * *(0.032)*	0.1773 ** *(0.044)*
	fam_far	The presence of family members in activities linked to the farm	0.0079 *(0.088)*	0.3042 * *(0.102)*	0.2856 * *(0.099)*
Environmental	per_env	Relative index of environmental perception (%)	0.6575 * *(0.141)*		
	ass_env	Access to conservation-oriented advisory/ extension/ support services	-0.2424 * *(0.081)*	-0.1823 ** *(0.089)*	-0.1350 *(0.092)*
Technical	n_bree_cat	Number of cattle breeds		0.03190 *(0.034)*	0.1548 * *(0.040)*
Socioeconomic	age	Age of the family leader (years)	0.0056 ** *(0.003)*	0.0001 *(0.003)*	-0.0041 *(0.003)*
	credit_num	Financial credit value (R$)	-0.0000002 * *(5.7E-08)*	-0.0000001 ** *(6.0E-08)*	-0.00000009 *(5.5E-08)*
Farm-related	clas_are	Farm size class used for classification and sampling	0.0761 * *(0.025)*	0.1245 * *(0.027)*	0.0921 * *(0.030)*
	cont_far	Farm location in proximity to other farms of the community	-0.0756 *(0.080)*	0.0163 *(0.088)*	0.16608 ** *(0.082)*
	nland_use	Number of land uses indicated on the farm	0.1422 * *(0.028)*	0.0857 * *(0.032)*	-0.0029 *(0.031)*
	ninc_land	Number of productive land uses on the farm	0.0874 * *(0.032)*	0.1770 * *(0.044)*	0.1671 * *(0.056)*
	d_far_pro	Distance from the family house to the production area (km)	-0.0006 * *(1.4E-04)*	-0.0005 * *(1.5E-04)*	-0.0004 * *(1.4E-04)*
		R-squared Adjusted	0.5499	0.4719	0.4423
		R-squared	0.4949	0.4074	0.3741
		Durbin-Watson stats	1.8274	1.8509	1.7298
		Akaike info criterion		1.7382	

Where: ** denotes 1% significance; * denotes 5% significance. Standard errors in brackets.
Source: Elaborated by the authors.

The number of cattle breeds was significant exclusively in equations 2 and 3. Among all respondents, nine cattle breeds were mentioned. The Nelore breed was reported in 36 farms and was primarily raised for beef production. The Girolando breed was found in 11 farms for milk production. The Curraleiro Pé-duro and "Mestiço" were traditional breeds adapted to the Cerrado environment, found in 15 and 17 farms, each serving different purposes within the farm system.

The socioeconomic factors exhibited a different significance than those identified in the initial hypotheses. In our model, the age of the family leader had a positive impact solely on the adoption of the system, indicating that older farm leaders are more likely to adopt the SPS. Conversely, the value of financial credit had a negative impact on both the adoption and production within the SPS, with a low coefficient, indicating that farmers with greater access to financial credit are less likely to adopt or produce within this system.

Farm-related factors were the most prevalent in the model, of which three variables showed significance across all equations. The farm's size had a significant and positive impact on adoption, production, and commercialization within the SPS. The distance of the family leader's residence to the productive area was also a significant factor in all equations, exhibiting a negative relationship as expected, given the challenges associated with surveilling the production area. The amount of income-generating land uses significantly impacted adoption, production, and commercialization within the SPS. In contrast, the total amount of land used on the farm only influenced adoption and production. Conversely, there was some evidence that the farm's community context may positively affect the commercialization of SPS products, indicating that farms located near villages or communities benefit from easier market access and enhanced opportunities for selling their products.

5. Discussions

The high SPS adoption rate of 70.6% in the region reflects the historical presence of these systems in the area, with reports between the respondents of its use dating back to the 1960s. Although SPS most likely existed long before, studies explicitly addressing this earlier period are lacking. SPS that rely on native trees are often more easily adopted, since they capitalize on existing trees of interest and avoid the need for planting, reducing costs and simplifying establishment relative to systems involving exotic species (Lima et al., 2017, 2022; Rodríguez et al., 2022). However, our data shows that established SPS were not currently used for production in all cases, nor were their products commercialized, indicating certain limitations. Challenges in managing the area (Freitas et al., 2020) or a preference for family subsistence (Rozaki et al., 2021) can reduce SPS intensification in favor of other, more profitable or productive land uses (Opdenbosch & Hansson, 2023).

The identification of 12 variables across the three equations, with at least one relevant factor from each predefined group, demonstrates that the adoption and intensification of the SPS are influenced by a multidimensional set of factors, spanning individual, community, and regional levels (Sandoval et al., 2023; Tschopp et al., 2022).

The relevance of the variable family labor for production and commercialization highlights its critical role in family subsistence by reducing production costs and improving economic returns (Bucheli et al., 2021). The lack of labor is a commonly reported barrier to adopting more sustainable practices (Mukhlis et al., 2022; Varela et al., 2022). Women and other family members often perform essential tasks in these systems to enhance efficiency, such as harvesting and selling NTFPs (Gonçalves et al., 2021; this study).

Water use is more critical for production than for commercialization, as water is indispensable for both animal and plant production (Varela et al., 2022). In contrast, product sales strategies are influenced by additional factors, such as the need to prioritize family subsistence (Rozaki et al., 2021). In the Cerrado, water resources are essential for sustaining the development and productivity of rural farms (Latrubesse et al., 2019). As reported by interviewees, the frequent use of water from rivers and springs in farm production underscores the importance of conserving these areas. It highlights their potential integration with SPS (Jara-Rojas et al., 2020), which offers notable benefits for water conservation by enhancing soil moisture, increasing infiltration, reducing runoff, and regulating microclimates (Bosi et al. 2020; Gomez et al., 2019). Recent studies (Mamedes et al., 2023) have demonstrated that payment for ecosystem services programs can successfully incentivize the conservation of water sources through SPS in the Cerrado (Oliveira et al., 2023).

According to our study, farmers with greater environmental awareness are likelier to adopt the SPS, illustrating the importance of personal environmental knowledge in adoption decisions (Cancino et al., 2016; Evangelista et al., 2024). In agreement with Zabala et al. (2017), we found that moral values and connections to nature are significant motivators for SPS adoption, which contributes to preserving native species and reinforcing the region's historical and cultural identity. Nevertheless, practical considerations, such as subsistence needs and broader tangible benefits, also influence adoption, illustrating the multifaceted nature of decision-making in the regional SPS context (Zabala et al., 2017, 2022).

Conversely, conservation-oriented advisory services had a negative impact on both SPS adoption and production intensity. This counterintuitive result may reflect their focus on farms that have not yet adopted SPS. Therefore, it suggests an opportunity to target these services better to promote SPS adoption. Additionally, capacity-building could enhance their effectiveness in supporting SPS implementation and scaling, aligning short-term actions with long-term sustainability goals (Sunariyo & Firdausi, 2024).

A diverse use of cattle breeds is found to have a positive relationship with the commercialization of SPS products. This diversity, which includes recognized and traditional breeds adapted to the region, provides opportunities for differentiation from mass markets, offering unique production advantages (Diakité et al., 2019; Mosnier et al., 2022). Our results suggest that the management of native SPS is more compatible when farmers decide to implement a business model based on a larger diversity of cattle breeds, hence allowing product differentiation.

Age, contrary to expectations, is found to have a positive association with SPS adoption. While older farmers are often considered less inclined to change land use or invest in new practices (Cancino et al., 2016; Jara-Rojas et al., 2020) our findings underscore the influence of the region's history of SPS adoption. However, as our study interviewed the head of the farm, this result may not solely represent an individual's decision. It could instead indicate a dynamic of intergenerational exchange, where the experience and established practices of the older generation are combined with the influence of younger family members involved in farm labor and decisions. This exchange is particularly relevant as these younger farmers, often described as more open to sustainable practices (Liu et al., 2024), are poised to continue and expand SPS in the future. Notably, age did not influence production and commercialization, suggesting that efforts to enhance these aspects can be targeted at farmers across all age groups.

The value of access to credit shows a negative relationship with SPS adoption. Although 70% of farmers use financial credit, high credit values are typically associated with production systems that require substantial initial investments (Jara-Rojas et al., 2020; Tschopp et al., 2022). In contrast, the SPS analyzed in this study typically relies on preserving native Cerrado trees and low management of the pasture, significantly reducing the highest costs of an SPS and minimizing the need for large credit amounts (Lima et al., 2017, 2022). Additionally, in Brazil, the highest rural credit allocations are directed towards large-scale farmers and monocultures (Moreira-Dantas et al., 2023), which helps explain the negative relationship between the value of financial credit and both SPS adoption and production. However, accessing credit for implementing SPS is often challenging due to institutional financing structures that tend to favor conventional and standardized production models (Cechin et al., 2021). While programs such as PRONAF aim to support smallholders, their specific credit lines may still pose challenges for those adopting SPS (Carrer et al., 2020).

We found evidence that larger farms are likelier to adopt SPS and produce and sell derived SPS products. In contrast, smaller farmers often face challenges in implementing sustainable practices (Kansanga et al., 2021) or achieving surplus production for commercialization due to the prioritization of family consumption (Rozaki et al., 2021). One viable strategy for small-scale farmers is engaging in associations or cooperatives, which can help facilitate the sale of surplus production, secure better market prices, and even support the processing and commercialization of tree-based products from SPS (de Mello et al., 2023b; Rodríguez et al., 2022).

The distance between the family leader's home and the production area is negatively significant for adoption, production, and commercialization. In contrast to the study of Rozaki et al., (2021), where the average distance is 1 km, and the significance is tied to internal access to production sites, our findings present a different scenario. The small coefficient observed in the equations, combined with a higher average distance, suggests the presence of farmers who reside in urban areas far from their farms. Given that SPS are more labor and management-intensive compared to conventional grazing systems, a greater distance between the farmers' homes and the production area discourages the adoption of SPS and leads to difficulties in achieving SPS productivity and profitability (Nguyen et al., 2020; Varela et al., 2022).

The farm's diversity of land uses and income from diversified activities shows a significant positive impact on the adoption, production, and commercialization associated with SPS in this study. Rois-Díaz et al. (2018) identified that adopters of the SPS are often motivated by the potential for product diversification. Conversely, highly specialized farmers are less likely to adopt, manage, and commercialize SPS. Additionally, the positive relationship with the number of profitable land uses indicates that SPS are typically operated by farms with access to markets. Our results support the notion that the absence of market access (Rois-Díaz et al., 2018) or difficulties in reaching the markets (Rodríguez et al., 2022) represent significant barriers to the adoption and intensification of SPS.

As expected, we found that farms near communities were more likely to commercialize SPS products. In contrast, SPS adoption and use of SPS products are not influenced by the proximity of other farms, given that SPS are a traditional practice that has been empirically shared and consolidated among farmers over generations (Rois-Díaz et al., 2018). The positive relationship between commercialization and community context is highligthed in the literature, which stresses the potential for creating associations and cooperatives to enhance productivity and knowledge about SPS (Abraham et al., 2022).

Overall, this study contributes to expanding our understanding of which factors influence the adoption and intensification of SPS. While our conclusions are based on data collected in a specific region of the Cerrado biome and may not fully represent its entire heterogeneity, this area reflects many of the socio-economic and land-use dynamics present across large portions of the biome, which enhances the relevance of our findings beyond the immediate study region. We also acknowledge that the study relies on self-reported information, which can be prone to bias; however, we minimized this risk by pre-testing the questionnaire, using a structured instrument, and a stratified sampling design. One specific limitation of this study was the inability to include a direct measure of management intensity within the SPS. Although the questionnaire was designed to capture data on practices such as planting, fertilization, and clearing, inconsistencies in its application to all SPS adopters prevented the use of this variable in the econometric model. The inclusion of such a variable would have provided a more direct proxy for the intensification of these systems, complementing the analysis based on product generation and commercialization. Future research could expand the geographic scope, include the characterization of leading products, analyze economic feasibility, explore target markets, and assess added value.

6. Conclusions

We conclude that SPS with native tree species are widely adopted in the region, reflecting their historical and traditional significance for local farmers. Given the broad range of relevant factors, the multidimensional approach proved valuable.

The high adoption rates among older farmers suggest that younger farmers represent a promising target group for future adoption efforts. At the same time, the intensification of SPS practices should be encouraged across all age groups. We found a positive correlation between SPS adoption and intensification among larger farms. Nevertheless, small farms could be strategic targets for SPS expansion and development. Water availability is highlighted as a key factor for production and commercialization, and SPS also contributes to water conservation and incentivizing adoption. Furthermore, farm proximity to communities enhances the commercialization of SPS products, highlighting the potential of cooperatives and associations to improve market access and profitability.

Based on our findings, we suggest developing a simultaneous two-stage governmental program that classifies two farmer groups according to their use of SPS. A group of "Not-yet-Adopters" would begin in the first stage, focusing on training support and awareness initiatives to increase adoption. The group of " Adopters" would directly transition to the second stage, aimed at intensifying SPS practices through improved product generation and commercialization. In case of a positive outcome for the "Not-yet-Adopters," the second stage would follow. This structured approach could facilitate tailored public interventions, enabling SPS economic and sustainable regional growth.

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Declaration of generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the author(s) used ChatGPT (version GPT-4.5) to translate, review the text, search for synonyms and improve the fluidity of writing. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

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Supplementary Matirials

Table S1. Factors, description, type, and options of answers of independent variables

Factors	Variable	Description	Type	Options of answers
Dependent	y_sps	Adoption of native SPS on the farm	Dummy	1 - Yes; 0 - Not
	y_prod_sps	Animal or plant-based products harvested from native SPS	Dummy	1 - Yes; 0 - Not
	y_com_sps	Commercialization of animal or plant-based products from native SPS	Dummy	1 - Yes; 0 - Not
Production Factors	emp_far	Hired labour on the farm	Dummy	1 - Yes; 0 - Not
	ass_prod	Access to production-oriented advisory/extension/ support services	Dummy	1 - Yes; 0 - Not
	fam_far *	The presence of family members in activities linked to the farm	Dummy	1 - Yes; 0 - Not
	use_wat *	Uses water resources on the farm for production	Dummy	1 - Yes; 0 - Not
Enviromental Factors	spring_river	Spring or river exists on farm	Dummy	1 - Yes; 0 - Not
	prev_fire	Use of fire prevention measures on the farm	Dummy	1 - Yes; 0 - Not
	law_m	Knowledge about forest laws and regulations	Multinomial	1 - Not; 2 - In parts ; 3 - Yes
	ass_env *	Access to conservation-oriented advisory/ extension/ support services	Dummy	1 - Yes; 0 - Not
	per_env *	Relative index of environmental perception (%)	Index	Percentage value (higher value, higher perception)
Technical Factors	kno_sps (4)	Knowledge about the management of SPS	Dummy	1 - Yes; 0 - Not
	n_bree_cat *	Number of cattle breeds	Discrete	Animal counting
	head_cat	Number of cattle heads	Discrete	Heads counting
	pru_sps	Pruning of trees in the SPS	Dummy	1 - Yes; 0 - Not
	purp_live	Livestock production model	Multinomial	0 - Absent; 1 - Dairy farming; 2 - Beef farming; 3 - Mixed
	prof_trai	Training of the family leader	Dummy	1 - Yes; 0 - Not
Socioeconomic Factors	age *	Age of the family leader (years)	Discrete	Years of age of the family leader
	Gender	Gender of the family leader	Dummy	1 - Male; 0 - Female

Factors	Variable	Description	Type	Options of answers
	Education	Education of the family leader	Categoric	1 - No instruction and <1year of study; 2 - incomplete elementary school; 3 - complete elementary school; 4 - post-grad education incomplete high school; 5 - complete high school; 6 - incomplete university education; 7 - complete university education; 8 - post-grad education
	inc_out	Availability of off-farm income	Dummy	1 - Yes; 0 - Not
	credit_num *	Financial credit value (R$)	Continuos	Value in R$
	less_inc	Indication of a period with financial hardship	Dummy	1 - Yes; 0 - Not
	col_ntfp_on	NTFP collected from native SPS on farm	Dummy	1 - Yes; 0 - Not
	col_ntfp_out	NTFP collected from native SPS outside the farm	Dummy	1 - Yes; 0 - Not
	num_hou	Number of family members in the household	Discrete	Number of people
Farm-related Factors	clas_are *	Farm size class used for classification and sampling	Categoric	I - área < 65ha; II - área entre 65ha e 130ha; III - área entre 130 e 260ha; IV - área >260ha
	area_ha	Total farm area (ha)	Continuos	Number of hectares
	cont_far *	Farm location in proximity to other farms of the community	Dummy	1 - In comunnity; 2 - Isolated
	aces_far	Road quality of access to the farm	Categoric	1 - Easy ; 2 - Medium; 3 - Hard; 4 - Inacessible
	d_far_pro *	Distance from the family house to the production area (km)	Discrete	Land use accounting
	nland_use *	Number of land uses indicated on the farm	Continuos	Value in kilometers
	ninc_land *	Number of productive land uses on the farm	Discrete	Land use accounting with financial income

Where: * = variables maintained in the final adjusted model.
Source: Elaborated by the authors.

Table S2. Total area, percentage within basins, and farm size class number sample, by municipalities within the study area

Municipality	Area (km²)	Percentual within basins	Class I	Class II	Class III	Class IV	Total
Vargem Grande do Rio Pardo	491.51	100.00%	2	2	2	2	8
Santo Antônio do Retiro	796.3	99.71%	4	4	4	4	16
Montezuma	1,130.41	99.64%	6	6	6	6	24
Indaiabira	1,004.149	99.62%	5	5	5	5	20
Rio Pardo de Minas	3,117.68	89.41%	14	14	14	14	56
São João do Paraíso	1,925.58	74.13%	7	7	7	7	28
Taiobeiras	1,220.05	39.68%	2	2	2	2	8
Total	9,685.665	99.8%	40	40	40	40	160

Source: Elaborated by the authors.

Table S3. Farm size class population across selected municipalities in the study area

Municipality	Class I	Class II	Class III	Class IV	Total
Montezuma	1,567	129	45	31	1,772
Indaiabira	1,183	101	75	52	1,411
Rio Pardo de Minas	7,293	442	149	68	7,952
Santo Antônio do Retiro	1,822	133	31	15	2,001
São João do Paraíso	4,394	186	67	73	4,720
Taiobeiras	316	55	27	56	454
Vargem Grande do Rio Pardo	799	75	26	15	915
Total	**17,374**	**1,121**	**420**	**310**	**19,225**

Source: Elaborated by the authors.

CHAPTER III:

DIVERSITY AND MARKET STRUCTURES OF NON-TIMBER FOREST PRODUCT TRADERS IN THE BRAZILIAN CERRADO

To be submitted to the **Ecological Economics**

Diversity and Market Structures of Non-Timber Forest Product Traders in the Brazilian Cerrado

Abstract

Non-timber forest products (NTFPs) play a key role in household subsistence and income generation worldwide, including in Brazil's Cerrado biome. Despite its remarkable ecological and productive diversity, the market potential of Cerrado NTFPs, particularly those associated with silvopastoral systems (SPS) using native tree species, remains underexplored. This study aimed to characterize NTFP markets in northern Minas Gerais (MG), classifying the main market segments and identifying their main products and species within different production contexts. We conducted 49 interviews with traders and NTFP trading farmers across two watersheds (Rio Pardo and São João do Paraíso) and main Cerrado urban centers in MG, applying k-means clustering to classify market profiles. Three distinct market scales emerged: (i) small-scale, locally based, with low species diversity and minimal product processing; (ii) medium-scale, characterized by a broader range of products, particularly processed items, still sourced from within the study watersheds; and (iii) large-scale, linked to major urban markets yet also present locally, offering higher-value, more diversified trade opportunities. Among the 20 species and 46 products recorded, only seven occurred in more than one market segment, suggesting limited cross-scale integration but highlighting key products with broader commercial reach. The coexistence of unique market niches, associated with the presence of large-scale traders in the region, reveals promising via for expanding producer access to higher-value markets, particularly for SPS adopters. These results highlight priority strategies for policy and market interventions to foster sustainable native species management, support SPS adoption, and expand NTFP commercialization across the Cerrado.

Keywords: native forest resources, silvopastoral systems, value chain, commercial networks

1. Introduction

Non-timber forest products (NTFPs) are a vital source of income and subsistence for many rural communities worldwide (Pandey et al., 2016; Silva et al., 2020a). According to the FAO (2020), NTFPs generate approximately US$7.7 billion annually and are linked to over 60 million formal jobs, with more than 3.5 billion people using these products worldwide (Shackleton and de Vos, 2022). Beyond their social and economic relevance, NTFPs are frequently associated with biodiversity conservation, as their extraction and management depend on maintaining native vegetation (Asamoah et al., 2024; Rosenfeld et al., 2024). Furthermore, appropriate management strategies can enhance the productivity of these systems while generating sustainable income (Belcher et al., 2005; Miranda-Gamboa et al., 2024).

In Brazil, the national production of NTFPs is monitored annually by the Brazilian Institute of Geography and Statistics (IBGE). In 2023, the most commercially relevant NTFPs generated a gross production value of R$2.2 billion (US$440 million), primarily from widely known products such as açaí (Euterpe sp.) and Brazil nuts (Bertholletia excelsa) (IBGE, 2024a). However, these statistics are widely acknowledged to underestimate the actual economic relevance of NTFPs, since informal marketing routes are not captured (FAO, 2020). Moreover, the potential of Brazilian NTFPs extends well beyond these flagship products, encompassing a broad diversity of species that vary across biomes and are not systematically monitored by IBGE (Afonso, 2022; Berte et al., 2023).

The Cerrado biome, harbors significant potential for NTFP development, with approximately 250 native species identified for use across food, medicinal, cultural, and construction purposes (Orioli et al., 2025). The commercial focus on these products has only gained traction in the last two decades, which is further evidenced by the very limited number of Cerrado species currently captured in IBGE's national monitoring scheme (Diniz et al., 2021; IBGE, 2024a; Walverde et al., 2021).

Cerrado NTFPs are sourced from both natural areas and traditional silvopastoral systems with native species (SPS), present in this biome (Berte et al., 2023; Lima et al., 2022, 2017). While these systems have long been used by local populations, they still lack adequate technical support and management strategies to scale production efficiently (Chapter 2). Nevertheless, the practice of maintaining native trees within pastures is highly valued by producers, who frequently prioritize species with market potential such as NTFPs to enhance the economic viability of SPS (Lima et al., 2017).

Despite its ecological richness and productive potential, the Cerrado's NTFP market remains in an early stage of development and is often overshadowed by the national and international visibility of Amazonian NTFPs (de Mello et al., 2020; Ribeiro et al., 2020). The great diversity of species and products, associated with variations in production scale and commercialization strategies, underscores the need for a deeper understanding of how these markets operate and what economic opportunities they offer, especially for SPS-adopting farmers (de Mello et al., 2023; Walverde et al., 2021).

Given this context, the objective of this study is to classify different NTFP markets in the Cerrado Mineiro region. To achieve this, we employ K-means clustering analysis to group traders based on their market characteristics and the types of products sold. Through a subsequent descriptive analysis of the species and products present in each identified cluster, this study seeks to highlight key differences and similarities among them, while identifying the main opportunities and barriers for SPS producers to access these markets more effectively and profitably.

2. Conceptual framework

NTFPs from the Cerrado have been increasingly recognized as key tools for promoting environmental conservation and the socioeconomic development of local communities (de Mello et al., 2023; Walverde et al., 2021). Given that income generation is one of the main factors shaping rural farmers' decisions in the Cerrado, understanding the economic and market potential of NTFPs is essential to increasing interest in sustainable practices and promoting the management of native species in productive areas (Aragão et al., 2022; Rosenfeld et al., 2024; Uprety et al., 2016). However, the NTFP market in the region remains incipient, characterized by significant heterogeneity in product types, trader profiles, sales scales, and product origins (de Mello et al., 2023; Diniz et al., 2021; Walverde et al., 2021). This diversity makes market analysis a key challenge for identifying barriers, opportunities, and entry points for local farmers, particularly those adopting SPS (Antunes et al., 2021; Orioli et al., 2025; Peerzada et al., 2021).

This study assumes that different trader profiles operate in distinct market niches, with structural and operational characteristics that influence the type of product sold, its origin, processing methods, and sales scale. Categorizing these profiles facilitates a deeper understanding of how NTFP diversity is expressed in the marketplace and how this diversity can be leveraged to expand value creation in rural areas. Drawing on interviews with traders and farmers involved in NTFP marketing, the study examines how market characteristics, such as type of trade, geographic location, scale, and sales method, allow the categorization of different market profiles. It also analyzes the products and species associated with each profile, highlighting both their specificities and overlaps. By exploring these dynamics, the study's conceptual framework integrates three key elements: (i) the supply of NTFPs in the Cerrado, based on the native species used; (ii) the diversity of market profiles and their structuring variables; and (iii) potential entry pathways for local producers, particularly those managing SPS. This analytical approach supports strategies for the economic valorization of NTFPs and their use as tools for productive conservation at the regional scale.

3. Material and Methods

3.1. Study area

The study area is located in the Cerrado, in the northern mesoregion of Minas Gerais state, Brazil, defined by the water basins of the Rio Pardo and São João do Paraíso, encompassing 809,848 hectares (Carvalho et al., 2009). Due to the size of the Cerrado and the absence of large commercial centers in the study region, we expanded the market analysis to two large municipalities in the state of Minas Gerais in the Cerrado biome (Montes Claros and Belo Horizonte).

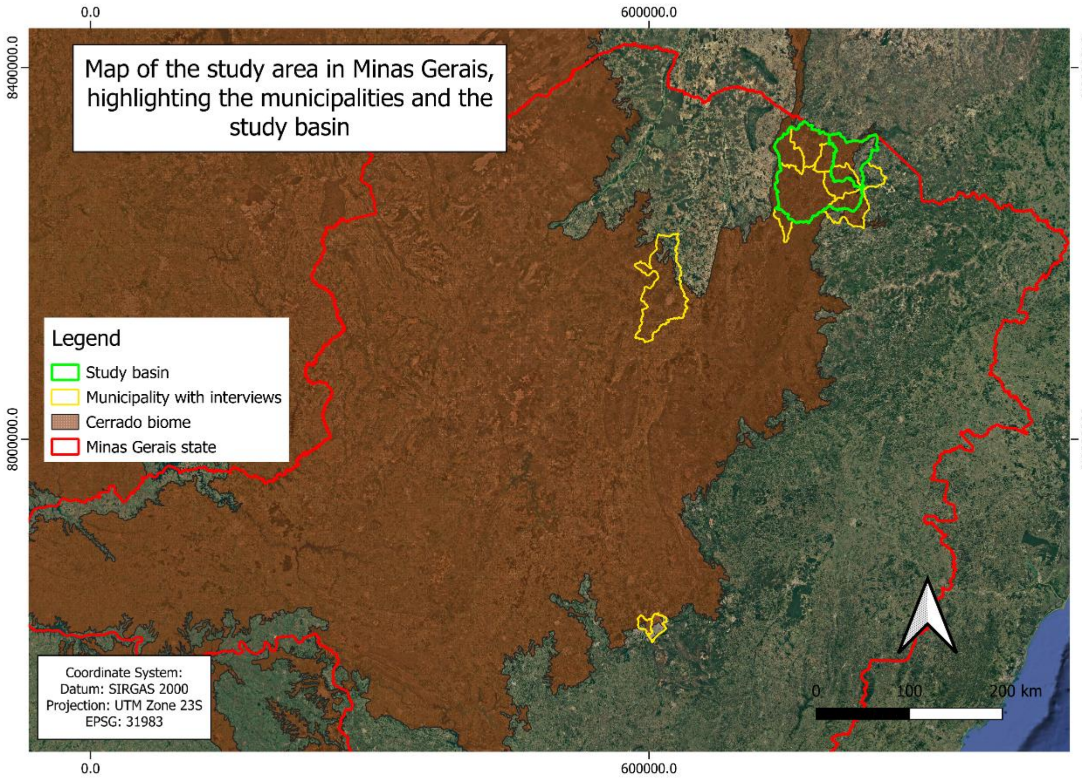

Figure 1. Map showing the municipalities where the interviews were conducted in the state of Minas Gerais, Brazil.
Source: Elaborated by the authors based on geospatial data from the Brazilian Institute of Geography and Statistics and primary data (IBGE, 2024).

3.2. Data colllection

We explored the trade in NTFP from the Cerrado through interviews with traders and farmers in the region. Farmers were included due to their involvement in the commercialization of NTFPs, thus constituting an integral part of these market chains. For the analysis, both farmers and traders were considered equally as market participants. During the period from December 2023 to March 2024, researchers conducted interviews in the municipalities present in the study area (Vargem Grande do Rio Pardo, Santo Antônio do Retiro, Montezuma, Indaiabira, Rio Pardo de Minas, São João do Paraíso, and Taiobeiras) and in the two major state centers within the biome (Montes Claros and Belo Horizonte), in the latter case focusing only on traders.

Each participant answered a semi-structured questionnaire focusing on the non-timber forest products sold in their business or by their farm. Traders were approached through visits to locations recognized for NTFP commercialization and by surveying urban centers in the selected municipalities, while farms were sampled exclusively within the study basin, proportionally to the size of each municipality and stratified across different farm-size classes. The same set of variables was collected for both groups. Details such as quantity, price, suppliers, processing, and marketing history of the products were answered. All participants interviewed signed the Free and Informed Consent Form, as required by the National Health Council under the Research Ethics Committee (Resolution 196/96). This study received approval from the Human Research Ethics Committee of the Federal University of Viçosa, under protocol CAAE no. 72996223.0.0000.5153, and is also registered with the National

System for Management of Genetic Heritage and Associated Traditional Knowledge (SisGen) under registration no. A88AFC2.

The interviews conducted allowed characterization at two levels, by traders and by product sold. In total, 49 interviews were conducted, comprising 23 with farmers in the region and 26 with traders, 13 of whom were outside the study region (Montes Claros or Belo Horizonte) (table 1). At the product level, 106 were listed among all the interviews, with a greater number among traders (80) than among farmers (26). We explored each of these levels in different ways, as presented in the data analysis.

Table 1. Distribution of interviews with traders and farmers across the municipalities included in the study

Within Study Basin?	Municipality	Interview - Trader	Interview - Farmer
Yes	Vargem Grande do Rio Pardo	0	1
	Santo Antônio do Retiro	1	5
	Montezuma	0	6
	São João do Paraíso	2	0
	Rio Pardo de Minas	3	11
	Taiobeiras	7	0
No	Montes Claros	5	0
	Belo Horizonte	8	0

Source: Elaborated by the authors.

3.3. Data analysis

3.3.1. By traders

At the trader level, broader questions about the NTFP market were explored. We selected 7 variables to characterize and cluster the trade profile in these products in the study region and the major urban centers of the state of Minas Gerais. Table 2 shows the description, type, and response options for each of the variables used.

The selected variables were standardized using Z-score normalization to ensure comparability across different measurement scales. The optimal number of clusters was determined through the Elbow Method, based on the total within-cluster sum of squares (WSS), which is a measure of cluster compactness. The logic of the Elbow Method is to run the clustering algorithm for multiple values of k and plot the corresponding WSS. While WSS always decreases as k increases, the optimal k is found at the 'elbow' of the curve, the point of diminishing returns where adding another cluster does not significantly improve the overall WSS. Based on the visual inspection of this plot from our exploratory tests, a three-cluster solution was selected as the most appropriate.

K-means clustering was then applied using this three-cluster configuration. The k-means algorithm was run with 25 random starts (nstart = 25) to reduce the likelihood of convergence to local minima. This approach increases the robustness of the clustering outcome by selecting the configuration with the lowest within-cluster variation among multiple initializations. Based on the total income generated by each segment, the clusters were subsequently labeled as small-scale (Cluster 1), medium-scale (Cluster 2), and large-scale (Cluster 3) market segments.

The cluster centroids were analyzed to assess the relative importance of each variable in defining the market profiles. In addition, the differences in the averages of the variables between the clusters were classified to highlight the most influential variables in differentiating the clusters. Bar graphs were generated to illustrate the importance of the variables and the average values per cluster. These results supported the characterization of distinct market profiles based on the structural and operational characteristics of NTFP traders.

Table 2. Characterization of the variables used in the clustering of traders

Code	Description	Type	Options of answers
munic	Municipality where the products are sold	Categoric	1 - Vargem Grande do Rio Pardo; 2 - Santo Antônio do Retiro; 3 - Montezuma; 4 - São João do Paraíso; 5 - Rio Pardo de Minas; 6 - Taiobeiras; 7 - Montes Claros; 8 - Belo Horizonte (capital)
type_ent	Type of enterprise	Categoric	1 - Farmer; 2 - Street Vendor; 3 - Street Market; 4 - Municipal Market; 5 - Beverage Distributor; 6 - Natural Products Store; 7 - Agroindustry; 8 - Central Market; 9 - SEASA Wholesale Food Market
locat_sup	Location of product suppliers	Categoric	1 – Northern mesoregion of Minas Gerais (Rio Pardo and São João Paraiso Paraíso basin); 2 - North of Minas Gerais; 3 - State of Minas Gerais; 4 - Outside of Minas Gerais
sal_method	Method in which the sale is made	Categoric	1 - Wholesale; 2 - Retail; 3 - Both;
sca_sal	Scale of sale of the enterprise	Categoric	1 - Municipal; 2 - Regional; 3 - Statewide; 4 - National; 5 - International
n_prod	Number of products sold from Cerrado NTFP	Numeric	Number of products
prod_process	Percentage of processed NTFP	Percentual	%

Source: Elaborated by the authors.

The variables in table 1 were assigned numerical values to reflect a hierarchical order of complexity, scale, or positive outcome. This ranking was critical for the clustering analysis. For example, municipallity 1 (Vargem Grande do Rio Pardo) has the lowest population, whereas municipality 8 (Belo Horizonte) has the highest. Similarly, for type of enterprise, the value ranges from a farmer (1) to a large-scale, specialized SEASA Wholesale Food Market (9). A lower value for local suppliers (1) indicates a local supply chain, whereas a higher value (4) signifies a more complex, broader network. For sale method, a value of 1 represents wholesale, while 2 represents retail, and 3 represents a combination of both, which can be seen as more versatile. Finally, the scale of sale variable reflects an increasing market reach, from municipal (1) to international (5). This ordinal arrangement ensures that the numerical representation of each variable corresponds to a meaningful, progressive scale, allowing the clustering algorithm to effectively group traders with similar profiles. The descriptive statistics by cluster of the variables used are presented in supplementary material (table S1).

3.3.2. By product

An exploration analysis was conducted to characterize the commercialization patterns of NTFPs across the three market segments identified through K-means clustering. The focus was on highlighting structural differences between merchant groups, considering product and species diversity, as well as economic aspects.

Each cluster was evaluated in terms of the total number of marketed products, the number of distinct product types and native species, and the total income generated. The analysis also included the average number of products and species commercialized per merchant, as well as the identification of items exclusive to each cluster. Products present in more than one cluster were explored using the average price and total quantity sold. These comparisons provided insights into both the breadth and specificity of commercialization strategies within each group.

Price and quantity data were standardized into comparable units within each product type to ensure consistency across observations. In cases where sales volume data were unavailable, production quantity was used as a proxy, provided that no sales data existed. A total of five products were excluded from the analysis because they lacked both production and marketing volume data. These procedures enabled consistent comparisons while maintaining the integrity and coverage of the sample.

By examining the internal composition of each cluster, this methodological approach facilitated a clearer understanding of how commercialization strategies vary among merchant groups, particularly in terms of economic scale, product diversification, and dependence on specific species. All analysis was conducted in R software version 4.4.1.

4. Results

4.1. Clustering of Cerrado NTFP Markets

Overall, clustering analysis identified three distinct Cerrado NTFP market segments based on the traders included in the study. The two principal dimensions (called “Dim1” and “Dim2”), which together explain approximately 65.5% of the total variation in the dataset, The medium-scale market segment (formerly Cluster 2) included the highest number of observations (19), while the small-scale (Cluster 1) and large-scale (Cluster 3) segments each comprise 15 observations (figure 2 – B). The small- and medium-scale segments are relatively close and exhibit some overlap. In contrast, the large-scale segments appears more distinct, particularly along Dim1 (figure 2 – A).

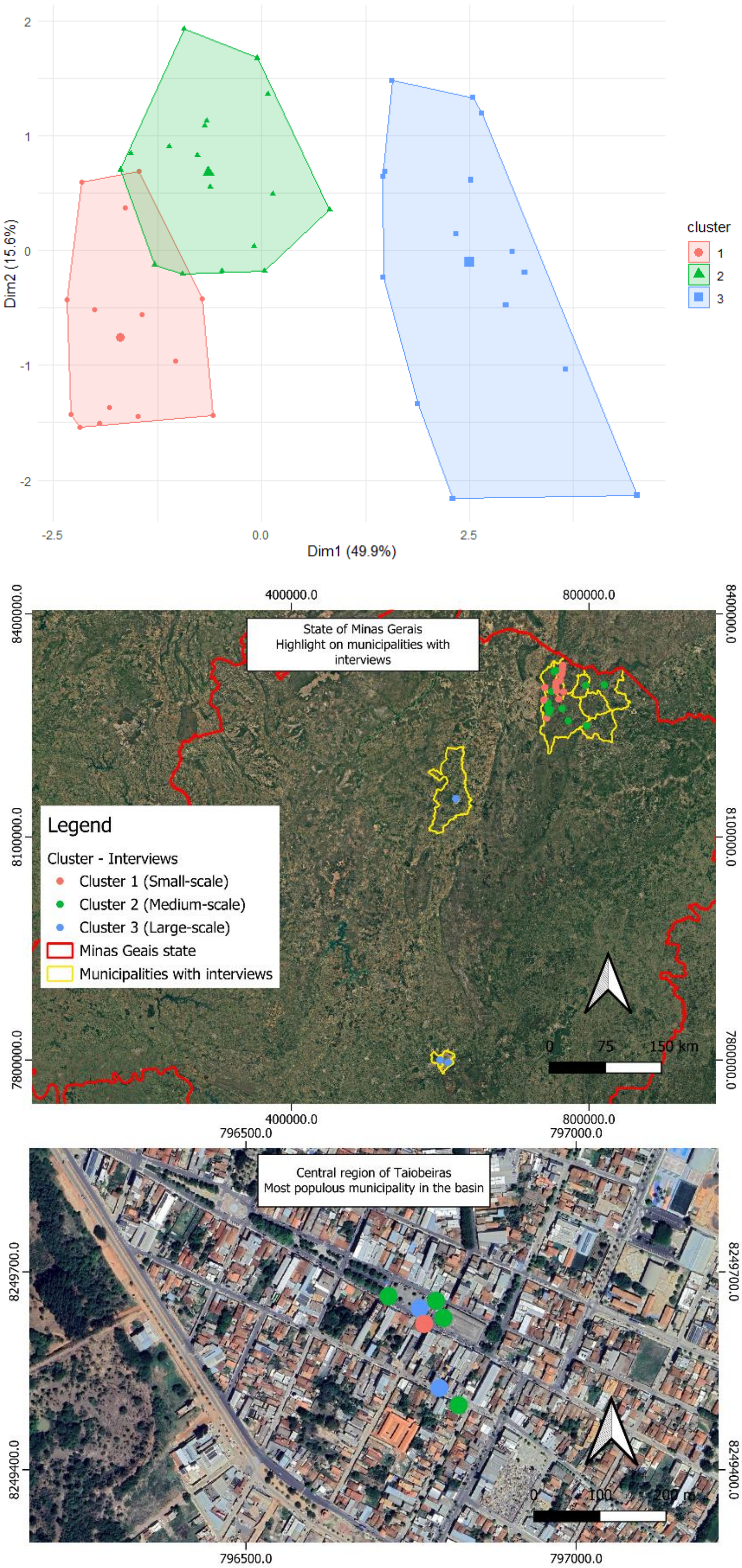

Figure 2. A – Cluster separation of NTFP traders in the Cerrado based on the two main dimensions identified through K-means classification. Each point represents one trader, grouped into three clusters (1 = small-scale traders, 2 = medium-scale traders, 3 = large-scale traders). The axes correspond to the two most relevant dimensions from the clustering analysis. **B** – Map of the state of Minas Gerais showing the municipalities where interviews were

conducted according to the cluster classification. **C** – Map of the urban center of Taiobeiras highlighting the presence of the three clusters within the study area.
Source: Elaborated by the authors.

Dim1 had four variables with a contribution above the average: type of enterprise, location of suppliers, municipality, and scale of sale (figure 3 – A). Dim2, which has a lower contribution to clustering, has two main variables, the sales method and the percentage of processed products (figure 3 – B). Of the 7 variables included in the analysis, only the number of products did not have a high representation in the dimensionalities represented in the figure.

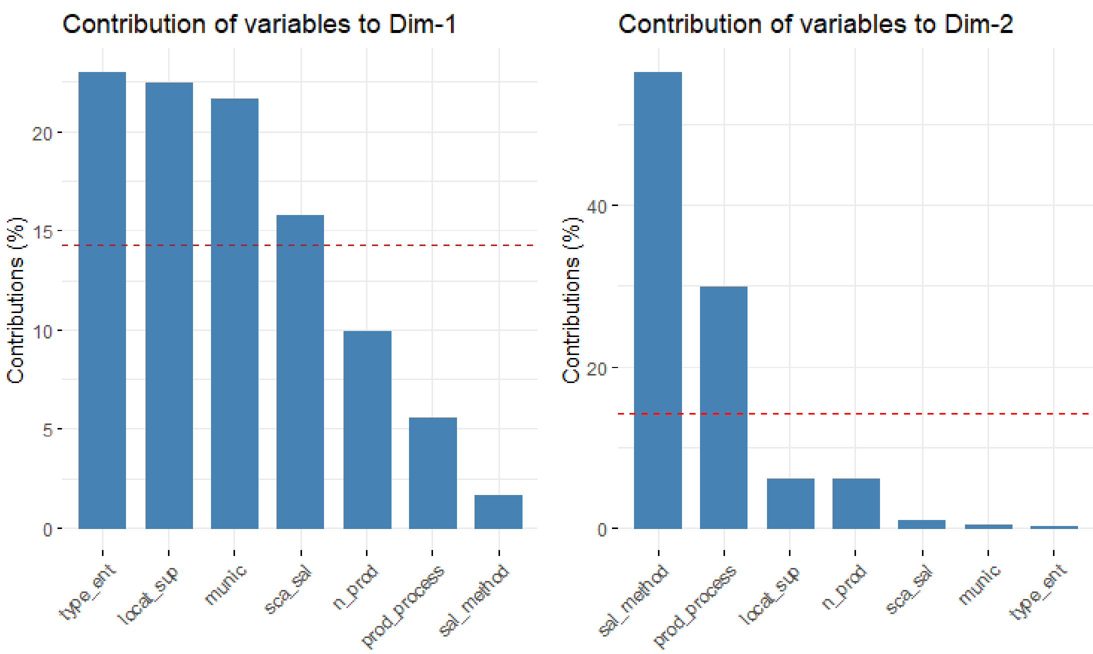

Figure 3. A – Contribution of the variables to dimension 1; **B** – Contribution of the variables to dimension 2. The dashed line represents the expected average value of the contribution for all the variables. Where: munic - municipality where the products are sold; type_ent - type of enterprise; locat_sup - location of product suppliers; sal_method- method in which the sale is made; sca_sal - Scale of sale of the enterprise; n_prod - number of products sold from Cerrado NTFP; prod_process - percentage of processed NTFP.
Source: Elaborated by the authors and generated by R software.

The small-scale market segment (cluster 1) exhibited negative values for all variables, particularly the percentage of products processed, the municipality, the sales method, and the type of enterprise, which included only farmers and street markets (figure 4). Therefore, this segment had a lower rate of processed products, underdeveloped sales methods, and is primarily found in less populated municipalities.

The medium-scale (cluster 2) market segment also presents several variables with negative scores, although generally of lower magnitude compared to those observed in the small-scale segment. Within the medium-scale segment, only two variables displayed positive scores: the percentage of processed products and the sales method (figure 4). Notably, the percentage of processed products in this segment even surpassed the corresponding value found in the large-scale segment (cluster 3). Among the negatively weighted variables, the scale of sales, the location of the suppliers, and the type of enterprise exert the greatest impact on this segment. Although this segment still shows a limited diversity of enterprise types, it includes new categories such as street vendors, municipal markets, and beverage distributors, in addition to farmers and street markets already present in small-scale market.

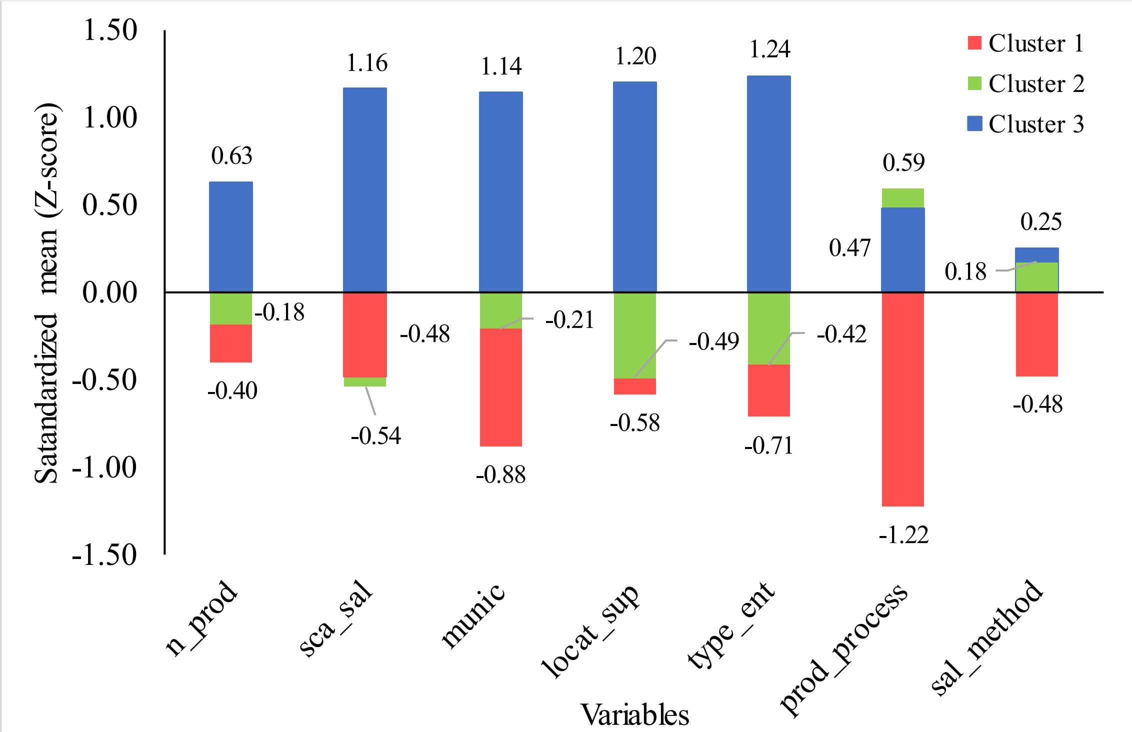

Figure 4. Importance of the variables in each cluster using the average value of the centroids (Z-score). Where: munic - municipality where the products are sold; type_ent - type of enterprise; locat_sup - location of product suppliers; sal_method- method in which the sale is made; sca_sal - Scale of sale of the enterprise; n_prod - number of products sold from Cerrado NTFP; prod_process - percentage of processed NTFP.
Source: Elaborated by the authors.

The large-scale market segment had positive centroid scores across all classes, with notable contributions from the type of enterprise, location of suppliers, municipality and scale of sale. This segment included all the traders outside the study region, as well as two enterprises based in the region's main urban center, Taiobeiras (figure 2 – C). These two local traders are characterized by being more developed enterprises (natural products store and agroindustry), with exclusively processed products and a larger scale of sales, even though they are within the study region.

The exploration analysis revealed clear distinctions among the three identified market clusters in terms of diversity and economic scale (table 3). The small-scale cluster showed the lowest figures across all variables, with only 10 distinct products, with 8 native species marketed, and 3 exclusive ones, generating a modest US$4,585.50 in total income by year. In contrast, the large-scale cluster exhibited the highest commercialization density, with 30 distinct products, 12 species, including 7 exclusive ones, and a total income exceeding US$570,000.00. This cluster also had the highest average number of products and species per trader (3.3 and 1.9, respectively), indicating broader market integration. The medium-scale cluster presented intermediate values, with 15 distinct products, 9 species, 5 exclusive ones, and an income of approximately US$21,280.20.

Table 3. Summary of product, species, and income characteristics across NTFP market clusters in the Cerrado

Cluster	Total products	Distint Products	Total species	Exclusive species	Annual Amount (US$)	Average number of products per trader	Average number of species per trader
1	21	10	8	3	4,585.50	1.5	1.3
2	33	15	9	5	21,280.20	1.8	1.4
3	47	30	12	7	570,383.10	3.3	1.9

Source: Elaborated by the authors.

4.2. Products

Out of the 43 NTFP products with recorded economic value, derived from 20 native Cerrado species, only 7 were commercialized in more than one market cluster (table S2). These overlapping products provide an opportunity to compare market behavior in terms of price formation and commercialization across distinct market environments (figures 5, 6, and 7).

The comparison of average prices reveals that, although there is a general trend of higher prices in large-scale markets, typically representing more structured and urbanized markets, this pattern does not hold for all products. For instance, Coquinho-azedo (raw) and Amburana seed exhibited higher average prices in the small- and medium-scale, respectively, compared to the large-scale (figure 5). This suggests that certain niche markets, often found in less developed regions, may offer favorable pricing for specific products.

The analysis of annual commercialization volume further reinforces the strategic role of Pequi (raw), which dominated the large-scale market segment with a substantially higher volume compared to other segments. Other products, such as Pequi oil and Coquinho-azedo (pulp), also showed larger sales volumes in the large-scale, confirming that more consolidated markets have greater absorption capacity and stronger consumer demand for certain Cerrado NTFPs (figure 6).

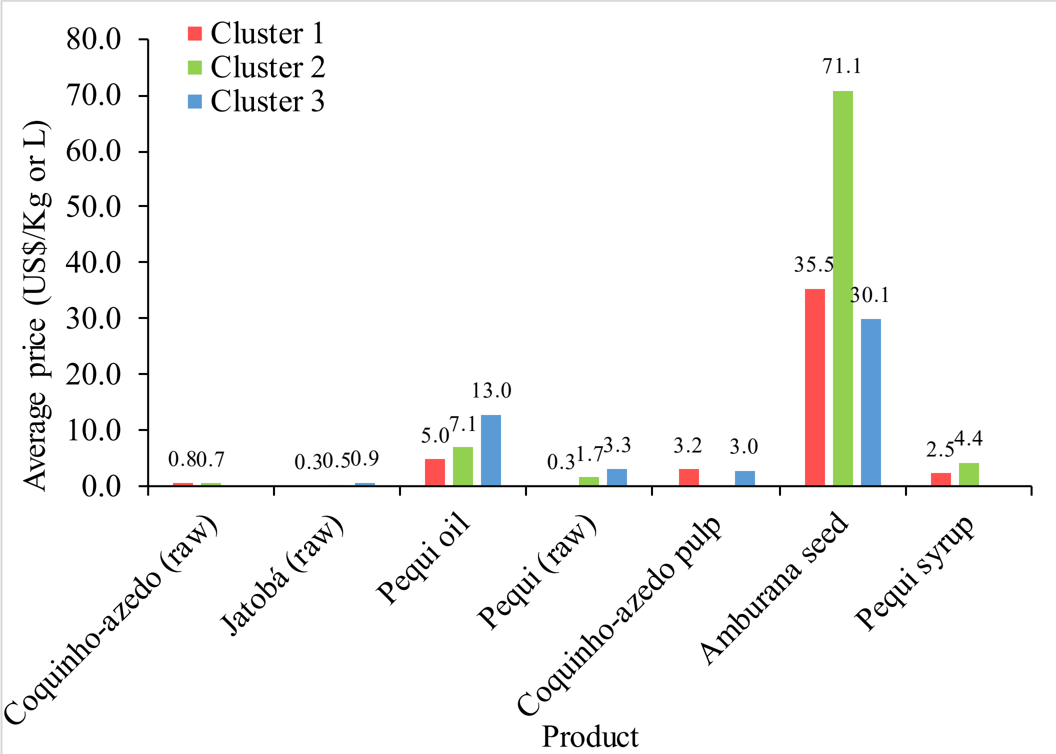

Figure 5. Average price (USD/Kg or L) of selected NTFP commercialized in the three identified market clusters. Only products present in more than one cluster are shown.
Source: Elaborated by the authors.

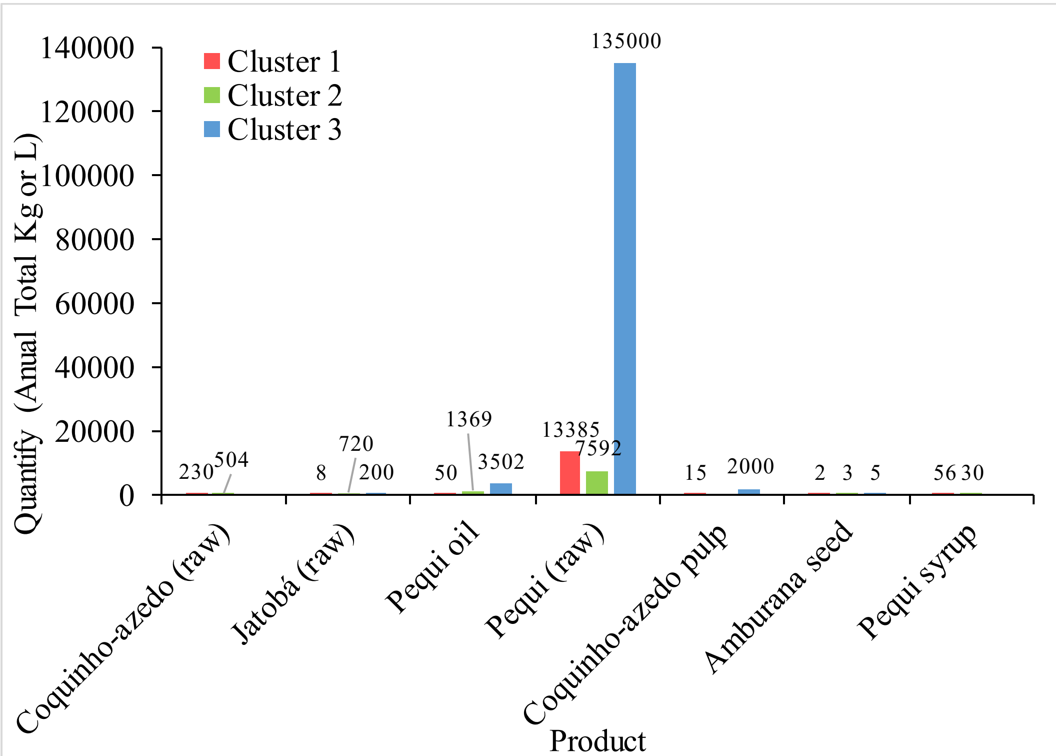

Figure 6. Annual commercialization volume of selected NTFP by market cluster. Data refers to total annual quantities aggregated (Kg or L) by product for each cluster.
Source: Elaborated by the authors.

Pequi dominates the financial volume in all clusters, but with different proportions. In the large-scale market segment, accounting for over 90% of the total commercial value, highlighting its central role in consolidated urban markets of the Cerrado. In contrast, the small-scale market segment displays a more balanced composition, where Pequi represents 41.5% of the revenue, followed by contributions from Sucupira (13.7%), Other species (38.8%), and minor shares from Coquinho-azedo and Amburana. The medium-scale market segment reflects a transitional market, with Pequi responsible for nearly 75% of the value, while other species, including other species (21.5%) and Jatobá (1.7%), also contributing to the total (figure 7).

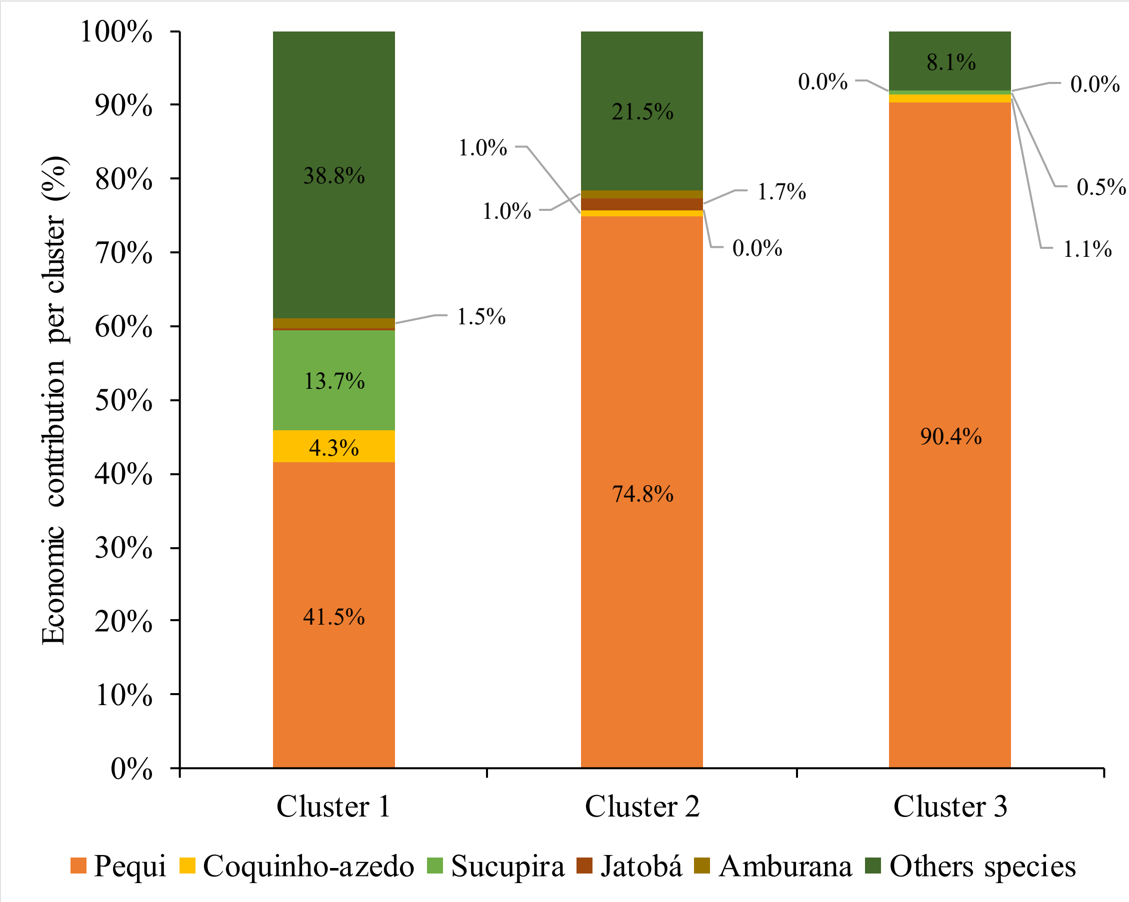

Figure 7. Relative economic contribution (%) of Cerrado native NTFP species across the three market clusters. The percentages represent each species' share of the total revenue generated in each cluster. "Other species" aggregates all remaining species not listed individually.
Source: Elaborated by the authors.

In addition to their economic significance, Pequi and Sucupira stand out for their diversified product offerings. Pequi alone is associated with 14 distinct product types identified across the clusters, ranging from raw fruit and pulp to oil and syrup, whereas Sucupira contributes with 4 processed products (table S2). This level of diversification indicates not only strong market acceptance but also a higher potential for additional value.

5. Discussion

The diversity of Cerrado NTFP, in both species and product types, reveals a wide and complex commercialization in northern Minas Gerais. Classifying these markets into distinct segments (clusters) offers strategic insights that can support farmers integrating native species into SPS on the market (de Mello et al., 2023; Huber et al., 2023; Ribeiro et al., 2020). Understanding each market segment enables farmers to align species and products from their farms with the most suitable and established markets, minimizing the need for significant financial investments or drastic land-use changes, an essential factor in strengthening the NTFP market (Mahonya et al., 2019; Masoodi and Sundriyal, 2020).

The clustering analysis indicates that the number of products is the least influential variable in defining market types. Instead, characteristics such as enterprise type, supply location, and scale of sales exert the greatest influence (figure 2). This suggests that access to more structured and profitable NTFP markets may rely less on product diversity and more on business structure and strategic positioning (Dinda et al., 2020; Huber et al., 2023). Within this context, processed products demonstrate greater adaptability in larger markets. Processing enables the generation of multiple products from the same species, often extending shelf life and increasing added value, factors that facilitate the expansion and consolidation of NTFP markets (Malazogu and Bottari, 2022; Meinhold and Darr, 2019).

At the small-scale segment, traders operate directly on the farm or at street markets in less populated municipalities (table S1). Limited demand restricts the scale of commercialization and significantly reduces expected economic returns in the local market (Ojha, 2024; Rosenfeld et al., 2024). The use of NTFP for local subsistence often determines the products available for sale, with only surplus production reaching the market (Mahonya et al., 2019; Mondo et al., 2024). The low presence of processed products reflects structural constraints in diversifying production and sustaining sales throughout the year, hindering the sustainable development of this market segment (Mondo et al., 2024; Nabaloum et al., 2025). Furthermore, the scarcity of more established or better-connected traders limits access to broader markets, leaving producers in smaller towns dependent on intermediaries to reach more profitable distribution channels. This limitation, however, can also act as a catalyst for forming cooperatives or other collective arrangements that strengthen bargaining power and improve returns (Antunes et al., 2021; Bartkus et al., 2021; Nghonda et al., 2023).

The medium-scale market segment represents an intermediate stage in the development of the NTFP market, characterized by farms and more established enterprises located in more populous towns, and by a higher proportion of processed products. While it remains below the large-scale segment in terms of market reach and enterprise sophistication, it serves as an entry point for local NTFP producers seeking markets for value-added products, as it is accessible to those already working with processed goods in the region (Magry et al., 2022; Meinhold and Darr, 2019). Although it offers better opportunities than the small-scale segment, limitations in business formalization and market scale may constrain price formation and long-term profitability (Antunes et al., 2021; Hazari et al., 2023; Tugume et al., 2019). Both the medium- and small-scale markets are accessible to regional farmers, either directly or through intermediaries, which function as intermediate stages in the value chain, potentially influencing transaction costs and bargaining power (Cole and Aitken, 2020).

The large-scale market segment is composed of more structured enterprises, often operating outside the study region, in the more urbanized areas of the Cerrado (table S1). This pattern indicates a strong link between business development, processing capacity, and access to broader markets, where a greater diversity of products is available and actively marketed (Nghonda et al., 2023; Okunlola et al., 2023). The inclusion of suppliers from multiple regions reflects these enterprises' integration into extensive commercialization networks, facilitated by the wide distribution and versatility of NTFPs in the Brazilian Cerrado (de Mello et al., 2023; Walverde et al., 2021). Their presence in large urban centers allows them to serve diverse market niches, fostering greater profitability and product diversification, particularly through processed items with extended shelf life (Darr et al., 2020; Okunlola et al., 2023; Shackleton and de Vos, 2022).

Although traders in the large-scale market segment are predominantly urban and external to the basin, their presence in Taiobeiras suggests opportunities for local integration (figure 2 – C). These businesses could serve as strategic links for regional farmers, providing support in navigating complex value chains within the region (Hazari et al., 2023; Meinhold and Darr, 2019). Strengthening processing cooperatives and offering training in value-added production may facilitate access to these markets, support SPS adoption, and foster the regional development of NTFP markets (Christian et al., 2024; de Alcântara et al., 2022; Peerzada et al., 2021).

The diversity of products sold and the presence of exclusive items across all market segments highlight the versatility and adaptability of the Cerrado NTFP market (table S2). Even in smaller markets, the presence of exclusive products and species indicates niche opportunities driven by specific consumer preferences and local ecological availability. This also underscores the potential for SPS adopters to manage a broader range of native species, although species and product diversity do not appear to influence access to different market segments (Hazari et al., 2023; Okunlola et al., 2023). Other markets not covered in this study, such as international markets, are also accessible to NTFP producers; however, accessing these markets often requires greater support in bureaucratic matters, which particularly limits small- and medium-sized farms (Martins and Teixeira, 2024).

The substantial economic differences among market segments appear closely linked to their scale of commercialization and degree of integration with other value chain actors, particularly in the medium- and large-scale segments. As more intermediaries become involved, a larger portion of the final price is distributed along the chain, which can raise the final market price but also adds complexity to coordination and governance (Nguyen et al., 2020; Souare et al., 2020). Although this structure can be more profitable, it requires greater management capacity from both producers and intermediaries, who can mutually benefit from effective collaboration (Cole and Aitken, 2020; de Alcântara et al., 2022).

The commercialization of 43 NTFP products from 20 native Cerrado species underscores the biome's significant economic potential to support diversified rural incomes. Of these 20 Cerrado species, only four are included in the PEVS survey (Pequi, Buriti, Babaçu, and Licuri), highlighting the underestimation of both the economic value and the diversity of products captured by IBGE in Brazil (IBGE, 2024a). Prior studies emphasize that such diversity can serve as an important source of supplementary income for smallholders and SPS adopters in the region (Berte et al., 2023; Orioli et al., 2025). The traditional knowledge held by Cerrado communities contributes to the conservation of NTFP species, as these plants remain useful for family subsistence and are actively maintained on farms (de Mello et al., 2023; Lima et al., 2017). Moreover, there is a gap between the popular uses of Cerrado species and their representation in scientific literature, with many potential new products, particularly processed NTFPs, yet to be developed for the market, which could increase both the value and appeal of Cerrado NTFP (Briceno et al., 2024; Guedes et al., 2017; Santos et al., 2020).

The fact that only seven products (Pequi raw, oil, and syrup; Coquinho-azedo raw and pulp; Amburana seed, Sucupira raw) are traded across more than one market cluster suggests differentiated demand patterns and market segmentation. These overlapping products likely represent those with broader consumer acceptance, supply availability, or existing processing and distribution infrastructure, making them strategic targets for promotion and scaling among SPS initiatives (Miranda-Gamboa et al., 2024; Walverde et al., 2021). Leveraging the empirical knowledge of collection, production, and diversification of NTFPs accumulated by agroextractivists in the Cerrado can enhance their capacity to penetrate broader markets and achieve larger commercialization scales (Diniz et al., 2021; Guéneau et al., 2020).

While prices are generally expected to be higher in more developed markets, such as those in large-scale market segments, some products achieve better unit prices in smaller, less structured markets. This is the case for Coquinho-azedo (raw and pulp) and Amburana seeds, whose higher prices in small- medium-scale segments reflect distinct market dynamics. Amburana seeds, for instance, are traditionally valued for their medicinal properties but now face declining demand, particularly in urban centers where pharmaceutical alternatives increasingly replace traditional remedies (Arjona-García et al., 2021; Ntakirutimana, 2025). Their higher prices in less urbanized areas likely reflect localized cultural value and scarcity, rather than broader market demand (Pereira and Da Silva, 2025; Silva et al., 2020b). Despite limited current use, Amburana still holds potential for integration into biopharmaceutical production chains, which a local SPS farmer could strategically explore (Bandopadhyay & Palit, 2024; Silva et al., 2020b).

Similarly, Coquinho-azedo has strong regional culinary importance in northern Minas Gerais, but it is less known outside this area, which contributes to its reduced market value in the large-scale market (Faria et al., 2008; Guéneau et al., 2020). Nevertheless, the species shows the highest commercialization volumes in that cluster, exclusive in Montes Claros, the largest urban center in the region, and a gateway for expanding Cerrado NTFPs to broader markets (França et al., 2024).

These examples highlight how localized, or niche markets, can offer attractive returns for specific products. For SPS adopters, this implies that successful commercialization strategies may not rely exclusively on integration with large urban centers but also on leveraging local demand, cultural relevance, and regional product identity (Faria et al., 2008; Lima et al., 2022, 2017).

The analysis of sales volume across clusters highlights the dominant role of Pequi (raw) in the large-scale, which exhibits substantially higher volumes compared to other market segments (figure 6). This cluster's association with more populous urban centers translates into stronger consumer demand, especially for high-profile species such as Pequi, currently the primary Cerrado NTFP in terms of market significance (Froes et al., 2021; Guéneau et al., 2020; Shackleton and de Vos, 2022). Pequi's rising prominence in Brazilian cuisine is driven by its distinctive flavor, nutritional benefits, and versatility in producing a wide range of derivative products, such as oil, nuts, and processed foods (Briceno et al., 2024; Guéneau et al., 2020; Lopes et al., 2024).

This commercial potential is capitalized by traders, as evidenced by Pequi's market diversity, 14 distinct products, including liqueurs, syrups, sweets, creams, farofa, and honey, underscoring its socioeconomic importance and capacity for product diversification (Guedes et al., 2017; Guéneau et al., 2020; Pinto et al., 2016). Minas Gerais, the leading producer state for Pequi extractives, plays a central role in this dynamic, with harvests spanning multiple regions, including the study area. Consequently, SPS adopters in this region are well positioned to enhance value addition through processed Pequi products (Berte et al., 2023; IBGE, 2024b; Silva et al., 2020c).

In terms of economic contribution, Pequi outperforms other species across clusters, particularly in medium- and large-scale markets, which exhibit the highest market demand. Its dominant share of commercial value on large-scale (over 90%) and significant presence in small- and medium-scale further solidify its status as the Cerrado's flagship NTFP, with extensive research corroborating its recognized economic returns and expanding production at the national level (IBGE, 2024a; Pinto et al., 2019; Silva et al., 2020a).

Meanwhile, the more balanced species composition observed in small-scale (table 3) reflects the broader potential of native Cerrado species in the study region. This diversity presents an opportunity for SPS adopters to explore complementary species alongside Pequi, potentially enhancing income diversification and ecological resilience of their farm (Mahonya et al., 2019; Masoodi and Sundriyal, 2020).

Among the relevant species in the small-scale segment market, Coquinho-azedo stands out as a rising product in regional markets, as previously discussed. Another notable species is Sucupira, which exhibits high product diversification (four identified products) and significant commercial relevance. Its traditional use, grounded in popular knowledge, emphasizes its medicinal potential, particularly for anti-inflammatory and analgesic purposes (Batalini et al., 2020; Hoscheid and Cardoso, 2015). Market-available products include seeds, capsules, extracts, and oils, reflecting a shift from traditional to more industrialized and higher-value applications. This trend is supported by scientific evidence confirming the pharmacological properties of the species (Batalini et al., 2020; Hansen et al., 2010), suggesting its growing role in the commercialization of medicinal NTFPs.

This study advances the understanding of the structure and diversity of the NTFP market in northern Minas Gerais, highlighting both its complexity and economic potential. By identifying distinct trader profiles and commercialization strategies, it offers a more nuanced view of how NTFPs are positioned within local and regional markets. Nonetheless, key challenges persist, particularly the lack of systematized data, the informal nature of many commercial arrangements, and the limited visibility of certain value chains and products. A key limitation is the non-probabilistic nature of the sample. Given the informal and unquantified universe of NTFP traders, a probabilistic sampling design was unfeasible. However, the purposive sampling strategy was effective in capturing a significant diversity of actors (49), products (46), and native species (22). Therefore, while the findings cannot be statistically generalized to the entire Cerrado biome, they provide a robust and unprecedented characterization of the market structures operating within the northern Minas Gerais region. The identification of these small-, medium-, and large-scale market segments is of great practical importance, as it offers a clear map of existing commercial channels that can be used to improve market access for local SPS adopters and guide policies for regional value chain development. Future studies should prioritize mapping value chains, analyzing consumer markets across regions, and identifying institutional mechanisms to formalize and scale commercialization. In addition, research on the integration of NTFPs into native-tree-based silvopastoral systems, through technical support, cooperative organization, and targeted incentives, can enhance the economic resilience and environmental sustainability of Cerrado farming systems. Future work should also examine the potential benefits and constraints for farmers themselves, depending on the type of market accessed, to better understand how different market strategies may influence rural livelihoods, economic returns and decision-making.

6. Conclusions

The commercialization of NTFP in northern Minas Gerais reveals a heterogeneous and dynamic market, structured around distinct trader profiles that vary in formality, specialization, and territorial reach. The study identified three clear trader segments, each characterized by specific marketing strategies, market access, and levels of integration into broader value chains. While local traders typically operate on a small scale with a limited product range, external traders and those based in urban centers demonstrate greater sophistication, product standardization, and connections to more stable, higher-value markets.

A key finding is the coexistence of differentiated markets within the study region and the presence of unique products circulating in each. The diversity of products and native species across these niches indicates a promising yet incipient market context, largely due to the limited number of products shared across all clusters. This duality highlights both the ecological richness and sustainable use potential of the region, as well as persistent challenges related to scale, logistics, institutional support, and market visibility, especially for products not widely recognized beyond their local markets.

By mapping market structures and exposing asymmetries among trader types and marketing environments, this research deepens the understanding of how NTFPs integrate into local and regional economies. These insights are valuable for shaping public policies aimed at promoting sustainable use of native species within the Cerrado, identifying key or emerging species, and improving market access for producers adopting silvopastoral systems with native trees. Strengthening direct access for farmers to small- and medium-scale markets, while facilitating indirect access to large-scale markets through the established presence of major traders in the region or cooperatives, could bridge current market gaps and enhance producer participation across different scales. Future initiatives that combine technical assistance, infrastructure development, and cooperative arrangements could be crucial to unlocking the full economic and ecological potential of this sociobiodiversity sector.

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Declaration of generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the author(s) used ChatGPT (version GPT-4.5) to translate, review the text, search for synonyms and improve the fluidity of writing. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

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Supplementary Materials

Table S1. Descriptive statistics by cluster of variables used for clustering of traders

Variables	Mean			SD			Min			Max		
	Cluster 1	Cluster 2	Cluster 3	Cluster 1	Cluster 2	Cluster 3	Cluster 1	Cluster 2	Cluster 3	Cluster 1	Cluster 2	Cluster 3
Municipality where the products are sold (munic)	3.33	4.68	7.40	1.45	1.25	0.74	2	1	6	6	6	8
Type of enterprise (type_ent)	1.27	2.05	6.47	0.70	1.27	2.13	1	1	2	3	5	9
Location of product suppliers (locat_sup)	1.07	1.16	2.80	0.26	0.50	0.86	1	1	1	2	3	4
Method in which the sale is made (sal_method)	1.73	2.21	2.27	0.80	0.63	0.70	1	1	1	3	3	3
Scale of sale of the enterprise (sca_sal)	1.60	1.53	3.53	0.63	0.51	1.06	1	1	2	3	2	5
Number of products sold from Cerrado NTFP (n_prod)	1.47	1.84	3.27	1.30	1.12	2.28	1	1	1	6	4	8
Percentage of processed NTFP (prod_process)	0.03	0.83	0.78	0.13	0.26	0.33	0	0.25	0	0.5	1	1

Source: Elaborated by the authors.

Table S2. Distinct species and products present in the 3 identified clusters

Species / Product	**C1**	**C2**	**C3**	**Total**
Pequi (*Caryocar brasiliense* Cambess.)	**1**	**1**	**1**	**3**
Raw pequi	1	1	1	3
Pequi oil	1	1	1	3
Pequi syrup	0	1	1	2
Pequi nut	0	1	0	1
Pequi cream	0	0	1	1
Pequi candy bar	0	0	1	1
Pequi paste candy	0	0	1	1
Pequi farofa	0	0	1	1
Preserved pequi slices	0	0	1	1
Pequi liqueur	0	0	1	1
Pequi flower honey	0	0	1	1
Whole preserved Pequi	0	0	1	1
Pequi pulp	0	0	1	1
Preserved Pequi pulp	0	0	1	1
Coquinho-azedo (*Butia capitata* (Mart.) Becc.)	1	1	1	3
Coquinho-azedo raw	1	1	1	3
Coquinho-azedo pulp	1	0	1	2
Jatobá (*Hymenaea* sp. L.)	1	1	1	3
Jatoba raw	1	1	1	3
Jatoba flour	0	1	0	1
Amburana (*Amburana cearensis* (Allemão) A.C.Sm.)	1	1	1	3
Amburana seed	1	1	1	3
Sucupira (*Bowdichia* sp. Kunth)	1	0	1	2
Sucupira seed	1	0	1	2
Sucupira capsule	0	0	1	1
Sucupira extract	0	0	1	1
Sucupira oil	0	0	1	1
Licuri (*Syagrus coronata* (Mart.) Becc.)	0	1	0	1
Licuri mat	0	1	0	1
Licuri broom	0	1	0	1
Licuri nut	0	1	0	1
Cipó-catitu (*Heteropterys trichanthera* A.Juss.)	0	1	0	1
Cipó-catitu basket	0	1	0	1
Cipó-catitu hamper	0	1	0	1
Baru (*Dipteryx alata* Vogel)	0	0	1	1
Baru nut	0	0	1	1
Shelled baru nut	0	0	1	1
Maracujá-do-cerrado (*Passiflora* sp. L.)	0	0	1	1
Raw cerrado passion fruit	0	0	1	1
Cerrado passion fruit pulp	0	0	1	1

Species / Product	**C1**	**C2**	**C3**	**Total**
Buriti (*Mauritia flexuosa* L.f.)	0	0	1	1
Raw Buriti	0	0	1	1
Buriti straw	0	0	1	1
Candomba (*Vellozia* sp. Vand.)	1	0	0	1
Candomba stem	1	0	0	1
Manderoba (*Carapa guianensis* Aubl.)	1	0	0	1
Manderoba seed	1	0	0	1
Fel da Terra (*Homalolepis ferruginea* (A.St.-Hil.) Devecchi & Pirani)	1	0	0	1
Fel da terra root	1	0	0	1
Batata-de-purga (*Operculina macrocarpa* (L.) Urb.)	1	0	0	1
Raw batata-de-purga	1	0	0	1
Babaçu (*Attalea speciosa* Mart. ex Spreng.)	0	1	0	1
Babaçu oil	0	1	0	1
Rufão (*Tontelea micrantha* (Mart.) A.C. Sm.)	0	1	0	1
Rufão oil	0	1	0	1
Coco-Babão (*Syagrus comosa* (Mart.) Mart.)	0	1	0	1
Coco-babão broom	0	1	0	1
Mamoninha (*Ricinus* sp. L.)	0	1	0	1
Mamoninha oil	0	1	0	1
Araticum (*Annona crassiflora* Mart.)	0	0	1	1
Raw Araticum	0	0	1	1
Mangaba (*Hancornia speciosa* Gomes)	0	0	1	1
Mangaba mil	0	0	1	1
Macaúba (*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.)	0	0	1	1
Macaúba coconut	0	0	1	1
Gravatá (*Bromelia* sp. L.)	0	0	1	1
Raw Gravatá	0	0	1	1

Source: Elaborated by the authors.

GENERAL CONCLUSION

This thesis combines three complementary studies to provide a comprehensive understanding of silvopastoral systems (SPS) featuring native trees in northern Minas Gerais. Taken as a whole, the findings reveal that SPS are widely adopted and historically rooted, yet they remain characterized by low management intensity and limited profitability when compared with other land uses. The analyses also show that adoption and intensification are influenced by distinct sets of factors, underscoring the need for public policies that go beyond simply promoting adoption and instead address the structural and market barriers that hinder system improvement. Integrating non-timber forest products (NTFPs) and identifying the most appropriate market niches emerge as key strategies to enhance SPS performance, linking biodiversity conservation with income generation. Together, these insights suggest that SPS can evolve from subsistence-oriented land use toward a more diversified and market-connected production model, provided that policy support, training, and complementary activities, such as ecosystem service provision, are effectively implemented. By connecting economic performance, adoption dynamics, and market opportunities, this thesis highlights practical pathways to make SPS more integrated, productive, and profitable for farming families while reinforcing their role as a sustainable land-use model in the Cerrado.