Synthesis of Economic Results of **Integrated Crop-Livestock-Forest Systems** in Brazilian Amazon and Cerrado biomes

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Synthesis of Economic Results of Integrated Crop-Livestock-Forest Systems in Brazilian Amazon and Cerrado biomes/ Julio Cesar dos Reis ...... [et al]. - Brasília - DF, Brazil: Embrapa Cerrados, 2025.

Technical Report: World Bank and Embrapa (Embrapa Cerrados, Embrapa Acre, Embrapa Agrossilvipastoril and Embrapa Gado de Corte), 112 p., 2025

1. Integrated Crop-Livestock-Forest Systems. 2. Agroforest Systems. 3 Economic Viability. 4. Public Policies. 5. Amazon. 6. Cerrado.

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This document is part of the Project “Synthesis of Economic Results of Integrated Crop-Livestock-Forest Systems in Brazilian Amazon and Cerrado biomes” nº 7211294, funding by World Bank, and was elaborated by Embrapa's Research Group.

Photos: Gabriel Faria, Journalist, Embrapa Agrossilvipastoril; Ronaldo Rosa technician, Embrapa Amazônia Oriental, Breno Rodrigues Lobato, Journalist, Embrapa Cerrados, Ana Maria Dantas de Maio, Analyst, Embrapa Pecuária Sudeste; Priscila Viudes, Analyst, Embrapa Acre.

1. Executive Summary

The adoption of sustainable agricultural systems in the Brazilian Amazon and Cerrado biomes is globally relevant due to the massive production of staple commodities in this region, as well as to the crucially important ecosystem services provided at the global scale.

These systems represent a strategic opportunity to intensify resource uses, while reconciling increasing productivity, diversifying production and, consequently, sparing land for conservation and restoration. Additionally, these systems are an important strategy to enhance household food security and income and increase resilience to market and climate risks by improving soil quality and reducing greenhouse gas emissions.

Policy developments to increase the adoption of sustainable agricultural systems have been pursued in Brazil, as indicated in international commitments at the Conference of the Parties (COP) - 15, in the 'Sectoral Climate Change Mitigation and Adaptation Plan for the Consolidation of a Low Carbon Economy in Agriculture' (ABC Plan and ABC + Plan) and in the ratification of the Paris Agreement in 2015.

Notwithstanding their great potential, there is limited information regarding the economic performance as well as the factors restricting widespread adoption of sustainable agricultural systems in Brazil; neither is there a comprehensive and accessible database with this information. These are crucial for farmers and policy-makers to assess these systems as alternatives to large-scale monocropping or extensive livestock, the two most representative agricultural systems in the Brazilian agriculture-forest frontier in the Amazon and Cerrado Biomes.

To advance the understanding on this research agenda, we present comprehensive results from two case studies assessing the economic performance of integrated crop-livestock-forest systems (ICLF), one located in the Amazon biome and other for the Cerrado biome. We also compare the results of these systems with those observed for a large-scale cropping system (soybean-corn) and an extensive livestock system.

Additionally, we provide detailed economic performance information for four representative case studies of Agroforestry Systems in the Amazon biome. These case studies are based on the experiences conducted by the Agroforestry Economic Reforestation and Intensification Project (Projeto Reca) in the state of Rondônia and experiences from relevant agroforestry systems adoption in the municipality of Tomé-Açu, state of Pará.

Main Results

A - Economic Comparative Analysis

Integrated Crop-Livestock-Forest Systems

A **typical crop farm** is defined by an intensive and specialized production system with two crop seasons per year: soybean (*Glycine max*) (October–February) and corn (*Zea mays*) (February–June/July), 600 ha of cultivated land area, and an **initial investment of 1,078.89 USD.ha^{-1}**.

A **typical livestock farm** is characterized by traditional cattle ranches with a low level of technology, low productivity and a large area, of approximately 1,000 ha, dedicated to rearing and fattening. This production system displays the lowest **investment value of 369.51 USD.ha^{-1}**.

The **integrated crop-livestock-forest system for the Amazon biome (ICLF - A)** is located in the municipality of Nova Canaã do Norte, in the north region of Mato Grosso within the Amazon Legal region, a new frontier for large-scale crop system in the state traditionally used for livestock production. The ICLF - A system was implemented in 2008 as a strategy to recover degraded pasture. The cultivated land area was 1,000 ha, and the **initial investment was 430.52 USD.ha^{-1}**.

The **integrated crop-livestock-forest system for the Cerrado biome (ICLF - C)** is located in the municipality of Nova Xavantina in the northeast of Mato Grosso, a traditional livestock region. The system was established in 2010 as a strategy to reclaim degraded pastures, and the forest was cultivated by farmers for drying soybeans (*Glycine max*), as well as to use in livestock infrastructure such as fences, troughs and corrals, and for timber commercialization. The cultivated land area was 600 ha, and the **initial investment was 1,024.30 USD.ha^{-1}**.

Production Costs, Net Revenue and Gross Profit*+

	Net Revenue USD.ha^{-1}	Production Cost USD.ha^{-1}	Gross Profit USD.ha^{-1}
ICLF - C	1,131.46	766.59	364.87
ICLF - A	993.10	858.77	134.33
Livestock	584.32	419.38	164.94
Crop	933.13	594.80	338.33

* Average Yearly Economic Results
+2024 prices (1 USD = 5.22 BRL)

The results indicate that the integrated systems offer the most favorable economic performance in terms of both net revenue and gross profit. While the production costs for integrated systems are higher, their revenue generation is more substantial, leading to better profitability.

These findings support the supposition that diversified land use systems like integrated systems can be more economically sustainable in the long-term compared to large-scale crop system and extensive livestock system.

Economic viability indicators

Indicators	ICLF - C	ICLF - A	Crop	Livestock
*NPVA (USD. ha^{-1})	87,44	31,95	6,62	2,10
**IRR (%)	15,78	13,40	8,81	8,85
***ROI (%)	12,93	11,68	8,50	8,70
Profitability Index	1,36	1,32	1,03	1,02
Payback (years)	7	8	7	5

*Annual Net Present Value per hectare
**Internal Rate of Return
***Return on Investment

The analysis of financial indicators highlights the superior financial performance of integrated systems relative to other land use systems analyzed. The ICLF-C system provides the highest NPVA, IRR, ROI, and Profitability Index, suggesting that it is the most financially attractive among the four land use strategies considered.

Both the representative large-scale crop and extensive livestock systems show lower financial returns across all indicators, with the extensive livestock system particularly standing out for its faster payback period but lower overall profitability. This result is explained by its low investment level.

These findings underscore the potential for integrated systems to offer more sustainable and profitable financial returns compared to more specialized systems

- Agroforestry Economic Reforestation and Intensification Project (Projeto Reca)

BR SAF RO 01: the perennial species consist of **cupuaçu** (*Theobroma grandiflorum* Schum.), **pupunha** (*Bactris gasipaes* Kunth) (for seed production), and **castanheira** “Brazil nut tree” (*Bertholletia excelsa* Humb. & Bonpl.). To ensure revenue generation in the initial years, the following temporary crops were cultivated: maize (*Zea mays*), rice (*Oryza sativa*), cassava (*Manihot esculenta Crantz*), and beans (*Phaseolus vulgaris*).

BR SAF RO 02: The perennial forest components include **cupuaçu** (*Theobroma grandiflorum* Schum.), **pupunha** (*Bactris gasipaes* Kunth) (for seed production), **copaiba** (*Copaifera* sp.), and **andiroba** (*Carapa guianensis*). Temporary crops cultivated comprised pupunha for heart-of-palm production and banana (*Musa spp*.).

- Tomé-Açu (PA) (Projeto Tipitamba)

The **AF 3** comprises the following species: 1,500 **black pepper** plants (*Piper Nigrum* L.), 188 **cupuaçu** trees (*Theobroma grandiflorum* Schum.), 45 **açaí palm** trees (*Euterpe oleracea* Mart.), 360 **paricá** trees (*Schizolobium amazonicum* Huber ex Ducke), and 15 **andiroba** trees (*Carapa guianensis*. Also, as part of systems’ forest reforestation was inclued **Brazil nut** (*Bertholletia excelsa* Humb. & Bonpl.), **copaiba** (*Copaifera* sp.), **cedar** (*Cedrela fissilis* Vell.), **uxi** (*Endopleura uchi* (Huber) Cuatrec.), **sapucaia** (*Lecythis pisonis* Cambess.), and **piquiá** (*Caryocar villosum* (Aubl.) Pers.).

For **AF 4,** the following species were adopted: **rice** (*Oryza sativa* L.), introduced at the beginning of the project, 2500 **black pepper** plants (*Piper Nigrum* L.), 625 **cocoa** trees (*Theobroma cacao* L.), 400 **açaí palm** trees (*Euterpe oleracea* Mart.), 400 **banana** plants (*Musa* spp.), 40 **mahogany** trees (*Swietenia macrophylla* K.), and 16 trees (*Spondias lutea* L.).

Economic viability indicators

Indicators⁺	BR SAF RO 01	BR SAF RO 02	AF 3	AF 4
Investment ($USD.ha^{-1}$)	653.76	1,191.71	636.11	1,819.24
Interest rate (%)	7.16	7.63	-	-
NPVA ($USD.ha^{-1}.year^{-1}$)	1,720.49	1,022.28	-	-
IRR (%)	40.30	32.00	-	-
ROI (%)	32.70	20.55	-	-
Benefit/Cost ($USD.ha^{-1}$)	2.50	1.75	5.60	9.20

*Annual Net Present Value per hectare
**Internal Rate of Return
***Return on Investment
⁺2024 prices (1 USD = 5.22 REAIS)

For **BR SAF RO 01**, over a 15-year period, this system would yield an annual profit (NPVA) per hectare of 1,720.49 $USD.ha^{-1}$. Also, the benefit/cost ratio indicates that for every USD spent, this system would return 1.50 $USD.ha^{-1}$.

BR SAF RO 02 presents an investment value 1.8 time higher than **BR SAF RO 01**, with an annual net profit (NPVA) per hectare 60% lower. Nonetheless, this system remains competitive, with an internal rate of return (IRR) higher than the discount rate used, and for every USD spent, it presented a return of 0.75 $USD.ha^{-1}$.

Even though **AF 3** has an investment value 2.84 times lower than **AF 4**, with the estimated revenue and cost values, its benefit/cost ratio is 5.6, while for **AF 4** this ratio was 9.2. This difference occurs mainly due to the higher revenue in **AF 4** from the sale of açaí and cocoa.

B - Barriers, Incentives and Public Policies to boost adoption of sustainable agricultural systems in Brazilian Amazon and Cerrado biomes

The adoption of sustainable agricultural systems involves multifaceted considerations, encompassing technical and productive dimensions, as well as the farmer's subjective understanding of the production systems and their projected economic viability. Additionally, technology uptake depends on the farmers' values and objectives, which can vary quite broadly.

Our research suggests numerous policy initiatives that could increase the adoption of sustainable agricultural systems in the Amazon and Cerrado regions. The set of policies presented does not comprehensively cover all policy options or potential alternatives for improvement. However, we examined the most pertinent issues that have been delineated along with this research and indicate the crucial ones to boost adoption of sustainable agricultural systems.

Table: Barriers, Public Policies, Incentives and Suggested Improvements.

(continue)

Financial					
Barriers	Farmers' Profile	Biome	Public Policy	Incentives	Suggested Improvements
1) Credit policies are not aligned with the cash-flow dynamic from sustainable agricultural systems. 2) Lack or poorly defined land tenure rights limit farmers' access to credit and increase incentives to deforest land to acquire ownership, particularly in the Amazon biome. 3) The unpreparedness of banks to evaluate the economic viability of sustainable agricultural systems.	1) Both 2) Small 3) Both	1) Both 2) Amazon 3) Both	1) Safra Plan and ABC Plan.	1) Public credit policies offering low-interest federal loans to fund investments or costs related to productive diversification. 2) Integrated bonuses within the Safra Plan 2023/2024 for farmers who adopt sustainable agricultural systems.	1) The need for comprehensive credit systems that embrace a longer-term perspective is crucial for supporting the transition to sustainable agricultural systems, particularly those with perennial species. The credit systems should take into account the economic, social and environmental outcomes of farm transformation*. 2) Promote improvements to increase the capacity efficiency and effectiveness of the Brazilian land regularization system.

Table: Barriers, Public Policies, Incentives and Suggested Improvements.

(continue)

Environmental					
Barriers	**Farmers' Profile**	**Biome**	**Public Policy**	**Incentives**	**Suggested Improvements**
1) Lack of regulation to implement Law 14.119 that established the Nacional Policy for payments of Environmental Services. 2) Lack of regulation of the carbon market. 3) Insufficient capacity of government institutions for speeding up the process of validating the Rural Environmental Registry restricts producers' access to rural credit	1) Both 2) Large 3) Both	1) Both 2) Both 3) Both	1) Forest Code Law. 2) ABC Plan. 3) National Policy for Payment for Environmental Services. 4) Brazilian Greenhouse Gas Emissions Trading System.	1) The land use change regulation. 2) The CAR serves as a prerequisite for participation in programs offering subsidized credit, such as the ABC Plan. 3) Payment for environmental services (PES); National Policy for Payment for Environmental Services (NPPES). 4) The establishment of the Brazilian Greenhouse Gas Emissions Trading System (SBCE), which imposes emission limits and institutes a marketplace for the trading of carbon credits.	1) Strengthen public investment in research to develop indicators and metrics that can serve as benchmarks for environmental policies. 2) Include as priority on the political agenda the establishment of the National Registry of Payment for Environmental Services (NRPES), the creation of the Federal Program for Payment for Environmental Services (FPPES), and the Brazilian Greenhouse Gas Emissions Trading System. 3) The implementation of the Carbon Credits Market can be a robust instrument to boost the adoption of sustainable agricultural systems*. 4) Improve and strengthen the infrastructure and human resources of the Rural Environmental Registry (CAR) to speed up environmental compliance and certification of the rural establishments in the Amazon and Cerrado biomes. 5) Implement mechanisms provided for the Forest Code to regularize environmental liabilities

Table: Barriers, Public Policies, Incentives and Suggested Improvements.

(continue)

Social and technical					
Barriers	Farmers' Profile	Biome	Public Policy	**Incentives**	**Suggested Improvements**
1) The lack of rural assistance. 2) Skilled workers´ availability to perform more complex tasks is limited. 3) The lack of educational policies and information about economic and socioenvironmental benefits from these systems. 4) Farmers exhibit solid cultural value preferences attributed to aspects such as well-being, security, and familiar relationships, which can mitigate the perceived benefits of ICLFs.	1) Both 2) Both 3) Small 4) Both	1) Both 2) Both 3) Both 5) Both	1) ABC Plan	1) Federally supported research and extension initiatives. 2) Farmers close to Embrapa's research and demonstration units had significantly higher adoption of sustainable agricultural systems. 3) Embrapa´s research on sustainable agricultural systems.	1) Strengthen and enforce the link between credit access and provision of specialized rural technical assistance*. 2) Strengthen and amplify the human and financial resources of the Brazilian National Rural Extension Agency (ANATER), and invest in the implementation of the National Policy for Technical Assistance and Rural Extension (PNATER)*. 3) Agricultural research institutions should increase collection, organization, and knowledge exchange on successful farms that have already adopted sustainable agricultural systems and work jointly with farmers to develop and disseminate best agriculture, livestock and forestry production practices and systems, for example, via demonstration plots and field days. 4) Research programs should be redesigned to emphasize whole-farm economic, social and environmental outcomes. 5) Implementing participatory design for research planning and implantation at farm level, particularly for agroforestry systems initiatives. 6) Implementing mechanisms to increase engagement of the youth and women in leadership of rural activities such as education, extension services and cooperatives. 7) Facilitating land purchases by young farmers.

Table: Barriers, Public Policies, Incentives and Suggested Improvements.

(continue)

Infrastructural and Market					
Barriers	**Farmers' Profile**	**Biome**	**Public Policy**	**Incentives**	**Suggested Improvements**
1) Absence of agricultural infrastructure in regions that are farther from existing consolidated soybean and corn production areas. 2) Market access and price concerns.	1) Both 2) Both	1) Cerrado 2) Both	1) Safra Plan, specific public investment in infrastructure and logistic and government direct purchase programs	1) Public policies focused on reducing transportation cost for commodities in Center-West region. 2) Certification initiatives tailored to products originating from sustainable agricultural systems represent a viable strategy for enhancing product profitability by adding value.	1) Strengthening the Federal Government Purchase Programs* 2) Increasing the prospect of marketing sustainable agricultural goods. 3) Encouragement of value chain enhancement towards differentiated markets* 4) Specific investments to improve logistic, especially in railways and waterways, to reduce transportation costs.

*Greater relevance to Agroforestry Systems (AFs).

C - Gaps in the current knowledge related to economic assessment of sustainable agricultural systems

- It is quite difficult to collect economic information infield studies, especially longitudinal datasets necessary for conducting economic viability analyses on integrated systems.
- Longitudinal studies conducted within actual farming contexts encounter a multitude of challenges, such as: i) market risks; ii) commercial risks; iii) economic risks, and iv) insufficient farmers' management and planning skills and capacity, particularly small and medium farmers who lack the means to hire private technical and management assistance.
- Due to the scarcity of available economic data, the majority of studies rely on controlled experiments or case studies conducted on-farm scale. This approach restricts the extrapolation at the landscape level and evaluation of real commercial farming challenges adopting of integrated systems.
- The literature review identified substantial variability in the methodological approaches of economic analysis. The absence of standardized protocols for data collection and analysis constrains a more robust comparison of economic performance across diverse agricultural systems.
- Given the limited availability of economic data, numerous studies tend to evaluate individual components as isolated subsystems, such as profitability of crop subsystems or productivity of livestock subsystems. However, this approach overlooks the fundamental characteristic of integrated systems, namely, the synergistic interactions among all subsystem.

Final Remarks

Beyond supplying data that supports the public policy agenda for promoting wider adoption of sustainable agricultural systems in Brazil, this research is also relevant on a global scale due to the considerable production volume and importance of Brazilian agriculture in addressing the increasing food demand worldwide.

The findings contribute substantially to the global objective of enhancing the efficiency of resource use, particularly natural resources, with the aim of minimizing the environmental impacts of agriculture. In this context, the implementation of sustainable agricultural systems can be considered as a key strategy for mitigating the environmental impacts of increasing food production to meet a growing global demand, while reducing greenhouse gas emissions and deforestation.

Given that farmers tend to be risk-averse, public policy aimed at fostering the adoption of sustainable agricultural systems should influence farmers' decision-making processes by accentuating their immediate perceptions regarding environmental and social outcomes, thereby reducing the predominance of the economic dimension and their focus on short-term profit maximization.

Therefore, public policy initiatives ought to be designed to underscore the advantages of sustainable agricultural systems while simultaneously providing institutional, technical, and financial support during the transitional phase, given its challenging nature for farmers.

The socio-political context is critical in shaping farmers' decision-making process. Consequently, the development and execution of public policies targeting the promotion of sustainable agricultural systems should prioritize addressing the barriers and knowledge gaps identified in preceding research phases and, notably, strengthening the extant array of incentives.

Summary

Figures

Tables

1. Introduction

The adoption of sustainable agricultural systems in the Brazilian Amazon and Cerrado biomes is globally relevant due to the massive production of staple commodities in this region, as well as to the crucially important ecosystem services provided at the global scale (Andersen et al., 2002; Malhi et al., 2008; Coe et al., 2013). The agricultural sector is one of the most dynamic of the Brazilian economy, and it has been central to providing the successive balance of trade surpluses in recent years (Freitas, 2016; MAPA, 2023). However, this sector is the major driver of deforestation in the Amazon and Cerrado regions and a significant source of greenhouse gas (GHG) emissions, representing 31% of Brazilian direct greenhouse gas emissions in 2020 (SIRENE, 2023).

Policy developments to increase the adoption of sustainable agricultural systems have been pursued in Brazil's Cerrado and Amazon regions, as indicated in international commitments at the Conference of the Parties (COP) - 15, in the 'Sectoral Climate Change Mitigation and Adaptation Plan for the Consolidation of a

2003; de Oliveira et al., 2013; Salton et al., 2014).

Low Carbon Economy in Agriculture' (ABC Plan and ABC + Plan) and in the ratification of the Paris Agreement in 2015 (Brasil, 2010, 2012a, 2016, 2021). Among these initiatives, there is an explicit commitment to increasing the areas of Integrated Crop-Livestock (ICLs) and Integrated Crop-Livestock-Forest systems (ICLFs) and Agroforestry Systems (AFs). The target is to add 10 million hectares to the current area of 17 million hectares of ILPFs by 2030, and incorporate 100 thousand hectares of AFs to improve agricultural sustainability.

Low carbon sustainable intensification of agricultural systems represents a strategic opportunity to intensify resource uses while reconciling increasing productivity, diversifying production and, consequently, sparing land for conservation and restoration (Balbino et al., 2011; Lemaire et al., 2014; Thornton and Herrero, 2014; dos Reis et al., 2023a). Additionally, these systems are an important strategy to enhance household food security and income and increase resilience to market and climate risks (Garrett et al., 2017; Thornton and Herrero, 2014; Szymczak et al., 2020). Furthermore, integrated systems can be used to recover degraded pasture areas because residual fertility and revenues from crop production may be diverted to restore soil quality and health, and fund further system improvements (Kluthcouski et al.,

In summary, the literature suggests that integrated systems have the potential to be a successful strategy to promote sustainable agriculture in the Brazilian Amazon and Cerrado since they enhance the productive capacity of the environmental resources used, provide positive economic returns, generate increasing levels of social welfare and, simultaneously, do not harm their capacity to continue over time (Herrero et al., 2010; Costa et al., 2018; dos Reis et al., 2021).

Notwithstanding their great potential, there is limited information regarding the economic performance and factors limiting widespread adoption of sustainable agricultural systems in Brazil; neither is there a comprehensive and accessible database with this information. This is crucial for farmers and policy-makers to assess these systems as alternatives to large-scale monoculture or extensive livestock, the two most representative agricultural systems in the Brazilian agriculture-forest frontier in the Amazon and Cerrado Biomes.

With the aim to build a baseline database with the economic results and the research gaps considering the adoption and potential impacts of wider adoption of sustainable low carbon agricultural systems in the Brazilian Amazon and Cerrado, the objective of this research was to conduct a comprehensive analysis of effective incentives to accelerate the adoption of the ICLFs and AFs in the Amazon and the Cerrado biomes, where ICLFs implementation is at a more advanced stage. The research consisted of a systematic literature review of economic and financial assessments of ICLFs adoption, identifying barriers, and providing recommendations to increase adoption of sustainable agriculture systems adoption in the region.

Beyond supplying data that supports the public policy agenda for promoting wider adoption of sustainable agricultural systems in Brazil, this research is also relevant on a global scale due to the considerable production volume and importance of Brazilian agriculture in addressing the increasing food demand worldwide. The findings contribute substantially to the global objective of enhancing the efficiency of resource use, particularly natural resources, with the aim of minimizing the environmental impacts of agriculture. In this context, the implementation of sustainable agricultural systems can be considered as a key strategy for mitigating the environmental impacts of increasing food production to meet a growing global demand, while reducing greenhouse gas emissions and deforestation.

In addition to this introduction, this study is structured as follows. Chapter two describes the methodology used. Chapter 3 presents the two sustainable agricultural systems considered in this research: ICLFs and AFs. Chapter 4 details the economic results of case studies of ICLFs and AFs from the Amazon and Cerrado biomes, as well as provides an estimate of the economic impacts of converting degraded pasture areas into ICLFs in these biomes. As a complement, we conduct a systematic literature review and present the general economic results found in the literature for both sustainable agricultural systems in the Amazon and Cerrado biomes. Chapter five focuses on discussion of the main barriers to adoption of ICLFs and AFs found in our systematic literature review, as well as the public policies that could be promoted to overcome these barriers. We also discuss the main incentives that could be used to boost the adoption of ICLF and AF systems in these biomes. In the sixth chapter, we present the main knowledge gaps and challenges in implementing long-term economic viability assessments of complex ICLFs and AF agricultural systems. A final section is dedicated to the final remarks.

2. Methodology

2.1 - Case Study Analysis

The scarcity of economic information emerges as one of the main issues explaining the relatively low adoption of sustainable agricultural systems (Cortner et al., 2019; dos Reis et al., 2023a). To advance the understanding on this research agenda, we present comprehensive results from two case studies assessing the economic performance of crop-livestock-forest integrated systems (ICLF), one located in the Amazon biome and other for the Cerrado biome. We also compare the results of these systems with those observed for a large-scale cropping system (soybean-corn) and an extensive livestock system, the two most representative agricultural systems in the Brazilian agriculture-forest frontier.

Additionally, we provide detailed economic performance information for four representative case studies of Agroforestry Systems in the Amazon biome. These case studies are based on the experiences conducted by the Agroforestry Economic

Reforestation and Intensification Project (Projeto Reca) in the state of Rondônia and experiences from relevant agroforestry systems adoption in the Amazon biome in the municipality of Tomé-Açu, state of Pará.

2.2 - Economic Impact Analysis

The projections of economic impacts resulting from the expansion of ICLF systems in the Brazilian Amazon and Cerrado biomes were conducted through an Input-Product model, based on the most recent IBGE (2017) Input Output Matrix and considering the findings of economic performance of two case studies assessed. This information is crucial for policy-makers to assess ICLFs and AFs as suitable alternatives to large-scale monoculture (soy and corn) or extensive livestock production systems in Amazon and Cerrado biomes. The basic formulation of the model is given by the equation: $x = (I-A)^{-1}f$, where x is the total production vector, I is the identity matrix, A is the technical coefficient matrix, and f is the final demand vector.

2.3 - Systematic Literature Review Approach

To compile existing literature regarding economic and financial aspects of adoption of Integrated Crop-Livestock-Forest systems and Agroforestry Systems in Brazilian Amazon and Cerrado biomes, as well as to perform the analysis of findings, this study employed a systematic literature review methodology based on ROSES protocol (RepOrting standards for Systematic Evidence Syntheses) (Tranfield et al., 2003; Siddaway et al., 2019; Haddaway et al., 2018; Haddaway and Macura, 2018; Shaffril et al., 2021). This methodological approach involved the scrutiny of both quantitative and qualitative studies employing diverse methodologies and theoretical frameworks to investigate the themes delineated in the research proposal.

3. Brazilian Sustainable Agriculture Alternatives: ICLFs and AFs

3.1 - Integrated Crop-Livestock-Forest Systems (ICLFs)

The integrated crop-livestock-forest systems (ICLFs) are a Brazilian technology developed at the beginning of the 1990s to boost sustainable intensification of agriculture and to increase the efficiency in productive resource use in agricultural systems in the Cerrado and Amazon biomes (Figure 1), particularly environmental resources (Kluthcouski et al., 2003; Macedo, 2009; Balbino et al., 2011). The initial focus of integrated systems was to associate soil conservation practices, such as no-tillage, for protection and reduction of soil loss, nutrient leaching, and improving efficiency of use of lime and fertilizers used to adjust soil fertility to achieve high productivity of crops such as soy, corn and cotton. At the same time, use of no-tillage practices contributes to increase soil organic matter (carbon stock) and, as a consequence, enhancing soil quality and its productivity, particularly in Cerrado and Amazon regions, areas characterized by fragile soils and with limited fertility to sustain continuous production of large-scale commercial crops (Kluthcouski et al., 2003; Vilela et al., 2011; Salton et al., 2014).

The main objective of ICLF systems is to improve agricultural sustainability through the integration of various production activities in the same area by intercropping and rotations that aim to obtain synergies among agroecosystem components (Nair, 1991; Wilkins, 2008; Balbino et al., 2011). Integrated crop-livestock (ICL) systems are substantially more common than integrated crop-livestock-forest systems in Brazil, accounting for 83% of the systems (Embrapa; Rede ILPF, 2017).

Integrated Crop-Livestock-Forest Systems models

i. ***Integrated crop-livestock (Agropastoral systems)***
Land use strategy: growing crops and livestock on rotational, intercropping, or in succession systems in the same area, or in the same agricultural year, or for multiple years in a continuous cycle.

ii. ***Integrated crop-forest (Silvoagriculture systems)***
Land use strategy: growing crops and forests through the intercropping of tree species, in general, timber trees, and agriculture crops (annual and perennial crops). The crop component may be cultivated in the initial phase while implementing the forestry component, or in cycles during the development of the system.

iii. ***Integrated livestock - forest (Silvopastoral systems)***
Land use strategy: raising animals and forest, in general, timber trees or trees to improve animal welfare in the same area. Animal component, in general, is introduced after the trees are able to withstand animals' movements across the area.

iv. ***Integrated crop-livestock-forest (Agrosilvopastoral systems)***
Land use strategy: growing crops, livestock, and forestry in rotational, intercropping or succession systems in the same area. The crop component may be cultivated in the initial phase while implementing the forestry component, or in cycles during the development of the system. Also, animal component, in general, is introduced after the trees are able to withstand animals' movements across the area.

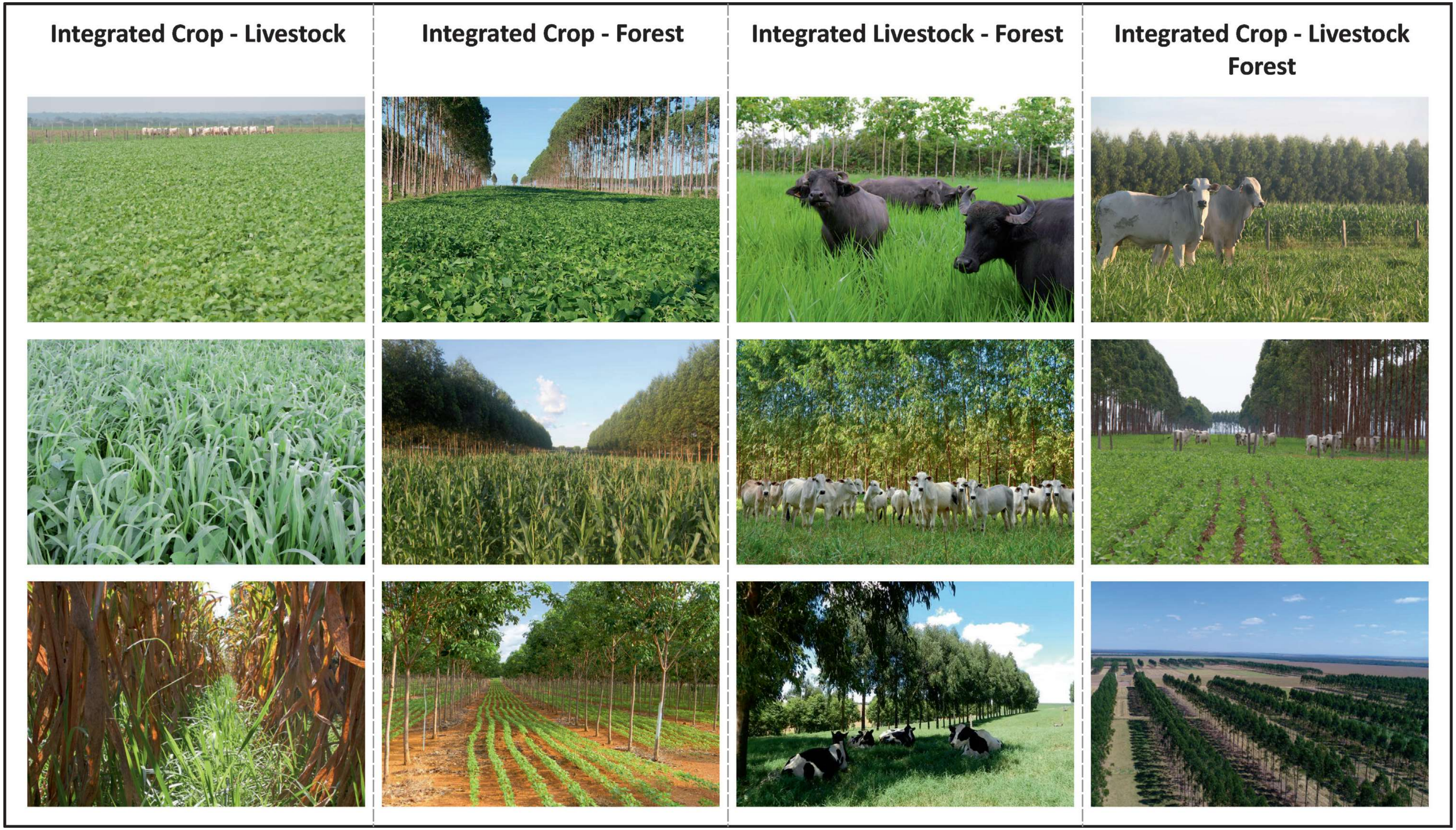


Figure 1: Integrated Systems: examples.
Source: Embrapa's Image Dataset.

3.2 - Agroforestry Systems (AFs)

It is a land use strategy that associates, in the same area at a given time, the cultivation of perennial component, such as tree or shrub species, fruit trees, timber trees, or green fertilizers, with semi-perennial component, such as banana, pineapple, cassava or some pasture species, planted at the beginning of the system implementation, and that it remains there for two to three years. This component plays a critical role in providing the necessary microenvironment to grow the perennial component. Finally, the short-cycle component, such as crops, provides initial cash flow. In some situations, animal component, particularly small animals such as hens, pigs and goats, are raised to self-consume and to improve income diversification. The AFs are suitable for small farming since they are labor-intensive (Nair, 1991).

There are various possible species arrangements in AFs (Figure 2), from those that approximate native vegetation landscapes which, through natural succession, re-establishing important ecological processes such as nutrient cycling, attracting fauna, carbon fixation, among others, to more simplified systems, which are also known as polycultures (Nair, 1991; Schembergue et al., 2017). Therefore, AFs optimize land use, reconciling environmental preservation with food production, conserving the soil, and reducing the pressure to use land for agricultural production. Another crucial issue is that AFs can be adopted to restore forests and recover degraded areas. AFs are allowed in legal reserve areas (LRA) and permanent preservation areas (PPA) of small properties or familiar farms; nevertheless, the share of exotic species, in general for timber exploration, may not exceed 50% of the total area to be recovered (Brasil, 2012b; Embrapa, 2023).

It is quite impossible to define a general pattern for AF components since the huge Brazilian biodiversity offers a myriad of species to be cultivated in these systems (Annex 1). On the other hand, economic, regional, and cultural aspects define a set of “core species”, broadly perennial or semi-perennial trees which, around them, the others species are grown to provide the conditions for “core species” to demonstrate their natural productive potential.

Figure 2: Agroforestry Systems: examples.
Source: Embrapa's Image Dataset.

4. Results

4.1 - Case Studies

4.1.1 - Integrated Crop-Livestock-Forest Systems (ICLFs)

The case study analysis was carried out considering the economic performance of two crop-livestock-forest integrated systems (ICLFs), one located in the Amazon biome and other for the Cerrado biome. In addition, we compare the results from these systems with those observed for a large-scale cropping system (soybean-corn) and an extensive livestock system, the two most representative agricultural land-use strategy in the Brazilian agriculture-forest frontier. This information is crucial for farmers and policy-makers to consider the ICLFs as viable alternatives to large-scale monocropping or extensive livestock.

The results indicate that ICLFs are economically competitive, even within regions highly specialized in commodity production. Moreover, the viability indicators corroborate the assertion that these systems are more resilient and tend to demonstrate superior economic performance in the long term. However, it is important to note that during periods of elevated commodity prices, mainly for grain, large-scale crop systems exhibit higher short-term profitability. Thus, a crucial public policy to bolster the adoption of sustainable agricultural systems, as underscored in preceding findings of this study, entails enhancing the recognition and economic return of long-term outcomes to reduce the emphasis on short-term private profit maximization.

a) Data source

Information about typical crop and livestock systems was provided by the Mato Grosso Institute of Agricultural Economics (IMEA) (Table 1). IMEA conducts a comprehensive yearly economic data collection focusing on the main agricultural commodities in Mato Grosso: soybean, corn, cotton, and beef cattle. These assessments entail comprehensive surveys conducted across all regions of Mato Grosso, employing focus group sessions involving farmers alongside representatives from agricultural entities and enterprises. The surveys serve to gather up-to-date information concerning aspects economic data such as costs, revenue, productivity, investments, farm size, management practices, labor, and infrastructure for each commodity across farms in Mato Grosso (IMEA, 2021).

Table 1: Farm descriptions[1].

Productive Systems	Region Mato Grosso	Production Area (ha)	Period	Investment.ha^{-1} (USD)
ICLF - C	Northeast	600	2011 - 2017	1,024.30
ICLF - A	North	1000	2008 - 2016	430.52
Livestock	Mato Grosso	1000	2016 - 2021	369.51
Crop	Northeast	600	2011 - 2017	1,078.89

For integrated systems, we used economic and environmental data from the Technological and Economic Reference Units Project (TERU Project) (Farias Neto et al., 2019), a collaborative research initiative between the Brazilian Agricultural Research Corporation (EMBRAPA) and IMEA, implemented in 2014, leveraging Embrapa's technology dissemination network within Mato Grosso.

b) Systems description

The **typical crop farm** is defined by an intensive and specialized production system with two crop seasons per year: soybean (*Glycine max*) (October–February) and corn (*Zea mays*) (February–June/July), 600 ha of cultivated land area, and an initial investment of 1,078.89 USD.ha^{-1}. We excluded land acquisition cost, since this analysis is focused on assessing the production activity performed, and because land prices have risen sharply in recent years following China's consolidation as the main Brazilian agricultural commodities importer. We chose the northeast region of Mato Grosso to define the typical crop farm since it concentrates 20% of soybean and 18% of corn production (IMEA, 2021). Crop farms use a high level of technology in all production stages with high investment in infrastructure and inputs.

In contrast, the **typical livestock farm** is characterized by traditional cattle ranches with a low level of technology, low productivity and large area, and approximately 1,000 ha dedicated to rearing and fattening. We chose livestock data from the state level since it is the most representative of extensive cattle ranch farms. Typical cattle ranchers do not invest in sophisticated infrastructure, only basic equipment, such as corrals, troughs and fences, and do not invest in pasture management. Hence, this production system displayed the lowest investment value: 369.51 USD.ha^{-1}. The most common cattle breed is the Zebu (*Bos*

1 Investment data were updated for 2024 using the Broad Consumer Price Index (IPCA), the official inflation index in Brazil. 2024 prices (1 USD = 5.22 REAIS).

taurus indicus), with an initial body weight of 330 ± 7.6 kg and a stocking rating of 0.84 head.ha^{-1}. The pasture is *Urochloa brizantha* cv. Marandu.

The **integrated crop-livestock-forest system for the Amazon biome (ICLF - A)** is located in the municipality of Nova Canaã do Norte, in the north region of Mato Grosso and in the Amazon Legal region, a new frontier for large-scale crop system in the state and a region traditionally used for livestock. The ICLF system was implemented in 2008 as a strategy to recovery degraded pasture. The cultivated land area was 1000 ha, and the initial investment was 430.52 USD.ha^{-1}. Eucalyptus (*Eucalyptus grancam* - hybrid) was planted in single-row (2m intra-row and 3m inter-row). Rice (*Oryza sativa*) and soybeans (*Glycine max*) were planted between the rows during three first agricultural years. From the fourth year onward, brachiaria (*Urochloa brizantha* cv. Marandu) was seeded and maintained in the area to serve as forage for the animals, taking advantage of residual fertility from crop rotation and promoting high-quality pastures over subsequent years. The livestock system is managed to rear and fatten Zebu cattle (*Bos taurus indicus*) and Galician Blond (*Bos taurus taurus*).

The **integrated crop-livestock-forest system for the Cerrado biome (ICLF - C)** is located in the municipality of Nova Xavantina in northeast Mato Grosso, a traditional livestock region. The system was established in 2010 as a strategy to reclaim degraded pastures, and the forest was cultivated for farmers' own use in drying soybeans (*Glycine max*), as well as in livestock infrastructure such as fences, troughs and corrals and for timber commercialization. The cultivated land area was 600 ha, and the initial investment was 1,024.30 USD.ha^{-1}. The land use management adopted the following general guideline: over the first four years, the area was cultivated with soybean (*Glycine max*) and eucalyptus (*Eucalyptus urograndis*, clone H13) planted in triple-lines with an intra-row spacing of 2 m and an inter-row spacing of 3 m, with 23m strips between each set of triple rows resulting in a density of 582 trees ha^{-1}. In 2013, pasture (*Urochloa ruziziensis*) was established after the soybean (*Glycine max*) harvest, and livestock activity remained until the forest was cut in 2017. The livestock system is managed for rearing and fattening, and the cattle breed is Zebu cattle (*Bos taurus indicus*), with an initial body weight of 251 ± 5.8 kg and a stoking rating of 4 head.ha^{-1}.

c) Results

i. Economic results

The annual economic results highlight the huge influence of market prices on agricultural systems' economic performance (Table 2 and Table 3). Typical crop farms showed high average production levels (soybean: 50.86 sc.ha^{-1}.year^{-1}; corn: 84.91 sc.ha^{-1}.year^{-1}), illustrating the positive response of intensive use of external inputs, particularly fertilizers, pesticides and high technology seeds. Hence, this farm presented higher production cost with an average of 594.80 USD.ha^{-1}.year^{-1}. As a consequence of rising agricultural commodity prices on the global market, mainly soybean, this system showed high average net revenue (933.13 USD.ha^{-1}.year^{-1}) and a remarkable average gross profit (338.33 USD.ha^{-1}.year^{-1}), two times bigger than typical livestock farm.

In contrast, the typical livestock farm showed low productivity (12.59 @ ha^{-1}.year^{-1}) and poor gross profit over the years, averaging 164.94 USD.ha^{-1}.year^{-1} (Table 3). However, following the substantial rise in beef cattle prices after 2019, the last years assessed displayed EXTREMELY high values for all economic results. For instance, gross profit in 2020 was 135% higher than that in the previous year, and 3.75 times higher than that in 2015, indicating an annual average gross profit growth rate of 30% over the five years. The results for annual net revenue are still more impressive. The annual growth rate achieved 34%, and the result in 2020 for a typical livestock farm (1,229.37 USD.ha^{-1}.year^{-1}) is similar to the result achieved by large-scale crop farm.

Table 2: Average production levels of integrated crop-livestock-forestry systems and large-scale cropping system in the Amazon and Cerrado biomes.

Production System	Beef cattle (@.ha-1)*	Soybean (sc.ha-1)**	Rice (sc.ha-1)**	Corn (sc.ha-1)**	Wood (m³.ha-1)***
ICLF – C (Cerrado)	16,22	44,10	-	-	27,37
ICLF – A (Amazon)	38,03	54,05	58,00	-	3,91
Livestock	12,59	-	-	-	-
Crop	-	50,86	-	84,91	-

*Beef production in @ produced.ha^{-1} (1 @ = 15 kg).
**Crops: soybean, corn, and rice production in sc.ha^{-1} (1 sc = 60 kg).
***Wood production in m^3.ha^{-1}.

Integrated crop-livestock-forest systems in the Amazon biome (ICLF - A) showed annual crop production levels slightly higher than that of the large-scale crop system (soybean: 54.05 sc.ha^{-1}.year^{-1}). Also, the crop component of this system produced 58.00 sc.ha^{-1}.year^{-1} of rice. Moreover, this system showed the highest livestock production (38.03 @ ha^{-1}.year^{-1}), a beef cattle production level three times greater than typical livestock farm, and produced 3.40 m^3.ha^{-1}.year^{-1} of eucalyptus timber. This higher diversity of agricultural goods explains the considerable net revenue performance: 993.10 USD.ha^{-1}.year^{-1} (Table 3) and an impressive net revenue growth rate of 41% yearly. However, the high production cost undermined the gross profit results. The transportation cost, associated with increasing prices of inputs, particularly calves, and the limited demand of planted timber in the region reduced the economic performance of this system. The restricted demand for planted timber in the region can be attributed to the absence of industrial facilities, such as pulp and paper industries, steel production plants, biomass-based energy production facilities, and furniture manufacturing industries.

Table 3: Average yearly economic results of integrated crop-livestock-forestry systems and large-scale cropping system in the Amazon and Cerrado biomes.

Production System	Net Revenue ($USD.ha^{-1}$)*	Production Cost ($USD.ha^{-1}$)*	Gross Profit ($USD.ha^{-1}$)*
ICLF – C (Cerrado)	1.131,46	766,59	364,87
ICLF – A (Amazon)	993,10	858,77	134,33
Livestock	584,32	419,38	164,94
Crop	933,13	594,80	338,33

* 2024 prices (1 USD = 5.22 REAIS)

Finally, integrated crop-livestock-forest systems in the Cerrado biome (ICLF - C) presented the best economic performance. This system showed the highest gross profit (364.87 $USD.ha^{-1}.year^{-1}$), 8% bigger thar the large-scale crop farm and two times bigger than livestock typical farm. This remarkable economic performance is explained, mainly, by the extremely high-performance of forest component associated with a smart market strategy to livestock commercialization. This farm has a long trajectory of beef cattle production, with established market connections. In addition, its location in the northeast of the state of Mato Grosso, closer to the capital Cuiabá and the border with the state of Goiás, gives it a considerable logistical advantage. Finally, its location has provided better opportunities for marketing timber, which is a determining factor in earning high returns from this product.

ii. Economic viability indicators

The economic viability indicators highlight the better performance of integrated systems in the long-term (Table 4). The integrated crop-livestock-forest system farm for the Cerrado biome (ICLF - C) showed the highest NPVA. ha^{-1} (87.44 USD) and the highest profitability index (1.36), demonstrating its great economic attractiveness. This result for NPVA, in our approach an estimative for Net Profit, is 13 times bigger than the result for large-scale crop farm and 41 times than typical livestock farm. This huge difference from typical livestock farm is explained by the possibilities to take advantage of the rising beef cattle price and, on the other hand, from the land use strategies to provide high-quality pastures along the dry season in Cerrado regions (May - September), reducing the share of supplementary feeding on production cost. However, this system displayed a higher payback value, seven years, due to its high initial investment (1.024.30 $USD.ha^{-1}$).

Table 4: Economic viability indicators: Weighted Average Cost of Capital (WACC), Annual Net Present Value (NPVA), Return on Investment (ROI) of integrated crop-livestock-forestry systems in the Amazon and Cerrado biomes.

Indicators*	ICLF – C (Cerrado)	ICLF – A (Amazon)	Crop	Livestock
WACC	8,02%	7,88%	8,02%	8,30%
NPVA	87,44	31,95	6,62	2,10
IRR	15,78%	13,40%	8,81%	8,85%
ROI	12,93%	11,68%	8,50%	8,70%
Profitability Index	1,36	1,32	1,03	1,02
Payback	7	8	7	5

*2024 prices (1 USD = 5.22 REAIS)

The integrated crop-livestock-forest system farm for the Amazon biome (ICLF - A) showed a return on investment (ROI) and a profitability index similar to that of the (ICLF - C). Spite of this relatively low annual gross profit, the ICLF - A displayed a ROI 48% and an IRR 51% higher than large-scale crop farm. Also, the difference between the IRR and the Weighted Average Capital Cost (WACC) for the ICLF - A compared to large scale crop farm suggests that the ICLF - A is a much more profitable investment option. For instance, the profitability index results indicated that for each dollar invested in ICLF - A, it generated 32 cents in profit, while the large-scale crop farm generated only 3 cents and the typical livestock farm only 2 cents. However, even with an investment level 2.4 times lower than the ICLF - C, the ICLF - A presented a higher payback, eight years. These results illustrated the relevance of logistics and market connections to explain agricultural economic performance.

Compared with the most profitable integrated system (ICLF - C), the crop farm displayed a ROI 35% lower. This result is significative since these systems presented similar investment (crop farm: 1,078.89 USD.ha^{-1}.year^{-1} and ICLF - C: 1,024.30 USD.ha^{-1}.year^{-1}). Furthermore, although its higher gross profit level, the huge administrative and financial expenses undermine their economic performance. This issue is illustrated by its low profitability index and by little difference between the IRR and WACC. These results demonstrate the high economic and market risks facing large-scale crop farms. Even in favorable price scenarios, the great total production cost hampers its economic return.

Finally, the livestock farm showed the poorest economic viability indicators. The IRR is quite similar to the WACC, indicating the poor economic performance of this system, generating revenues just to maintain the activity. Similar result is observed for the profitability index; this system generates only two additional cents for each dollar invested. Moreover, the NPVA.ha^{-1} (2.10 USD) reveal the limited capacity of typical livestock farms to generate net profit and, as consequence, investing in new technologies. Increasing productivity and reducing operating costs, especially in supplementary feeding, is

decisive for livestock farmers to improve their economic performance. The low payback, five years, for this farm is explained by its lower investment level (369.51 USD.ha^{-1}).

d) Discussion

i. Integrated systems economic results and better long-term performance

Despite the greater initial investment, integrated systems showed a similar payback but a higher ROI and profitability index than crop and, particularly, livestock system, indicating their better long-term performance (Table 4). These results corroborate the literature indicating that integrated systems are more resilient and an economically viable alternative for typical land use strategies in Amazon and Cerrado biomes (Herrero et al., 2010; Poffenbarger et al., 2017; dos Reis et al., 2020).

Additionally, our results highlight the relevance of land use management in determining the economic results. The integrated systems provide diversification benefits by offering different products over the year and improving synergies between subsystems, as indicated by its higher productivity level (Ryschawy et al., 2012; Sneessens et al., 2016). In contrast, the timber production, although it displayed crucial importance for the best economic viability indicators of integrated crop-livestock-forest systems, mainly for ICLF -C, requires specific expertise on forest management, higher organization levels and consolidated market niches to demonstrate its economic potential (Sneessens et al., 2016, 2019).

Also, our results illustrated the potential of integrated systems to boost the production level, intensifying land use in already cleared areas. The remarkable differences in beef cattle production in integrated systems are explained by land use intensification and, as a consequence, better pasture quality. The average productivity of beef cattle in ICLF - A was three times higher than production in typical livestock farm. On the other hand, the difference in average soybean yield between ICLF - A and typical crop farms was only 6.26%. In fact, the major impacts of integrated systems on crop

production are diminishing unitary production costs, being more efficient in environmental resource use and less dependent on external inputs (Costa et al., 2018; Szymczak et al., 2020; dos Reis et al., 2021).

Consequently, due to the great influence of the economic result on the producers' decision-making process, the high initial investment and the great complexity of production activity, the integrated systems adoption rate should be higher among crop farmers than cattle ranchers (Cortner et al., 2019; Garrett et al., 2020). Therefore, even showing a higher potential to increase efficiency in livestock production, the economic impact of integrated systems adoption in crop areas tends to be stronger.

ii. Implications for other regions

Despite its context-dependent feature, our findings on the potential economic results for adoption of sustainable agricultural systems in the Brazilian Amazon and Cerrado regions as an alternative for large-scale monocropping and extensive livestock can be used as a reference for other tropical regions. Agriculture in tropical regions must include sustainable soil management and carbon sequestration as crucial strategies to avoid harming their capacity to continue producing over time (Howden et al., 2007; Lobell et al., 2008; Tubiello et al., 2015).

Moreover, our results corroborate integrated systems' potential to reclaim degraded pastures at a low cost while providing revenue from crop and forest products. This issue is particularly relevant for regions in Latin America, Africa and Asia focused on livestock production that face pasture degradation problems with cattle ranchers with limited financial capacity (Calle et al., 2009; Campos et al., 2009; Bottazzi et al., 2014; Haile et al., 2019; Krishnamurthy et al., 2019). In addition, the sustainable intensification provided by integrated systems can be useful to collaborate with deforestation policies, particularly in other countries in the Amazon region, either on large farms or by smallholders who historically use slash

and burn systems (Bowman et al., 2012; Garrett et al., 2017; Latawiec et al., 2017a; Krishnamurthy et al., 2019).

4.1.2 - Agroforestry Systems (AFs)

Agroforestry Systems optimize land use by reconciling environmental preservation with food production, conserving soil, and alleviating pressure on land use for agricultural production. Moreover, currently, these agricultural productive systems represent significant alternatives for the environmental restoration, both within legal reserves and permanent preservation areas, particularly for small farmers (Embrapa, 2023). However, some legal rules must be considered: i) agroforestry systems are permitted in Legal Reserve Areas (ARL), Permanent Preservation Areas (APPs) of small properties, or rural family farms of up to four fiscal modules; ii) they are also allowed in Restricted Use Areas (such as wetlands and Pantanal plains) with slopes between 25º and 45º, as well as in consolidated areas; and iii) the planting of exotic species alongside native species of regional occurrence must not exceed 50% of the total area to be restored (Embrapa, 2023).

The possibility of using Agroforestry Systems in APPs and ARL is crucial for encouraging increased adoption of these productive systems. It enables the economic exploitation of an area perceived solely as a financial cost of agricultural activities by farmers. Moreover, with the prospect of growth in the carbon credit market in Brazil, these systems can offer significant economic returns. Therefore, the demand for technical recommendations in AFs is steadily increasing.

On the other hand, the availability of consistent information regarding the economic viability of these systems is extremely limited due to challenges in both data collection processes and the management of information, particularly among small farmers. Additionally, the need for long-term monitoring is essential, considering that production systems based on perennial tree species require a longer period to reach the expected production stage.

Despite these challenges, and owing to the work carried out by Embrapa in the Amazon region since the late 1970s, it has been possible to gather information from **four representative case studies for Agroforestry Systems in the Amazon biome**. These case studies are based on the experiences conducted in the Agroforestry Economic Reforestation and Intensification Project (Projeto Reca) in the state of Rondônia (Projeto Reca, 2024), which stands as the main reference regarding the adoption of productive agroforestry systems in the Amazon biome (Lunz and Melo, 1998; Sá et al., 2000; Franke et al., 2008) and experiences from another seminal example of agroforestry system adoption in the Amazon, the municipality of Tomé-Açu, in Pará.

The Projeto Reca began in 1989, and the initial agroforestry systems established were based on cupuaçu, pupunha, and Brazil nut species. This system will be depicted in the case study **BR SAF RO 01** (Oliveira et al., 2015). A second generation of more diversified productive arrangements, with a greater presence of fruit species and exploitation of non-timber products, was implemented in the early 2000s, and will be portrayed in this study by the case study **BR SAF RO 02** (Oliveira et al., 2021). From Tomé Açu's agroforestry systems, **AF 3** and **AF 4** initially, the areas were allocated for monoculture cultivation of black pepper in the 1990s, and subsequently converted to agroforestry systems. Due to the inclusion of timber species in the composition of the AFs, these systems entail a long-term planning horizon of 30 years, influenced by the development of the species and productive utilization of the timber component.

a) Data source

The economic and agronomic data for the implementation and maintenance of the **BR SAF RO 01** system was collected through a technical panel conducted in March 2016. This panel involved the participation of local technicians and extensionists with recognized experience and knowledge in commercial multi-strata agroforestry systems, as well as farmers from the Projeto Reca. Technical coefficients for the agroforestry system were

developed considering the use of production factors - inputs, labor, and machinery - as well as the productivity of components for a 1 ha area. The information utilized reflects common cultural practices in the region for each activity performed in the system. The analysis period spanned 15 years. The interest rate employed was 7.14%, which corresponds to the savings rate in 2014, the year when the system was implemented. The prices were updated for the year 2024.

On the other hand, the economic and agronomic information for the **BR SAF RO 02** was collected directly from the farmer, who gathered and recorded all information over a rare 14-year period: from 2006 - the year of implementation - until 2020, a situation rarely found in the literature. Embrapa's systematic monitoring occurred during the last four years of this period. As with the previous case study, technical coefficients for the agroforestry system were developed considering the use of production factors - inputs, labor, and machinery - as well as the productivity of components for a 1 ha area. The analysis period spanned 20 years. The interest rate employed was 7.63%, which corresponds to the savings rate in 2007, the year when the system was implemented. The prices also were updated for the year 2024.

The **AF 3** and **AF 4** database was obtained within the Tipitamba Project, carried out for from Embrapa Eastern Amazon Research Center, Pará, Brazil, and made available by Rego (2016). The data were collected through interviews conducted in 2015, with the collaboration of the Cooperativa Agrícola Mista de Tomé-Açu (CAMTA) and the Associação dos Produtores e Produtoras da Agricultura Familiar do Município de Tomé-Açu (APRAFAMTA). Project collaborators conducted a comprehensive survey and collected information of all activities carried out within the analyzed productive systems, including production, labor, inputs, machinery, and operational time.

The production costs were estimated based on the monetary value of inputs and labor in Tomé-Açú. Meanwhile, revenues, derived from the commercialization of the production, were estimated based on the prices of products in the local market and the sale of products to CAMTA. For system planning, a 30-year period was considered, given that **AF 3** and **AF 4** include timber components requiring lengthy development periods, with commercialization occurring at the end of the cycle. Similar to the approach adopted for **BR SAF RO 01** and **BR SAF RO 02**, economic data were updated to the year 2024.

b) Systems description

The agroforestry system **BR SAF RO 01** is situated within the Baixa Verde region, in the Reca Project, Nova Califórnia district, Porto Velho Municipality, Rondônia. Established in 1990, this AS occupies an area formerly covered by primary forest subjected to the slash-and-burn method, a traditional practice in the region (Bowman et al., 2012; Garrett et al., 2017; Latawiec et al., 2017). The soil within the AF area is classified as Red-Yellow Argisol, and the prevailing climate, according to Köppen's classification, is of the (Aw) type, characterized as hot and humid equatorial, with high levels of precipitation, averaging 2,250 mm annually (Oliveira et al., 2015).

The production system under investigation, encompassing an area of 1 hectare, constitutes an agroforestry consortium of intercropped species with a regular distribution per unit area, necessitating agronomic and economic planning for its implementation. The perennial species consist of **cupuaçu** (*Theobroma grandiflorum* Schum.), **pupunha** (*Bactris gasipaes* Kunth) (for seed production), and **castanheira** "Brazil nut tree" (*Bertholletia excelsa* Humb. & Bonpl.). To ensure revenue generation in the initial years of the system, the following temporary crops were cultivated: maize (*Zea mays*), rice (*Oryza sativa*), cassava (*Manihot esculenta Crantz*), and beans (*Phaseolus vulgaris*).

The implementation of **BR SAF RO 01** (Table 5) started with soil sampling (0 cm - 20 cm and 20 cm - 40 cm depths) and site preparation involving

stump removal using a tractor, followed by harrowing, root picking, and subsequent leveling with a grader. Subsequently, pit marking was conducted for the core-species chosen, in this case **cupuaçu**, arranged in double rows with a spacing of 4 m x 7 m x 14 m, totaling 240 plants. ha^{-1}. The remaining species were allocated with the following spacing and number of plants per hectare: Brazil nut tree (12 m x 21 m): 40 plants. ha^{-1} and pupunha for seed production (two plants between Brazil nut trees, every 4 m): 80 plants. ha^{-1}. For the annual species, the area was divided into three strips, with five rows for maize (spacing 1 m x 1 m with two plants per pit): 6,000 plants.ha^{-1}; five rows for rice (spacing 0.30 m x 0.40 m): 20,000 plants.ha^{-1}; and four rows for cassava (spacing 1 m x 1 m): 2,400 plants.ha^{-1}. Following maize and rice, beans were sown (spacing 0.30 m x 0.40 m): 40,000 plants.ha^{-1}. Rice was only sown in the first year, with maize and beans replanted in the second year of cultivation.

Table 5: Average production level - BR SAF RO 01 in the state of Rondônia, Amazon biome.

Products	Production Period	Average production
Cupuaçu (kg.ha^{-1})	Year 4 - 15	5,336.0
Pupunha (kg.ha^{-1})	Year 4 - 15	101.17
Castanheira (20 L can.ha^{-1})	Year 12 - 15	4.0
Maize (kg.ha^{-1})	Year 1- 2	1,400.0
Beans (kg.ha^{-1})	Year 1- 2	450.0
Cassava (kg.ha^{-1})	Year 1- 2	3,600.0
Rice (kg.ha^{-1})	Year 1	500.0

The **BR SAF RO 02**, also part of the Reca Project, is situated in the district of Nova Califórnia, municipality of Porto Velho, Rondônia, Brazil, in a region proximate to the borders of Acre, Amazonas, and Rondônia, representing one of the country's most recent agricultural frontiers. The soil within the agroforestry system area has been classified as Plinthic Red-Yellow Argisol, while the prevailing climate of the region is characterized as hot and humid equatorial (Aw) according to Köppen's classification, with an average annual precipitation of 2,250 mm. The dry season is pronounced from June to August, and the average annual temperature stands at 25.5°C, with daily maximums exceeding 35°C (Oliveira et al., 2021).

The **BR SAF RO 02** was established in 2006 on an area previously utilized as Tanzânia grass pasture (*Panicum maximum* cv. Tanzânia-1), which had been planted in 2001. Prior to its conversion, this area had been occupied by primary forest. Due to the inadequate development of the pasture, the landowner opted to replace livestock farming with an agroforestry system. The perennial forest components of **BR SAF RO 02** include **cupuaçu** (*Theobroma grandiflorum* Schum.), **pupunha** (*Bactris gasipaes* Kunth) (for seed production), **copaiba** (*Copaifera* sp.), and **andiroba** (*Carapa guianensis*). Temporary crops cultivated in the system comprised pupunha for heart-of-palm production and banana (*Musa spp*.). The studied model corresponds to a 1-hectare module.

For the implementation of **BR SAF RO 02** (Table 6), land preparation involved stump removal using a tractor, harrowing, root picking, and subsequent leveling with a grader. The species were allocated with the following spacing and number of plants per hectare: cupuaçu trees (6 m x 4 m) x 8 m: 272 plants.ha^{-1}; pupunha for seed production (12 m x 12 m): 64 plants.ha^{-1}; andiroba and copaiba (24 m x 12 m): 32 plants. ha^{-1} for each species. For intercropping, rows of pupunha for heart-of-palm production were introduced between the cupuaçu tree rows (spacing 6 m x 1 m: 1,700 plants.ha^{-1}); and banana trees were planted within the cupuaçu tree rows with the other tree species (spacing 6 m x 4 m: 384 plants.ha^{-1}). The banana trees were cultivated until the 4th year, while pupunha for heart-of-palm production was maintained until the 11th year.

Table 6: Average production level - BR SAF RO 02 in the state fo Rondônia, Amazon biome.

Products	Production Period	Average production
Cupuaçu (kg.ha^{-1})	Year 6 - 20	6,550.0
Banana (bunch)	Year 1 - 4	367.5
Pupunha-seed (kg.ha^{-1})	Year 6 - 20	156.26
Andiroba (can .ha-1)	Year 12- 20	1.0
Pupunha-heart of palm (kg.ha^{-1})	Year 2- 11	378.5

The **AF 3** was established in 2006. The productive area covers 0.6 hectares, classified as a family organic farm. The AF comprises the following species composition: 1,500 **black pepper** plants (*Piper Nigrum* L.) spaced at 2 m x 2 m intervals, 188 **cupuaçu** trees (*Theobroma grandiflorum* Schum.) spaced at 6 m x 4 m intervals, 45 **açaí palm** trees (*Euterpe oleracea* Mart.) planted on the side of the productive system, 360 **paricá** trees (*Schizolobium amazonicum* Huber ex Ducke) spaced at 4 m x 4 m intervals, and 15 **andiroba** trees (*Carapa guianensis*) planted randomly. The **Brazil nut** (*Bertholletia excelsa* Humb. & Bonpl.), **copaiba** (*Copaifera* sp.), **cedar** (*Cedrela fissilis* Vell.), **uxi** (*Endopleura uchi* (Huber) Cuatrec.), **sapucaia** (*Lecythis pisonis* Cambess.), and **piquiá** (*Caryocar villosum* (Aubl.) Pers.) species are part of the system through forest reforestation and do not follow a regular spacing pattern.

Due to its dynamic nature, the species exhibit distinct permanence periods in the AFs. Thus, the production was carried out the following the temporal scheme: black pepper was introduced in year 1 and remained until year 5; cupuaçu and açaí were introduced in year 2 and remained until the end of the planning period; paricá and andiroba were introduced in year 3, with scheduled harvests planned for periods 18 and 30, respectively.

The **AF 3** features the commercialization of fresh cupuaçu, açaí, and andiroba fruits, black pepper grains, and paricá and andiroba wood. Since andiroba also contributes to fruit production, the harvest is conducted only at the end of the planning period. An overview of the production from the areas is presented in Table 7.

Table 7: Average production level - AF 3 in the state of Pará, Amazon biome.

Products	Production Period	Average production
Pimenta-do-reino (kg.ha-1)	Year 2 - 5	3875.0
Cupuaçu (kg.ha-1)	Year 5 – 30	4790.87
Açaí (kg.ha-1)	Year 5 – 30	937.5
Andiroba - frutos (kg.ha-1)	Year 8 – 30	1542.75
Paricá (m^3.ha-1)	Year 7, 11 and 14	235.78
Andiroba - madeira (m^3.ha-1)	Year 30	50.0

The **AF 4** was established in 2000. The area covers 1 hectare, with the system classified as entrepreneurial. The following species were adopted: **rice** (*Oryza sativa* L.), introduced at the beginning of the project, with a spacing of 0.4 m x 0.2 m, 2500 **black pepper** plants (*Piper Nigrum* L.) spaced at 2 m x 2 m intervals, 625 **cocoa** trees (*Theobroma cacao* L.) spaced at 4 m x 4 m intervals, 400 **açaí palm** trees (*Euterpe oleracea* Mart.) spaced at 5 m x 5 m intervals, 400 **banana** plants (*Musa* spp.) spaced at 5 m x 5 m intervals, 40 **mahogany** trees (*Swietenia macrophylla* K.) spaced at 16 m x 16 m intervals, and 16 trees (*Spondias lutea* L.) spaced at 25 m x 25 m intervals.
Similarly to **AF 3**, the species composing **AF 4** exhibit distinct implantation and permanence in the system. Thus, the following temporal dynamics were observed: rice remains in the AF only in the first year; banana and black pepper are introduced in year 1 and remain until periods 5 and 7, respectively; cocoa, açaí, mahogany, and yellow mombin were introduced in year 3 and remain until the end of the presented 30-year planning period.

The banana present in **AF 4** is solely intended for self-consumption and thus is not commercially traded. There is commercialization of rice grains and black pepper, dried cocoa beans, fresh açaí and yellow mombin fruits, and mahogany wood, harvested at the end of the 30-year AF cycle. The production period and productivity of **AF 4** are presented in Table 8.

Table 8: Average production level - AF 4 in the state of Pará, Amazon biome.

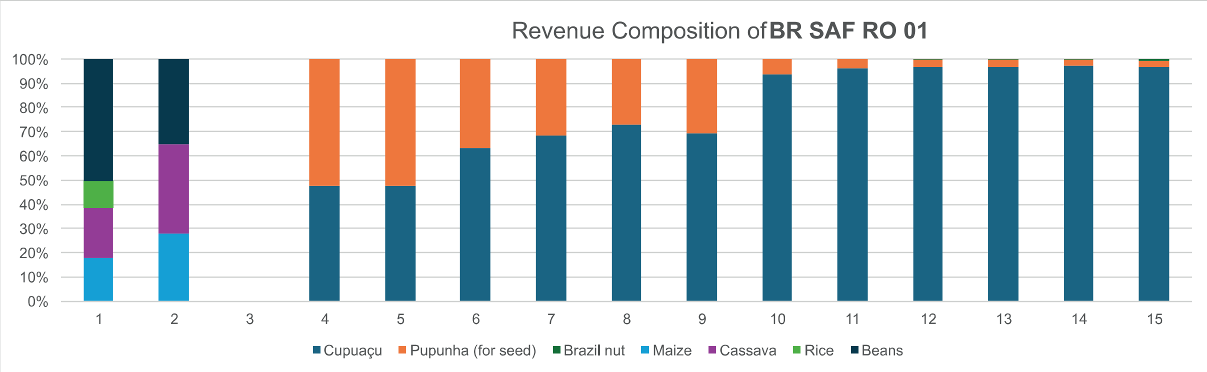
Products	Production Period	Average production
Arroz (kg.ha^{-1})	Year 1	2000.0
Pimenta-do-reino (kg.ha^{-1})	Year 2 – 7	4867.0
Amêndoa de cacau (kg.ha^{-1})	Year 7 – 30	510.0
Açaí (kg.ha^{-1})	Year 7 – 30	5850.0
Taperebá (kg.ha^{-1})	Year 6 – 30	2445.0
Mogno (m^3.ha^{-1})	Year 30	80.0

c. Results

i. Economic results

The AFs from Projeto RECA (**BR SAF RO 01** and **BR SAF RO 02)** feature perennial native species fruits such as cupuaçu and Brazil nut as the main products. However, both AFs include short-cycle crops to provide income to the farmer in the initial years. **BR SAF RO 01** is characterized by greater crop diversification in the first year, with bean sales accounting for 50.13% of revenue, rice 11.28%, cassava root 21.05%, and corn 17.54% (Figure 3a). Over the years, peach palm seeds and cupuaçu begin to produce and become the most profitable products, with cupuaçu fruit sales accounting for 63% of revenue in the 6th year. In **BR SAF RO 02**, with less production diversification, bananas account for 60% of the system's revenue in the first three years, giving way to heart of palm, which represents 100% of the system's revenue in the 5th year (Figure 3b).

(a)



(b)

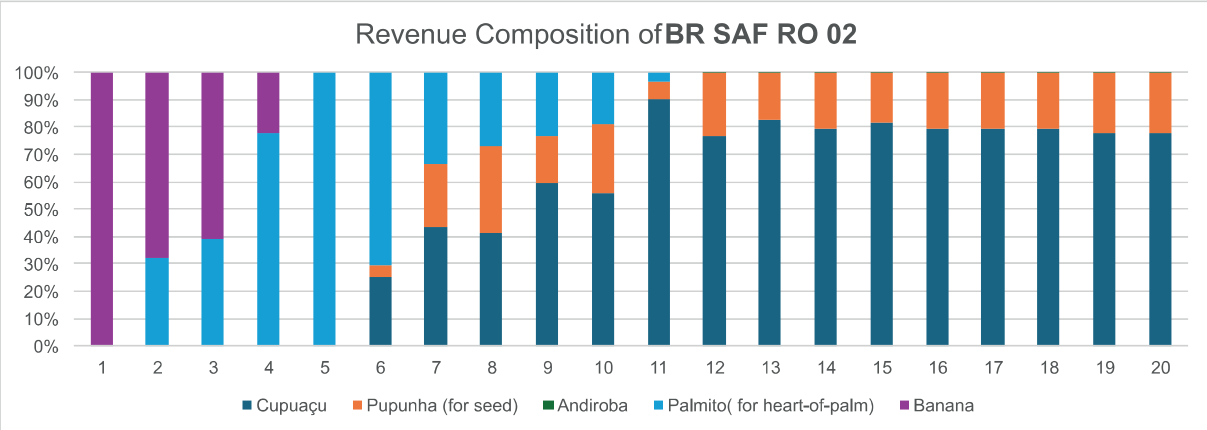
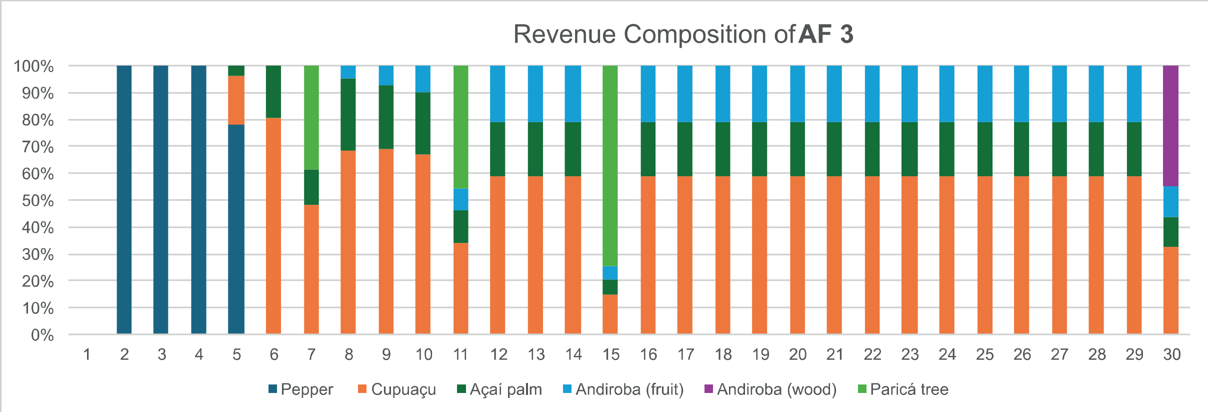


Figure 3: Revenue Composition of BR SAF RO 01 (a) and BR SAF RO 02 (b) in the state of Rondônia, Amazon biome.

For the AFs in Tomé-Açu (**AFs 3** and **AFs 4**), a 30-year analysis was considered due to the timber component (andiroba in **AF 3** and mahogany in **AF 4**), which would be sold in the 30th year. The establishment of these systems aimed to represent two distinct producer profiles: a model representative of small family farm (**AF 3**) and a business model practiced by the Tomé-Açu cooperative (**AF 4**).

In the initial years, with the establishment of crops, not only is there a higher expenditure on inputs, but also a lower diversification of the products sold, considering that most crops have not yet begun to produce. For an AF to remain profitable over the years, it is necessary to consider the time for each component to produce, as well as to enable a fast-cycle, low-cost crop that maintains positive cash flow. In **AFs 3** and **AFs 4**, black pepper served this role. Although it exhibits significant price variability over time and is not always profitable, its cultivation is traditional in Tomé-Açu region, and in both systems, its sale accounted for 100% of revenue in the initial years (year 1-4 in **AF 3** and year 2-5 in **AF 4**). Revenue diversification begins in years 5 and 6 for **AF 3** and **AF 4**, respectively, with the commercialization of cupuaçu and açaí in **AF 3** (Figure 4a), and cocoa beans in **AF 4** (Figure 4b).

(a)



(b)

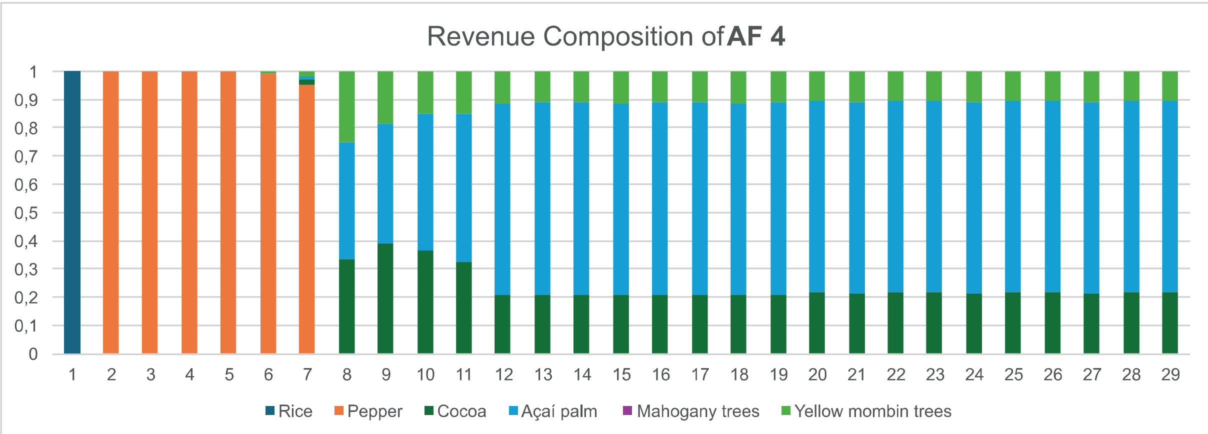


Figure 4: Revenue Composition of AF 3 (a) and AF 4 (b) in the state of Pará, Amazon biome.

In the revenue composition, cupuaçu and açaí stand out. Cupuaçu has a significant impact on the gross revenue of **AF 3**, and its production dynamics have changed over time, becoming increasingly relevant to the system. From the 6th year onwards, approximately 60% of the system's revenue comes from cupuaçu sales, except for years when paricá wood is sold. This system's distinguishing features include organic production and the utilization of all parts of the cupuaçu fruit (pulp, peel, and seed), resulting in the product being sold for 11% more than the market price in Tomé-Açu.

In **AF 4**, açaí is the primary product sold, representing an average of 60% of the system's revenue. This system deserves attention due to the presence of cocoa, which is a fruit of significant economic importance to the state of Pará and has emerged as one of the main species chosen by producers when selecting species for inclusion in the AFs. However, in the analyzed system, cocoa exhibited a productivity 27.4% lower than the state average. It is believed that this lower productivity is due to the lower tree density per hectare.

In both **AF** 3 and **AF 4,** becomes profitable as early as the second year, demonstrating the potential for operational profit generation (Figure 5). By the 5th year post-implementation, both systems are in a maintenance phase, resulting in a 13-fold reduction in input costs compared to the previous year.

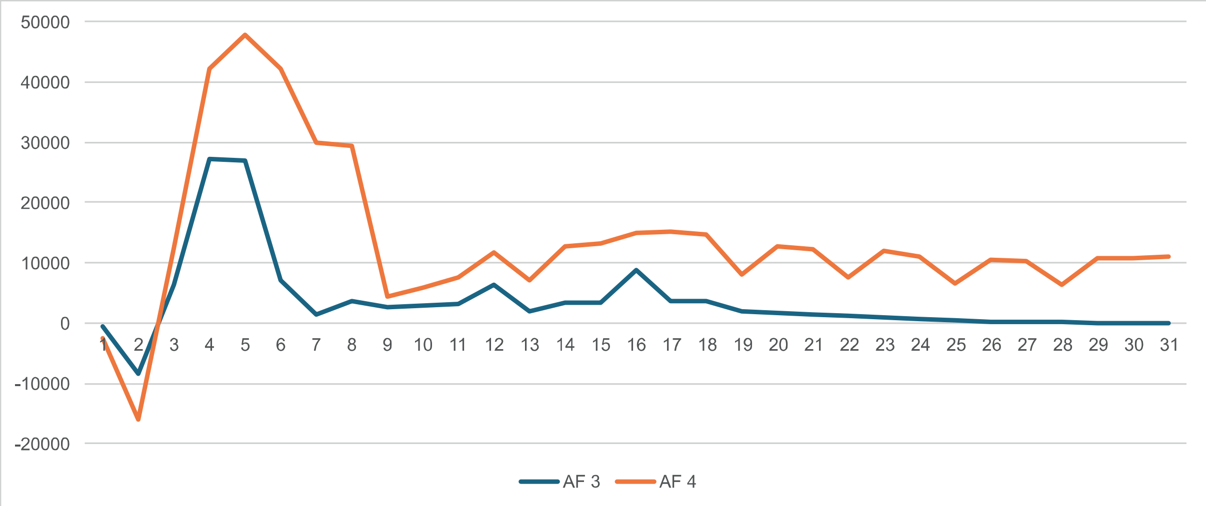


Figure 5: Operational profit dos AFs 3 e AFs 4 in the state of Pará, Amazon biome.
* 2024 prices (1 USD = 5.22 REAIS)

Upon observing the annual results of the two systems in Tomé-Açu (**AF 3** and **AF 4**) and the two systems in Rondônia (**BR SAF RO 01** and **BR SAF RO 02**) (Table 9), all four systems proved capable of covering the operating costs of their productions, considering the evaluated periods. The systems in Tomé-Açu exhibit the highest profits, primarily due to lower production costs and the sale of products with higher added value.

Table 9: Average Yearly Economic Results of agroforestry systems in the states of Rondônia and Pará, Amazon biome.

Area	Net Revenue (USD.ha-1)*	Production Cost (USD.ha-1)*	Gross Profit (USD.ha-1)*
BR SAF RO 01	3,677.00	1,468.52	2,208.48
BR SAF RO 02	2,437.96	1,396.38	1,041.58
AF 3	4,638.48	811.15	3,827.32
AF 4	7,956.03	840.03	7,116.01

* 2024 prices (1 USD = 5.22 REAIS)

ii. Economic viability indicators

The economic viability indicators highlight the economic potential of Agroforestry Systems in the Amazon biome (Table 10). Due to the adoption of AFs being primarily by small-scale farmers, the areas occupied by these systems tend to be smaller when compared to areas dedicated to commodities. Another characteristic of AFs is lower mechanization, as their implementation is more labor-intensive. These two characteristics result in a low initial investment value allocated to implementing the systems.

Table 10: Economic viability indicators - Interest rate, Annual Net Present Value (NPVA), Return on Investment (ROI) and Benefit/Cost of agroforestry systems in the states of Rondônia and Pará, Amazon biome.

Indicators*	BR SAF RO 01	BR SAF RO 02	AF 3	AF 4
Investment (USD.ha^{-1})	653.76	1,191.71	636.11	1,819.24
Interest rate (%)	7.16	7.63	-	-
NPVA (USD.ha^{-1}.year^{-1})	1,720.49	1,022.28	-	-
IRR (%)	40.30	32.00	-	-
ROI (%)	32.70	20.55	-	-
Benefit/Cost (USD.ha^{-1})	2.50	1.75	5.60	9.20

* 2024 prices (1 USD = 5.22 REAIS)

While in ICLFs the investment value refers to machinery and infrastructure, in AFs the investment value corresponds to expenditures on inputs, labor wages, and equipment (hoes, shears, files, etc.) to implement the production system. Also, the economic analysis period of AF systems needs to be long so that the revenues from the core-species, generally native forest species, can be considered. Hence, the combination of low investment value and a long evaluation period results in high cash flow values, and, consequently, high NPV and internal rate of return values.

For **BR SAF RO 01**, over a 15-year period, this system would yield an annual profit per hectare (NPVA) of 1,720.49 USD.ha^{-1}. Also, the benefit/cost ration indicates that for every real spent, the system would return 2.50 USD.ha^{-1}. **BR SAF RO 02** presents a value 1.8 times higher than **BR SAF RO 01**, with an annual net profit

(NPVA) per hectare 60% lower. Nonetheless, this system remains competitive, with an internal rate of return (IRR) higher than the discount rate used, and for every USD spent, it presented a return of 1.75 $USD.ha^{-1}$. For both **BR SAF RO 01** and **BR SAF RO 02**, the discount rates used were the savings rates for the years of implementation 2014 and 2007, respectively. Savings rates were chosen due to the farmers' profile. Despite engaging in agricultural production, an activity with many inherent risks, their investor profile is predominantly conservative.

AF 3 and **AF 4** present an investment of 636.11 $USD.ha^{-1}$ and 1,819.24 $USD.ha^{-1}$ respectively. Given the low initial investment and the long assessment period due to the extended production cycle period of the core species within these systems, conventional viability indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) lack the requisite robustness to contribute for farmers' decision-making processes effectively. Consequently, an indicator that illustrates the cash flow dynamics of these systems most succinctly is the benefit-to-cost ratio. Even though **AF 3** has an investment value 2.84 times lower than **AF 4**, with the estimated revenue and cost values, its benefit/cost ratio is 5.60, while for **AF 4** this ratio was 9.20. This difference occurs mainly due to the higher revenue in **AF 4** from the sale of açaí and cocoa, as seen in the Figure 4b.

4.2 - Potential economic impacts of ICLF expansion over the Cerrado and Amazon biomes

In December 2023, the Ministry of Agriculture and Livestock (MAPA) established the National Program for the Conversion of Degraded Pastures (PNCPD). This initiative outlines the goal of recovering 40 million hectares of degraded pastures within a decade. Currently in the process of implementation, the PNCPD aims to establish a financial framework, facilitated by contributions from BNDES and external sources, to support the adoption of sustainable agricultural practices. These practices include Intensive Crop-Livestock-Forestry Integration (ICLFs) and Sustainable Agroforestry Systems (AFs).

Pasture degradation generally occurs through two primary mechanisms: “agricultural degradation” and “biological degradation.” “Agricultural degradation” is characterized by excessive weed proliferation, which limits cattle from selecting and consuming forage, thereby reducing the pasture’s productive capacity. In contrast, “biological degradation” refers to a decline in pasture productivity due to soil deterioration. This deterioration is marked by an increase in bare soil, which exacerbates erosion and leads to the loss of organic matter and essential soil nutrients. “Biological degradation” is more severe, as it not only affects pasture quality but also compromises soil health. (Dias-Filho, 2017).

Degraded pastures diminish biomass production capacity, leading to reduced livestock productivity. Additionally, they cause environmental damage by depleting organic matter, inhibiting soil microbial activity, increasing erosion, and elevating greenhouse gas emissions. Restoring 40 million hectares of degraded pastures offers significant environmental and economic benefits. However, the recovery process requires a variety of techniques and involves considerable costs, which vary based on the level of degradation and the specific biome.

Given the potential for recovery degraded pasture areas through adoption of Integrated Crop-Livestock-Forestry systems, we conducted an analysis to evaluate the prospective economic impacts of this expansion. To carry out this analysis, we use reference data from case study presented ant section 4.1.1 (Tables 2 and 3), alongside corresponding information regarding degraded pasture areas within these biomes. This data elucidates the financial and productive parameters characterizing ICLFs economic performance in comparison to large-scale crop and extensive livestock production systems.

Brazilian pastures exhibit significant diversity in types and quality. MapBiomas (2024) data indicate that the Cerrado biome contains around 14 million hectares of low-vigor pastures and 20.8 million hectares of medium-vigor pastures, while the Amazon biome holds approximately 8.5 million hectares of low-vigor and 22.2 million hectares of medium-vigor pastures, all of which are suitable for restoration. Figure 6 shows the spatial distribution of pastures in Brazil, categorized by quality within the Cerrado and Amazon biomes.

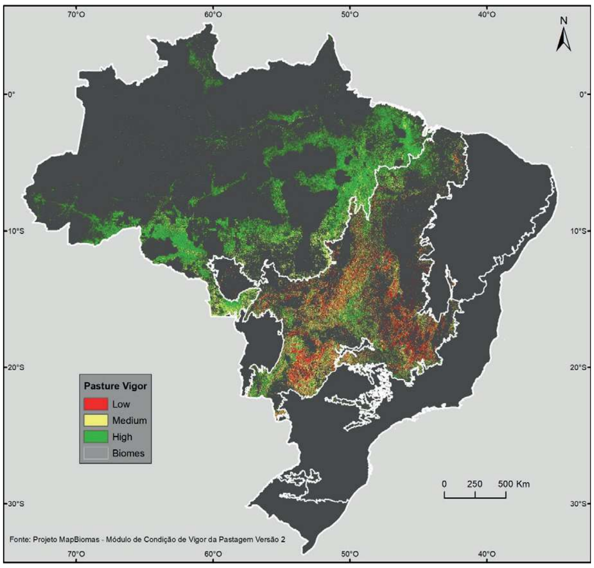


Figure 6: Pasture areas in the Cerrado and Amazon biomes.
Source: MapBiomas (2024)

The extrapolation exercise involves expanding ICLFs alongside other traditional systems (typical livestock and typical crop - soybean/corn) in medium-vigor pasture regions. These areas, which are already productive, have the potential for improvement through the adoption of sustainable production systems like ICLF. Due to their intermediate level of degradation, the costs of restoration are relatively lower than low-vigor pastures, making them ideal candidates for initial recovery. Thus, the exercise targets the rehabilitation of 20.8 million hectares of medium-vigor pasture in the Cerrado biome and 22.2 million hectares in the Amazon biome.

As the focus is to assess the economic impacts of the large-scale adoption of ICLFs in Brazil, the projections focus solely on the economic outcomes of these activities, including the annual gross revenue generated by the implemented system. Table 11 presents the projected annual financial results following the expansion of ICLFs and traditional systems (typical livestock and typical crop - soybean/corn) across medium-vigor pasture areas in the Cerrado biome.

Table 11: Economic projections of costs and benefits of 20.8 million hectares of pasture recovery in the Cerrado biome.

Economic Indicator	Production System		
	Typical ICLF	Typical Livestock	Typical annual Crop
Net Revenue*	$23.5	$12.1	$19.4
Production Cost*	$15.9	$8.7	$12.3
Gross Profit*	$7.6	$3.4	$7.0
Production beef cattle (Tonnes.ha^{-1})**	5.0	3.9	-
Productivity – soybean (Tonnes.ha^{-1})**	919.2	-	1,060.1

*$ Values in billions
**Values in millions

Considering that the 20.8 million hectares of medium-vigor pasture were occupied with ICLF areas, US$23.5 billion would be generated in revenues, US$15.9 billion in production costs, totaling US$7.6 billion in gross profit for farmers, per year, after implementation. The production generated by this system would comprise the supply of 5 million tons of beef and 919 million tons of soybeans in the Brazilian market. Hence, the economic benefits of ICLF recovery would outweigh those generated by traditional production systems.

To assess the potential impacts on the Brazilian economy, we utilized an Input-Output (I/O) model, incorporating the latest data available from the Input-Output Matrix for Brazil for the year 2015 (IBGE, 2017). We projected the expansion of production by adoption of ICLFs across 20.8 million hectares of medium-vigor pasture within the Cerrado biome. The findings illustrate the impacts in terms of production levels, income generation, employment opportunities, and gross value-added within the economy.

Table 12 presents the production, employment, income, and gross value-added multipliers for the ICLFs, livestock, and crop activities. Multipliers serve as indicators of sectoral participation within the economy. As the ICLF sector is not individually delineated in the Input-Output (I/O) matrix, the multiplier for the agriculture sector was employed as a proxy. This multiplier was derived from the aggregation of the 12x12 I/O matrix (IBGE, 2017), which encompasses activities from agriculture, livestock, forestry, and fishing. Conversely, the multipliers for traditional livestock and crop systems were extracted from the disaggregated 67x67 I/O matrix (IBGE, 2017), reflecting the diverse sectors within the economy.

Table 12: Sectoral multipliers as indicators of performance of ICLF and typical livestock and annual cropping systems.

Multiplier	Production	Employment	Income	Gross Value-Added
ICLF*	2.54	9.62	0.41	1.24
Livestock	2.80	11.62	0.50	1.33
Crop	2.40	7.07	0.34	1.12

Source: Vale; Perobelli (2020).
*Multipliers refer to the aggregation of the agricultural, livestock, forestry, and fishing sectors listed in the 12x12 I/O matrix (IBGE, 2017).

The total output multiplier of 2.54 implies that a $1 million change in demand for ICLF activities yields $2.54 million of output in the economy. Similarly, the total employment multiplier of 9.62 suggests that a $1 million increase in demand for ICLF generates 9 jobs within the economy. As for the total income multiplier, which amounts to $0.41 million, a $1 million shift in demand for ICLF activities results in $0.41 million of income generated within the economy. Moreover, the Value-Added multiplier indicates that every $1 million of final demand in the ICLF sector contributes $1.24 million of value-added to the economy. The same interpretation applies to the multipliers for the livestock and crop sectors.

It should be noted that the findings presented must be interpreted with caution since the ICLF multiplier represents the agricultural sector in an aggregated way and not the specific multiplier of the ICLF sector. The livestock multiplier represents the multiplier of the aggregate livestock sector, which encompasses other types of livestock in addition to cattle production. Likewise, the crop multiplier incorporates diverse crop types. For this reason, the livestock multipliers reported in Table 12 are higher than those of the ICLF and agriculture sectors.

The recovery of 20.8 million hectares in the Cerrado biome through ICLF systems is projected to generate $23.5 billion in net revenue, as shown in Table 11. This would result in an estimated $59.9 billion in total economic production, affecting the entire production chain and creating approximately 159,580 jobs: 57,580 direct and 102,100 indirect. This economic activity is expected to generate $9.8 billion in income and $29.3 billion in value-added. Since the gross revenue from ICLFs surpasses that from traditional livestock or large-scale crop systems, the overall economic impact is anticipated to be significant. With a projected gross revenue of US$993.10 per hectare (Table 3), the expansion of 22 million hectares of ICLFs in the Amazon biome alone would inject US$56.2 billion into the Brazilian economy. This expansion would mobilize approximately 53,860 direct and 95,690 indirect jobs, generating $9.1 billion in income and $27 billion in value-added (Table 13).

Table 13: Production, employment and income projections, by type of production system in the Cerrado and Amazon biomes.

Sector / Projections	Production	Employment	Income	Value-Added
ICLF-C (Cerrado)	$59.9	159,580	$9.8	$29.3
ICLF-A (Amazon)	$56.2	149,550	$9.1	$27.4
Livestock	$40.2	99,540	$6.1	$16.3
Crop	$53.5	96,770	$6.6	$21.8

*$ Values in billions

The combined expansion in both biomes is expected to mobilize 300,000 jobs, marking a substantial 20.6% increase in formal employment within the Brazilian agricultural sector. Additionally, there would be an 8.4% increase in agricultural value-added. Considering the high level of informality in this sector, this expansion is likely to engage even more labor resources, further contributing to economic growth and development.

The expansion of ICLFs in Brazil not only generates significant economic benefits but also offers positive environmental outcomes. The increased productivity of livestock within ICLFs allows for higher beef production per hectare compared to traditional livestock systems. This efficiency leads to a "land-sparing" or "forest-saving" effect. Table 14 illustrates the productivity per hectare, the production resulting from the expansion over medium-vigor pasture areas, and the "land-sparing" effect by production system and biome.

The "land-sparing" or "forest-saving" effect of ICLFs stems from their ability to achieve higher productivity per unit of land compared to traditional agricultural systems. By optimizing production on existing agricultural land, ICLFs diminish the need to expand agricultural activities into natural ecosystems, such as forests. This reduces pressure on forests and other natural habitats, supporting biodiversity conservation, preserving wildlife habitats, and mitigating deforestation. Ultimately, adopting ICLFs promotes sustainable land use, fosters environmental stewardship, and contributes to the long-term health and resilience of ecosystems.

Table 14: Land-sparing effect of wider adoption of ICLF in the Cerrado and Amazon biomes.

Biome / Production System	Cerrado		Amazon	
	ICLF	Traditional livestock	ICLF	Traditional livestock
Productivity beef cattle (@ produced. ha^{-1})	16.22	12.59	38.03	12.59
Produced area	20.8 million ha		22.2 million ha	
Annual production (Tonnes)	5.0 million	3.9 million	12.6 million	4.2 million
Area required for traditional livestock to produce the same as ICLF	-	26.8 million ha	-	67.2 million ha
Land-sparing effect	6 million ha		44.9 million ha	

The expansion of ICLFs across 20.8 million hectares in the Cerrado biome is expected to produce approximately 5 million tons of beef cattle. In comparison, the same land area under traditional cattle ranching would yield about 3.9 million tons of beef. To produce 5 million tons of beef using traditional livestock methods, a much larger land area - around 26.8 million hectares - would be required. Therefore, the adoption of ICLFs over the 20.8 million hectares of medium-vigor pasture in the Cerrado biome would result in a significant "land-sparing" effect, equivalent to approximately 6 million hectares. This saved area is comparable to the size of 40 cities of São Paulo.

This effect would be even more pronounced in the Amazon biome, where productivity in ICLFs can be up to three times higher than in traditional systems, potentially saving around 44 million hectares. This area is equivalent to an astonishing 296 cities the size of São Paulo. It should be noted that the data on average productivity per hectare of ICLF in the Amazon is based on a model property specializing in high-productivity cattle production. Even with alternative productivity parameters, ICLF tends to demonstrate higher efficiency. The greater the productivity, the less land is required. Consequently, adopting sustainable production systems like ICLF could save millions of hectares, significantly reducing deforestation, particularly in the Amazon biome.

4.3 - Systematic Literature Review

To complement the findings discussed in the case studies and to illustrate the economic potential of the sustainable agricultural systems considered in this research, we provide a summary of the economic results derived from the studies selected through the systematic literature review.

4.3.1- General Results

Recent studies aimed to identify the economic benefits provided by sustainable agriculture systems. It is noteworthy in these studies the focus on assessing the capacity of integrated systems to minimize market risks due to diversification, and on evaluating the economic performance of these systems in comparison with continuous crop systems and continuous extensive livestock systems. However, in Brazil, there are a limited number of studies considering the ICLF systems, as well as the agroforestry systems, as feasible strategies for promoting sustainable development in agriculture (Cortner et al., 2019; Garrett et al., 2020, 2017). As a synthesis of the systematic literature review carried out, Table 15 and 16 displays the results for the studies selected.

The general information from Tables 15 and 16 supports the hypothesis that agroforestry systems are more suitable to small farms. On the other hand, integrated crop-livestock-forestry systems are more frequently adopted by large farmers, as an alternative to large-scale monocropping or as a strategy to improve profitability in extensive livestock systems. Moreover, the results suggest a spatial

concentration of these different sustainable agricultural systems: Amazon biome displays a huge concentration of agroforestry systems and Cerrado biome, particularly due to its environmental agriculture suitability and better infrastructure networks (roads, grain processing and storage capabilities), concentrates the integrated crop-livestock-forestry systems. It is noteworthy that most integrated systems in the Amazon biome are concentrated in Mato Grosso, in the agriculture forest-frontier. This highlights the perspective that adoption of ICLF systems is influenced by the possibility of large-scale crop production, availability of degraded pasture in areas with environmental suitability and good infrastructure conditions for expansion of these systems without pressuring for further deforestation.

Taking into account the enormous difficulty to build time-series economic data, most studies present only annual information as revenue and production cost. Also, there is great variability in the economic approaches implemented to assess the field information, limiting comparison among the studies. Hence, and considering the small sample, the information from Table 15 and Table 16 represents a general guide to understand the economic performance of these agricultural systems in both biomes.

4.3.2 - Integrated Crop-Livestock-Forest systems

Table 15 displays the economic performance of ICLF systems from Amazon and Cerrado biomes. As discussed previously, the number of studies providing robust economic information from ICLF systems is quite limited, particularly to assess their economic viability. The most recent study found indicated the investment to implement an ICL system in northwest region from Mato Grosso was 905.49 USD.ha^{-1} and the investment to implement a ICLF system at same region was 1,037.18 USD.ha^{-1} (dos Reis et al., 2023a).

The revenue from integrated systems displays considerable variability, ranged from 430.45 USD.ha^{-1} to 1,859.82 USD.ha^{-1}, illustrating the

huge diversity of production conditions of these agricultural systems. The similar situation of huge variability was observed considering production cost, ranged from 259.28 $USD.ha^{-1}$ to 1,415.14 $USD.ha^{-1}$. The highest values were observed from ICLF systems and may be explained by both: revenue associated with a diversified production supply over the year, taking advantage of market conditions; and production cost related to the initial values to implement the forest component as well as the additional operation cost to manage it.

The viability economic indicators found suggest the positive performance of integrated systems in the long-run. This result highlights the economic potential of integrated system providing high revenue level over the years. Also, the integrated systems displayed positive beneficial/cost relation suggesting that these systems present high capacity to generate return considering the initial investment. The payback values found for integrated systems support this perception. Even displaying high investment levels, the integrated systems showed short payback period.

Table 15: Economic and Financial information from sustainable agricultural systems in Amazon and Cerrado: Integrated Systems.

(continue)

Productive Systems	Biome	Farmers' profile	Annual Revenue*	Production Cost*	NPV*	IRR	B/C	Payback (years)	Source	Year**
ICL	Amazon	Large	958.94	633.32	-	-	-	-	(dos Reis et al., 2023b)	2020
ICL	Amazon	Large	1,236.51	943.02	-	-	-	-	(dos Reis et al., 2023b)	2020
ICL	Amazon	Large	1,557.52	816.24	-	-	-	-	(dos Reis et al., 2023b)	2020
ICL	Cerrado	Large	430.45	259.28	136.25	22.1%	1.7	4	(dos Reis et al., 2020)	2019
ICL	Cerrado	Large	854.01	577.29	30.99	12.0%	1.1	5	(dos Reis et al., 2023a)	2023
ICL	Cerrado	Large	1,265.26	836.18	-	-	-	-	(dos Reis et al., 2021)	2020
ICL	Cerrado	Large	-	440.03	-	-	-	-	(Pereira, 2019)	2018
ICL	Cerrado	Large	-	871.22	-	-	-	-	(Pereira, 2019)	2018
ICL	Cerrado	Large	631.98	504.53	-	-	-	-	(Pereira, 2019)	2018

Productive Systems	Biome	Farmers' profile	Annual Revenue*	Production Cost*	NPV*	IRR	B/C	Payback (years)	Source	Year**
ICL	Cerrado	Large			240.04		11.1	2	(Pereira, 2019)	2019
ICLF	Amazon	Large	1,514.49	1,415.14	-	-	-	-	(Pereira, 2019)	2018
ICLF	Amazon	Large	534.98	939.03	-	-	-	-	(Pereira, 2019)	2018
ICLF	Cerrado	Large	941.43	637.85	72.75	16.0%	1.3	7	(dos Reis et al., 2023a)	2023
ICLF	Cerrado	Large	1,859.82	894.58	-	-	-	-	(Pereira, 2019)	2018
ICLF	Cerrado	Large			219.52		6.2	5.3	(Pereira, 2019)	2019
ICLF	Cerrado	Large			94.95		2.5	11.1	(Pereira, 2019)	2019
ICLF	Amazon	Large	993.88	400.56	-	-	-	-	(Pereira, 2019)	2018
ILF	Amazon	Large	497.77	398.71	-	-	-	-	(dos Reis et al., 2023b)	2020

* Values in USD (American Dollar). Exchange rates from Ipeadata, the official Brazilian Government department for economic data: http://www.ipeadata.gov.br/Default.aspx

** Reference year for economic data analysis.

4.3.3 - Agroforestry Systems

Our findings illustrated the huge economic performance variability of agroforestry systems, evidencing that each agroforestry system presents specific production conditions regarding the farmer's objectives, their productive skills and infrastructure, and the core-species chosen. The annual revenue observed ranged from 640.86 USD.ha^{-1} to 2,781.39 USD.ha^{-1}, and the production cost from 587.04 USD.ha^{-1} to 2,550.52 USD.ha^{-1}. These values are explained by the diverse land use strategies related to agroforestry systems management, as well as the differences in the core-species.

On the other hand, the most findings indicated similar beneficial/cost relation values, and all studies provided values higher than 1, indicating that the agroforestry systems, spite of the economic, social and regional differences in productive conditions, displayed economic potential to generate revenue greater than the cost to implement and manage them. For the payback indicator, two studies indicated 9 years to recover the initial investment. However, the others indicated similar values, around 5 years, a period similar those observed to integrated systems.

The diversification of products from agroforestry systems also may provide economic risk mitigation. However, to achieve this situation, the farmers need to improve their management and planning skills to generate cash flow in the short run.

Table 16: Economic and Financial information from sustainable agricultural systems in Amazon and Cerrado: Agroforestry Systems.

Productive System	Biome	Farmers' profile	Annual Revenue*	Production Cost*	NPV*	IRR	B/C	Payback (years)	Source	Year**
Agroforestry System	Amazon	Small	1,694.79	1,319.40	-	28.45%	1.3	-	(de Oliveira et al., 2017)	2016
Agroforestry System	Amazon	Small	-	-	454.82	34.54%	1.6	6	(de Oliveira et al., 2016)	2016
Agroforestry System	Amazon	Small	2,437.01	667.35	1,769.66	35.4%	3.7	5	(Arco-Verde and Amaro, 2014a)	2014
Agroforestry System	Amazon	Small	2,438.21	1,140.95	1,297.26	19.4%	2.1	9	(Arco-Verde and Amaro, 2014b)	2014
Agroforestry System	Amazon	Small	-	-	349.91	34.5%	1.6	6	(de Oliveira et al., 2016)	2016
Agroforestry System	Amazon	Small	-	-	520.31	70.0%	2.6	-	(Rodrigues et al., 2017)	2017
Agroforestry System	Amazon	Small	640.86	-	-	-	-	-	(Botelho, M. G. L. et al., 2023)	2021
Agroforestry System	Amazon	Small	768.20	587.04	-	-	-	-	(Homma et al., 2013)	2013
Agroforestry System	Cerrado	Small	2,764.46	2,550.52	213.73	10.5%	1.1	9	(Garcia et al., 2021)	2020
Agroforestry System	Cerrado	Small	2,781.39	1,997.37	783.37	21.7%	1.4	6	(Garcia et al., 2021)	2020

* Values in USD (American Dollar). Exchange rates from Ipeadata, the official Brazilian Government department for economic data: http://www.ipeadata.gov.br/Default.aspx

** Reference year for economic data analysis.

5. Barriers, Public Policies and Incentives to boost the adoption of sustainable agricultural systems

The current area occupied by ICLFs in Brazil is still relatively small: 17 million hectares, accounting for 7% of the total area occupied by agriculture and livestock (Embrapa; Rede ILPF, 2017; IBGE, 2020; Polidoro et al., n.d.). Some factors explain this relatively low adoption rate of ICLF systems, such as: i) cultural barriers, ii) high initial investment, iii) supply chain limitations and shortage of qualified labor, iv) lack of information, v) lack of technical assistance, and vi) lack of information about the economic performance of ICLF systems (Cortner et al., 2019; Embrapa; Rede ILPF, 2017; Skorupa and Manzatto, 2019). On the other hand, financial and non-financial incentives have been offered to boost the adoption of ICLF and AF in Brazil. However, only a small proportion of the total annual budget for rural credit made available by the Brazilian Government thought the Safra Plan has been allocated to promote wider adoption of ICLFs and AF systems and best production practices (Assad et al., 2020). To contribute with this debate, we will discuss the main barriers to adopt sustainable agriculture in the Amazon and Cerrado biomes and the most relevant public policies implemented to deal with them. Also, we will highlight incentives to enhance adoption of both systems based on the findings of the systematic literature review (Table 17 to Table 20).

Table 17: Barriers, Public Policies and Incentives to boost the adoption of sustainable agricultural systems: Financial*.

			Financial		
Barriers	**Farmers' Profile**	**Biome**	**Public Policy**	**Incentives**	**Suggested Improvements**
1) Credit policies are not aligned with the cash-flow dynamic from sustainable agricultural systems. 2) Lack or poorly defined land tenure rights limit farmers' access to credit and increase incentives to deforest land to acquire ownership, particularly in the Amazon biome. 3) ICLF requires a higher initial investment. 4) Credit mechanisms and rural insurance are often focused on single commodities and not on the annual production flow of the different crops e animals in ICLFs and AFs systems 5) The unpreparedness of banks to evaluate the economic viability of sustainable agricultural systems.	1) Both 2) Small 3) Both 4) Large 5) Both	1) Both 2) Amazon 3) Both 4) Large 5) Both	1) Safra Plan and ABC Plan.	1) Public credit policies offering low-interest federal loans to fund investments or costs related to productive diversification. 2) Integrated bonuses within the Safra Plan 2023/2024 for farmers who adopt sustainable agricultural systems.	1) The need for comprehensive credit systems that embrace a longer-term perspective is crucial for supporting the transition to sustainable agricultural systems, particularly those with perennial species. The credit systems should take into account the economic, social and environmental outcomes of farm transformation**. 2) Promote improvements to increase the capacity efficiency and effectiveness of the Brazilian land regularization system. 3) Enhance the provision of subsidies, interest rate discounts for farms using sustainable agricultural systems and best production practices. 4) Credit lines could be tailored to align payments to the flow and quantity of products generated by the system, akin to the mechanism observed with the Rural Producer's Certificate (CPR)**.

*Items organized in order of importance

**Greater relevance to Agroforestry Systems (AFs).

5.1 - Financial Barriers

Credit policies are not aligned with the cash-flow dynamic from sustainable agricultural systems (dos Reis et al., 2023b, 2020). Existing funding lines prioritize annual profit outcomes over risk reduction, in part due to insufficient data on financial returns from different types of ICLFs and AFs in the Amazon and Cerrado biomes. These systems tend to present short-term negative economic results due to higher initial investment requirements, as well as operational challenges facing new adopters of more intensive, and diversified production systems. Credit lines designed to promote adoption of these systems, particularly Renovagro (ABC Financing), offer an insufficient grace period for the systems to achieve a significant level of productive maturity and positive economic cash flow. As a result, this inadequacy hinders the producer's ability to meet installment payments.

Poorly defined land tenure rights limit farmers' access to credit and increase incentives to deforest land to acquire ownership, particularly in the Amazon biome. Funding institutions tend to connect credit operations to farmer´s payment capacity, and land tenure is an usual instrument to hedge these financial operations. Therefore, the limited land use regularization tends to increase risk perception by financial institutions (Schembergue et al., 2017; Luiz et al., 2023; Silva, et al., 2023). This situation is particularly relevant for small farmers, who are more susceptible to market prices fluctuations, possess lower income levels, and have limited capacity to provide the financial assurances required by financial agents to secure credit. The deficiencies in operational infrastructure and qualified human resources results in low efficiency and efficacy of the Brazilian land regularization system, exacerbating this problem.

ICLF requires a higher initial investment. A recent study indicated that the investment to implement an ICL system in the northwest region from Mato Grosso was USD 905.49 ha^{-1}, and the

investment to implement an ICLF system, in same region, was USD 1,037.18 ha^{-1} (dos Reis et al., 2023b). These values are higher than those required for both typical large-scale annual cropping systems (USD 880.71 ha^{-1}) and extensive livestock systems (USD 374.15 ha^{-1}) from the Cerrado biome.

Credit mechanisms and rural insurance are often focused on single commodities. Credit mechanisms that only cover planting costs or the purchase of new machinery are inadequate for transforming farming practices from specialized systems to diversified, sustainable agricultural systems. The existing credit mechanisms and rural insurance services in Brazil are based on anticipated outcomes for a single crop, focusing exclusively on one product. To enhance de adoption of diversified agricultural systems, it is crucial that these services are redesigned to consider the costs and expected results for the entire cropping season, incorporating all productive activities undertaken by the farmer throughout the period.

The unpreparedness of banks to evaluate the economic viability of sustainable agricultural systems is a significant barrier towards wider adoption of these systems. Financial agents possess limited understanding and insufficient information regarding the economic indicators (e.g. costs, revenue, payback period) of the potential of sustainable agricultural systems. Moreover, they lack suitable tools to assess the financing projects. Additionally, due to legal requirements - particularly those related to compliance to environmental law - and the need to meet performance targets based on the number of credit transactions and the volume of funds disbursed, financial agents tend to favor credit lines that are less restrictive in terms of regulatory and bureaucratic requirements and for which they have more operational familiarity (Tanure et al., 2024).

5.1.1 - Public Policy strategies to overcome these barriers

Safra Plan and ABC Plan[2]

The Rural Credit Safra Plan provides financial support for production of agricultural goods, which consists of loans below market interest rates. The current Safra Plan (2024/2025) encompasses a budget totaling R$ 400.49 billion in direct loans and a supplementary R$ 108 billion in Agribusiness Letters of Credit (LCA), for issuing Rural Product Notes (CPR). Notably, the plan offers preferential interest rates ranging from 4% to 12.5%, representing a financial incentive compared to prevailing rates accessible to the agricultural sector (Brasil, 2024). An additional of R$ 76 billion are designated for small farmers with interest rates ranging from 2% to 4%, with special investment directed towards women and the youth, and in areas such as bioeconomy, agroecology, and forestry.

5.1.2 - Current Incentives

Public credit policies offering low-interest federal loans to fund investments or costs related to productive diversification. The Safra Plan 2024-2025 offer several specific credit lines for adopting sustainable agricultural systems, such as ICLF and AF. Also, this public policy innovates by offering different interest rates, grace periods, and credit guarantees according to farmer´s profiles.

Moreover, to incentivize sustainable practices, **the Brazilian government has integrated bonuses within the Safra Plan 2024/2025 for farmers who adopt sustainable agricultural systems (ICLF and AF) and practices such as: i)no-tillage agriculture; ii) bio-inputs for biological control, nutrition and abiotic and**

2. The Safra Plan applies to diverse agricultural activities such as planting, trading, investment in infrastructure, irrigation systems, recovery of degraded pastures, agroecology, and adoption of low-carbon agriculture systems (Brasil, 2024). Regarding Brazil's Low-Carbon Agriculture Plan (ABC Plan), specific credit lines are allocated for Integrated Crop-Livestock-Forest systems and Agroforestry Systems initiatives (Brasil, 2012b, 2021). In 2022, the uptake of ABC loans was R$1.9 billion, with a notable concentration observed in the Central-West region (R$ 650.3 million) and the Southeast (R$ 428.5 million).

biotic stress relief; and iii) grass-legume mixed pastures with biological nitrogen fixation capability to replace N fertilizers and reduce greenhouse gas emissions from cattle production. Consequently, a 0.5% interest rate reduction is granted for adopting pasture restoration, agroecological cultivation, and sustainability certification (Brasil, 2024).

5.1.3 - Suggested Improvements

The need for comprehensive credit systems that embrace a longer-term perspective is crucial for supporting the transition to sustainable agricultural systems. The credit systems should consider the outcomes of farm transformation, including economic risk mitigation, reduction of negative social and environmental externalities, and enhancement of soil health and quality, in relation to the private returns from agricultural production.

Alongside the provision of subsidized credit, it is imperative to tailor payments to align with the cash flow generation capacity inherent in sustainable agricultural systems, particularly those that include perennial plant species and livestock. Typically, this capacity is lower during the initial years but demonstrates a systematic increase over time (dos Reis et al., 2020; Garrett et al., 2020). Existing funding tend to prioritize short-term profit outcomes over risk mitigation or have insufficient data concerning the financial returns associated with production systems exhibiting long-term performance.

Enhance the provision of subsidies or tax breaks for farms using sustainable agricultural systems and practices. This type of targeted benefit would allow greater returns for farmers, while accounting for collective social and environmental benefits that their productive activity provides, which goes beyond production of food, fiber and biofuel.

Credit lines could be tailored to link payments to the quantity of produce generated, akin to the mechanism observed with the Rural Producer's Certificate (CPR). The CPR functions as a security instrument tied to a commitment to future delivery of agricultural goods, thereby providing financial support to producers throughout the production and marketing phases (Brasil, 1994). This improvement is particularly relevant for Agroforestry Systems' farmers.

Table 18: Barriers, Public Policies and Incentives to boost the adoption of sustainable agricultural systems: Environmental.

Environmental					
Barriers	**Farmers' Profile**	**Biome**	**Public Policy**	**Incentives**	**Suggested Improvements**
1) Lack of regulation to implement Law 14.119 that established the Nacional Policy for payments of Environmental Services. 2) Lack of regulation of the carbon market. 3) Increasing of land prices, particularly land suitable for implementation of large-scale monocropping systems. 4) Insufficient capacity of government institutions for speeding up the process of validating the Rural Environmental Registry restricts producers' access to rural credit	1) Both 2) Large 3) Large 4) Both	1) Both 2) Both 3) Cerrado 4) Both	1) Forest Code Law. 2) ABC Plan. 3) National Policy for Payment for Environmental Services. 4) Brazilian Greenhouse Gas Emissions Trading System.	1) The land use change regulation. 2) The CAR serves as a prerequisite for participation in programs offering subsidized credit, such as the ABC Plan. 3) Payment for environmental services (PES); National Policy for Payment for Environmental Services (NPPES). 4) The establishment of the Brazilian Greenhouse Gas Emissions Trading System (SBCE), which imposes emission limits and institutes a marketplace for the trading of carbon credits.	1) Strengthen public investment in research to develop indicators and metrics that can serve as benchmarks for environmental policies. 2) Include as priority on the political agenda the establishment of the National Registry of Payment for Environmental Services (NRPES), the creation of the Federal Program for Payment for Environmental Services (FPPES), and the Brazilian Greenhouse Gas Emissions Trading System. 3) The implementation of the Carbon Credits Market can be a robust instrument to boost the adoption of sustainable agricultural systems**. 4) Improve and strengthen the infrastructure and human resources of the Rural Environmental Registry (CAR) to speed up environmental compliance and certification of the rural establishments in the Amazon and Cerrado biomes 5) Implement mechanisms provided for the Forest Code to regularize environmental liabilities

*Items organized in order of importance

**Greater relevance to Agroforestry Systems (AFs).

5.2 - Environmental Barriers

Lack of policy to implement payment for ecosystem services. In general, Brazilian farmers expect to be rewarded for the climate mitigation benefits their sustainable intensification efforts provide (Cortner et al., 2019; Tanure et al., 2024).

Lack of regulation of the carbon market. A primary environmental benefit offered by sustainable agricultural systems is their positive carbon balance, wherein these systems sequester more carbon than they emit (Oliveira et al., 2018; dos Reis et al., 2021). Consequently, the potential for generating carbon credits and subsequently monetizing this service tends to enhance the economic viability of such systems.

Increasing of land prices, particularly land suitable for implementation of large-scale monocropping systems. In contexts characterized by elevated prices, particularly land prices, farmers tend to prioritize the adoption of agricultural systems that yield higher returns in the short- term; i.e. large-scale monocropping.

Insufficient capacity of government institutions for validating the Rural Environmental Registry. restricts producers' access to rural credit. The Rural Environmental Registry is an important instrument for territorial management, enabling the characterization of land use in Brazil. However, as its self-declaratory characteristic, this information base lacks validation and requires ongoing monitoring, necessitating both substantial institutional effort and financial investment for its effective operationalization.

5.2.1 - Public Policy to deal with these barriers

Forest Code Law, ABC Plan, National Policy for Payment for Environmental Services,

Brazilian Greenhouse Gas Emissions Trading System

The New Forest Code Law plays a crucial role by mandating that agricultural properties allocate a specific proportion of their land for conservation purposes (80% for the Amazon biome, 35% for savanna areas in the Legal Amazon region, and 20% for the Cerrado biome) (Brasil, 2012a).

Additionally, in 2012, revisions to the Forest Code Law introduced the Rural Environmental Registry (CAR), which necessitates farmers to register their property with state environmental agencies and formulate a plan to ensure compliance with conservation requirements (Brasil, 2012a).

5.2.2 - Current Incentives

The land use change regulation provides incentives for enhancing the intensification of land use and, consequently, promotes the adoption of sustainable agricultural systems (Agostinho et al., 2023; Leite-Moraes et al., 2023). Specific public policy, the ABC Plan, and its connection with other public policies such as National Policy of Climate Change and The New Forest Code (Brasil, 2010, 2012b; MAPA, 2021) improved regulatory practices of land use changing, restricting forest clearing and encouraging sustainable intensification (Garrett et al., 2018).

The CAR serves as a prerequisite for participation in programs offering subsidized credit, such as the ABC Plan. Thus, as a complement to the Forest Code Law, the CAR plays a crucial role in encouraging the adoption of sustainable agricultural systems (Leite-Moraes et al., 2023).

In Brazil, primary forms of payment for environmental services (PES) encompass reforestation and the mitigation of emissions

resulting from deforestation and forest degradation (REDD), with substantial involvement from the private sector and international funding. These initiatives are predominantly concentrated in the Amazon region.

In 2021, the Brazilian government enacted the **National Policy for Payment for Environmental Services (NPPES)**. This public policy delineates fundamental concepts, objectives, guidelines, actions, and criteria for implementation of a comprehensive legislative framework for Payment for Environmental Services (PES). Despite its approval in 2021, the legislation remains pending implementation and is subject to Congress deliberation regarding procedural frameworks for execution.

Recently, the Brazilian Deputies approved a proposal (PL 2148/15) aimed at regulating the carbon market in Brazil. **This legislative text outlines the establishment of the Brazilian Greenhouse Gas Emissions Trading System (SBCE), which imposes emission limits and institutes a marketplace for the trading of carbon credits**. Presently, the proposal is under review in the Senate. There is anticipation that it will be ratified in 2024 (ACN, 2024). The carbon credit market will emerge as a robust financial mechanism upon enactment, boosting the adoption of ICLFs and AFs.

5.2.3 - Suggested Improvements

To implement a robust PES program, Brazil must **need to encourage research to develop metrics that can serve as benchmarks for environmental policies**. It is imperative elaborates consistent and generalizable indicators and methodologies for monitoring the environmental impacts of agricultural production.

Include as priority on the political agenda the establishment of the National Registry of Payment for Environmental Services (NRPES) and the creation of the Federal

Program for Payment for Environmental Services (FPPES). Payment for environmental services may take various forms, including monetary compensation, the provision of social improvements to rural and urban communities, compensation linked to certificates of emission reduction resulting from deforestation and degradation, loans, issuance of green bonds, and compliance with Environmental Reserve Quotas mandated by the Forest Code Law (Brasil, 2021b).

The implementation of the Carbon credits market can be a robust instrument to boost the adoption of sustainable agricultural systems. Currently, carbon credit commercialization in Brazil occurs in voluntary markets, where agents who want to neutralize their emissions can buy credits from others who have them. In the context of the Paris Agreement, there is the provision for carbon credits to be traded for forest restoration, representing a possible future opportunity for integrated production systems using the forest component. Legislation about the credit market in Brazil is also recent. The Ministry of Environment and Climate Change (MMA) Report nº 518/2020 instituted the Forest+ Carbon modality, and the MMA Report nº 288/2020 aimed to encourage the voluntary, public, and private market for native forest carbon credits. Similarly to the PES, the carbon credits market is still being structured, and has great potential given the enormous possibilities for reforestation in Brazil.

Despite its self-declaratory feature and occasional inconsistencies regarding area delineation, the **CAR** has emerged as a significant instrument for monitoring designated conservation areas within private properties. However, achieving the expected effectiveness the CAR **needs fundamental**

improvements in the process of delineating areas and monitoring land use within these locations. As example, the government should implement mechanisms using geoprocessing technologies to accelerate the remote validation and ensure the accuracy of the Rural Environmental Registry.

Implement **mechanisms provided for the Forest Code to regularize environmental liabilities.** As a result of non-compliance with the New Forest Code Law, there is a significant number of farmers in Brazil with environmental liabilities subject to taxation and fines, and they may even face legal responsibility for the improper use of their land. The urgency of implementing Environmental Regularization Programs (PRAs) has increased due to heightened international commercial restrictions, particularly from the European Union, as well as limitations on access to agricultural credit provided by the Brazilian federal government. However, the availability of information and successful experiences regarding the regularization of these areas remains limited, particularly concerning the necessary investment and expected economic returns. To enhance environmental regularization, it is essential to expand and strengthen initiatives such as the National Program for Productive Environmental Regularization (PRAVALER), which aims to demonstrate the economic benefits for farmers through productive environmental recovery. This includes overall improvements in property management, encouraging the use of productive species for environmental compliance, and facilitating payments for environmental services.

Table 19: Barriers, Public Policies and Incentives to boost the adoption of sustainable agricultural systems: Social and technical.

Social and technical					
Barriers	**Farmers' Profile**	**Biome**	**Public Policy**	**Incentives**	**Suggested Improvements**
1) The lack of rural assistance. 2) Skilled workers´ availability to perform more complex tasks is limited. 3) The lack of educational policies and information about economic and socioenvironmental benefits from these systems. 4) Farmers exhibit solid cultural value preferences attributed to aspects such as well-being, security, and familiar relationships, which can mitigate the perceived benefits of ICLFs. 5) Succession at farm level is being compromised due to reduction in birth rate and migration of the youth to the cities in search for higher education and better job opportunities	1) Both 2) Both 3) Small 4) Large 5) Both	1) Both 2) Both 3) Both 4) Both 5) Both	1) ABC Plan	1) Federally supported research and extension initiatives. 2) Farmers close to Embrapa's research and demonstration units had significantly higher adoption of sustainable agricultural systems. 3) Embrapa´s research on sustainable agricultural systems.	1) Strengthen and enforce the link between credit access and provision of specialized rural technical assistance**. 2) Strengthen and amplify the human and financial resources of the Brazilian National Rural Extension Agency (ANATER), and invest in the implementation of the National Policy for Technical Assistance and Rural Extension (PNATER)**. 3) Agricultural research institutions should increase collection, organization, and knowledge exchange on successful farms that have already adopted sustainable agricultural systems and work jointly with farmers to develop and disseminate best agriculture, livestock and forestry production practices and systems, for example, via demonstration plots and field days. 4) Increase use of innovations such as Embrapa's e-Campo platform for distance learning. 5) Research programs should be redesigned to emphasize whole-farm economic, social and environmental outcomes. 6) Increase support for creation of multi-actor and cross-sectoral groups and networks such as the ILPF Network as a further step in supporting wider adoption of sustainable agricultural systems. 7) Implementing participatory design for research planning and implantation at farm level, particularly for agroforestry systems initiatives. 8) The inclusion, in the ABC+ Plan, of specific actions aimed at improving communication to raise social awareness of the environmental outcomes of agricultural practices. 9) Implementing mechanisms to increase engagement of the youth and women in leadership of rural activities such as education, extension services and cooperatives. 10) Facilitating land purchases by young farmers.

*Items organized in order of importance

**Greater relevance to Agroforestry Systems (AFs)

5.3 - Social and Technical Barriers

The lack of rural assistance is a crucial structural issue. The specialized nature of many research and rural assistance systems fails to provide adequate extension services to train farmers to implement sustainable agricultural systems. Studies have demonstrated the relevance of Embrapa's demonstrative units to improving sustainable agriculture system adoption. However, to transfer the technology, it needs an improving rural assistance network (Gil et al., 2015).

Skilled workers´ availability to perform more complex tasks is limited. Farmers frequently report that finding or training skilled labor to work in integrated systems is quite difficult. Also, they highlighted that the risks of training new labor were high due to high turnover (Cortner et al., 2019). Adopting integrated systems imply the intensification of productive factors usage and, as consequence, demand more management skills. Consequently, low labor availability creates strong incentives for farmers, particularly large-area owners, to specialize on a single crop or animal husbandry and to increase mechanization of production practices.

The lack of educational policies and information about economic and socioenvironmental benefits from sustainable agricultural systems. An effective public policies and rural extension programs may be necessary in promoting awareness and facilitating the transition to more sustainable production systems. If the knowledge and information is not spread out, there is no appreciation and understanding for the multiple benefits of sustainable agricultural systems, such as soil conservation, biodiversity, and ecosystem services and income generation.

Farmers exhibit solid cultural value preferences attributed to aspects such as well-being, security, and familiar relationships, which can mitigate the perceived benefits of ICLF systems, despite the promise of higher financial returns. The decision to transition to a new production system represents a significant change in a farmer's daily routine. Furthermore, in rural regions, traditional agricultural practices are maintained from generation to generation, making adopting new techniques difficult (Mores et al., 2022). This cultural feature is more relevant for cattle ranchers since they expressed little desire to take on greater managerial intensity (Latawiec et al., 2017; Cortner et al., 2019).

Succession at farm level is being compromised due to reduction in birth rate and migration of the youth to the cities. The demographic transition as well as the economic dynamics impact the entire agricultural sector, not just the adoption of sustainable agricultural systems. The search for job opportunities that offer higher incomes, coupled with improved access to information and professional training opportunities, encourages young people to migrate to urban areas.

5.3.1 - Public Policy to deal with these barriers

ABC Plan

5.3.2 - Current Incentives

Federally supported research and extension initiatives specifically targeting sustainable agricultural systems play a crucial role in fostering the adoption of these systems. Also, long-term agronomic and animal health research efforts enhance agricultural yields, while economic research aids in identifying the most efficient systems (Skorupa and Manzatto, 2019).

Our findings indicated that farmers close to Embrapa's research and demonstration units had significantly higher adoption of sustainable agricultural systems (Gil et al., 2015). Demonstration farms and extension programs can help spread information about the potential benefits of sustainable agricultural systems and technical details about how to operate such systems. Additional field experiments should be established in regions best primed for adoption, particularly in livestock regions located near slaughterhouses, but close to consolidated crop areas where cropping supply chain infrastructure is also available.

Since the 1980s, Embrapa has been actively engaged in research on sustainable agricultural systems. In the early 1990s, six existing Embrapa state research units in the North region were restructured into Agroforestry Research Centers, a change that bolstered research and development efforts in agroforestry systems (Flores, 1991). Subsequently, federal research on ICLF systems increased considerably during the 2000s. One outcome of this process was establishing a research unit in the state of Mato Grosso, **Embrapa Agrossilvopastoral**, with a primary focus on ICLF systems. Embrapa Agrossilvopastoral is a hub for research on low-carbon agriculture technologies, facilitating collaboration among researchers from various Embrapa centers and fostering effective communication among experts in sustainable agriculture practices.

5.3.3 - Suggested Improvements

A significant enhancement to the ABC credit policy would be integrating credit

disbursement with the provision of specialized rural technical assistance. Credit policies frequently lack sufficient integration with the provision of technical assistance to facilitate the adoption of sustainable agricultural systems. Such assistance is indispensable, as the requisite knowledge and skills for managing diversified agricultural systems are frequently lacking following years of specialization (Price and Hacker, 2009; Milhorance and Bursztyn, 2019). The absence of such technical support is frequently cited by farmers as a relevant barrier to the adoption of sustainable agricultural practices (Cortner et al., 2019; Tanure et al., 2024).

It is imperative to invest in the National Policy for Technical Assistance and Rural Extension (PNATER) by improving staffing levels. This is essential due to the enhanced demand for services vis-à-vis the limited number of technical assistants available. Furthermore, it is critical to provide comprehensive training for technicians to provide them with the knowledge to advise farmers seeking to adopt sustainable agricultural systems effectively. To address this need, training programs can be organized through collaborative efforts between ATER agencies and various entities, including National Service for Rural Learning (SENAR), Embrapa units, educational institutions such as Technical Institutes (IFs) and universities, as well as non-governmental organizations (NGOs).

Agricultural research institutions should increase gatherings, organization, and knowledge exchange on successful farms that have already adopted sustainable agricultural systems and work jointly with farmers to develop and disseminate successful forms of them, for example, via demonstration plots and field days (Skorupa and Manzatto, 2019). Access to information about outcomes from experiments and outcomes on the commercial farms of early adopters could be significantly improved through social media to increase exposure to the technology. Agricultural researchers and practitioners should foster knowledge exchange regarding sustainable agricultural

systems between farmers and other cross-sectoral stakeholders. Also, cooperatives could play a crucial role in organizing local exchanges among farmers and to enhance diversification of products by identifying new markets.

Research programs should be redesigned to emphasize whole-farm outcomes (Meynard et al., 2017). Current agricultural research paradigms prioritize yields over comprehensive farm outcomes, including economic risk reduction, resilience, production diversity, cost minimization, and input efficiency. This yield-centric approach tends to undervalue objectives significant to farmers and society while disregarding externalities. Hence, future research and development efforts must adopt a more comprehensive approach that encompasses the analysis of market, ecological, cultural, and governance factors, along with farmers' perceptions of these factors.

The creation of multi-actor and cross-sectoral groups can be a further step in supporting sustainable agricultural systems. Farmers' networks have proved to be influential on perceptions of specific technologies (Lubell et al., 2014). Also, this collective organization initiative may be especially useful when these groups are supported by participatory scenario building (Ryschawy et al., 2017). Spatial analysis of adoption patterns at the state level in Mato Grosso has shown that adopters of integrated systems are more educated and have better access to technical assistance and sectorial information than continuous crop farmers or extensive cattle ranchers (Gil et al., 2015; dos Reis et al., 2023b).

Implementing participatory design for research planning would facilitate the exchange of knowledge on technical, social, and policy issues, leading to the development of regionally appropriate models of sustainable

agricultural systems (Craheix et al., 2015). Research and technology transfer activities should involve farmers to aid in codifying existing knowledge and lessons learned (Skorupa and Manzatto, 2019). Furthermore, promoting the active engagement of local communities in both the planning and execution phases of research, **particularly for agroforestry systems initiatives**, is essential to ensure that these systems are connected to farmers' profiles. Such inclusive practices confer legitimacy and enhance operational efficacy, fostering ongoing and fruitful dialogue (Castilho et al., 2018; Lucas et al., 2023).

The inclusion, in the ABC+ Plan, of specific actions aimed at improving communication to raise societal awareness of the environmental outcomes of agricultural practices should promoted greater input efficiency usage and diversification as an alternative means to reduce environmental impact, a context that encourage adoption of sustainable agricultural systems.

Facilitating land purchases by young farmers could aid in modifying the habits, priorities, and knowledge gaps prevalent within current farming cultures. Cultural features emerge as significant barriers, particularly among older farmers, as this group tends to be less receptive to new ideas (Latawiec et al., 2017b). Current agricultural technological transitions face impediments stemming from deeply embedded habits of specialization, farm income and profit maximization prioritization, and from a need for more awareness regarding holistic farm management and the environmental impacts of existing production systems.

Table 20: Barriers, Public Policies and Incentives to boost the adoption of sustainable agricultural systems: Infrastructural and Market.

Infrastructural and Market					
Barriers	**Farmers' Profile**	**Biome**	**Public Policy**	**Incentives**	**Suggested Improvements**
1) Absence of agricultural infrastructure in regions that are farther from existing consolidated soybean and corn production areas. 2) Market access and price concerns.	1) Both 2) Both	1) Cerrado 2) Both	1) Safra Plan, specific public investment in infrastructure and logistic and government direct purchase programs	1) Public policies focused on reducing transportation cost for commodities in Center-West region. 2) Certification initiatives tailored to products originating from sustainable agricultural systems represent a viable strategy for enhancing product profitability by adding value.	1) Strengthening the Federal Government Purchase Programs** 2) Increasing the prospect of marketing sustainable agricultural goods. 3) Encouragement of value chain enhancement towards differentiated markets** 4) Specific investments to improve logistic, especially in railways and waterways, to reduce transportation costs.

*Items organized in order of importance
**Greater relevance to Agroforestry Systems (AFs).

5.4 - Infrastructural and Market Barriers

In regions that are farther from existing consolidated soybean and corn production areas, there is an absence of agricultural infrastructure such as silos to store grains and multinational traders to create competitive market access conditions. In addition, in some agricultural regions, where economies of scale have favored agribusiness specialization around a single product, there may be limited supply chain infrastructure or marketing channels for non-commodities products (Garrett et al., 2013a, 2013b). Also, poor road quality increases the transportation costs associated with accessing resources.

Market access and price concerns encompass a perceived deficiency in grain storage infrastructure, long transportation distances, poor road conditions and low domestic demand for superior quality or environmentally agricultural goods, which represent additional difficulties in competing with export markets. Moreover, farmers highlight the absence of cooperatives and rural unions to provide organizational structure and bargaining power for sustainable agricultural goods.

5.4.1 - Public Policy to deal with these barriers

Safra Plan, specific public investment in infrastructure and logistic and government direct purchase programs

5.4.2 - Current Incentives

Public policies focused on reducing transportation cost for commodities in Center-West region, for instance, the Ferrogrão Project and the construction of locks on the Teles Pires River in Mato Grosso aims to facilitate the flow of grain production to ports in Pará. This infrastructure may positively influence the adoption of

sustainable agricultural systems, particularly ICL, as it endeavors to streamline both production processes and the procurement of inputs, thereby bolstering the competitiveness of the Brazilian agricultural sector in the global market.

Certification initiatives tailored to products originating from sustainable agricultural systems represent a viable strategy for enhancing product profitability by adding value. Furthermore, such certifications meet an expanding demand for environmentally friendly products. An initial example is the collaboration between research and marketing organizations to establish branding strategies for beef production derived from sustainable agricultural systems such as "Carbon Neutral Beef" and "Low Carbon Beef" (Alves et al., 2015; de Almeida and Alves, 2020), that underscore the increasing emphasis of both public and private institutions on associating intensified production with environmental conservation while potentially opening up new market opportunities.

5.4.3 - Suggested Improvements

Strengthening the Federal Government Purchase Programs, which enables the government to purchase agricultural goods at a minimum target rate if farmers cannot find a better market, is a fundamental financial incentive for small farmers since they provide a demand-side push to maintain production and income generation for small scale production at local/regional products. The Food Acquisition Program (PAA) was created on July 2, 2003, by art. 19 of Law nº 10.696, to strengthen family farming and promote food and nutritional security. In order to guarantee commercialization and promote access to adequate food for people in situations of social and food vulnerability, the government buys products directly from family farmers, with no need for a bidding process, and

distributes them to people in situations of food and nutritional insecurity. The National School Food Program (PNAE) consists of the transfer of federal financial resources to assist students enrolled in all stages and modalities of primary education in all public schools to contribute to the growth and biopsychosocial development, learning, school performance, and the formation of healthy eating habits, through food and nutrition education actions and the provision of meals that cover their nutritional needs during the school term[3].

Increasing the prospect of marketing sustainable agricultural goods as locally sourced and environmentally friendly, thereby fostering distinct markets within crop, livestock, and forest value chains, holds a significant potential push factor in regions where consumers exhibit solid preferences for environmental conservation or locally sourced food items.

Encouragement of value chain enhancement towards differentiated markets assumes crucial importance to incentivize adopting sustainable agricultural practices, creating a territorial identity for associated products, and creating new marketing opportunities for firms operating within these value chains. Initiatives such as labeling programs and certifications might contribute meaningfully to this initiative.

Specific investments to improve logistic and reduce transportation cost. Transportation costs and logistical constraints are recurrent issues in discussions regarding the limited competitiveness of Brazilian products and the challenges in accessing certain international markets. Investments in railway and waterway infrastructure, alongside the modernization of ports are imperative to facilitate trade and enhance the competitiveness of Brazilian products on the global market.

3 In the PNAE, a bill is being processed to amend Article 14 of Law No. 11,947/2009 for increasing to 50% the obligation for government direct purchase of family farming products. The current value is 30%. For PAA, in 2023, the program was restarted, and more than R$ 250 million were earmarked for the direct purchase of food from family farmers.

5.5 - National Integrated Crop-Livestock-Forestry Policy

In 2013, Brazil implemented the **National Integrated Crop-Livestock-Forestry Policy (NICLFP)** (Brasil, 2013) aimed at reclaiming degraded pastures, increasing agricultural productivity and quality, improving farmer income, and mitigating deforestation pressures and GHG emissions. This law defines ICLF systems as a priority for preferential loans and other infrastructure benefits, e.g., energy, irrigation, and storage grain.

Taking advantage of the existence of the NICLFP within the Brazilian legal system and materializing its prescribed actions could generate significant advancements in promoting the adoption of ICLF systems. These actions include:

i) Establishing regional and national action plans to expand and enhance ICLF systems, with active participation from local communities.
ii) Encouraging the adoption of traceability and certification mechanisms for livestock, agricultural, and forestry products originating from ICLF systems.
iii) Providing training for rural extension agents, whether from the public, private, or third sectors, to address social, environmental and economic aspects of processes such as diversification, rotation, consortium, and succession in agricultural, livestock, and forestry activities.
iv) Establishing and promoting rural credit lines that are aligned with the objectives and principles of the NICLFP and reflect societal interests.

However, this public policy needs regulation, which constrains its effectiveness. Furthermore, its overlap with initiatives under the ABC Plan results in the NICLFP possessing a somewhat abstract nature, constituting a legislative framework with objectives that overlap with actions already underway in other plans. Therefore, it was not included in Table 17 to Table 20.

The lack of governmental coordination, the subordination of the environmental agenda to the economic agenda, budgetary constraints on the implementation of effective structural changes in production processes, and the recent weakening of institutions responsible for controlling and combating the degradation of natural resources, such as IBAMA, contribute to explaining the limited effectiveness of the public policies discussed in this section as tools to enhance the widespread adoption of sustainable agricultural systems (Barbosa et al., 2021; Nolte et al., 2017).

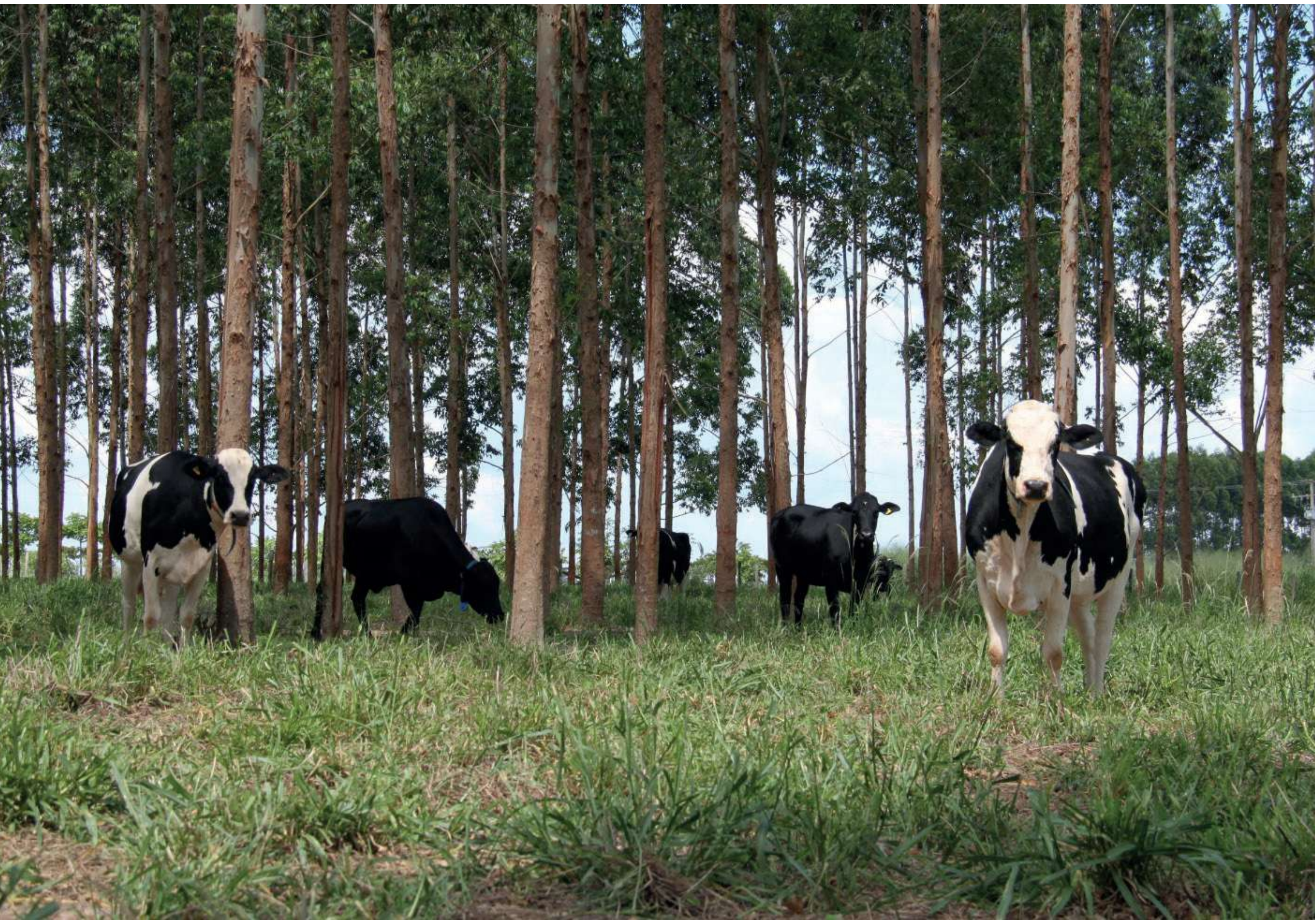
The Safra Plan has been the primary credit instrument for agricultural production in Brazil, and the amounts offered have shown a trend of constant growth. However, as indicated in the previous discussion about the public policies, the participation of specific lines dedicated to promoting sustainable agricultural systems remains low, and the high bureaucratic demands discourage the access to these resources.

Moreover, while the Ministry of Agriculture shows some inclination towards sustainable agricultural production, other areas such as environment, transportation, and energy exhibit actions that deepen an economic growth model based on the intensive and excessive exploitation of natural resources, incentives for increased fossil fuel consumption, and a lack of initiatives to expand the generation and use of renewable energy sources. This dichotomy in Federal Government agenda signaling complicates the implementation of actions, particularly large investments with medium- to long-term impacts.

Finally, the absence of investments in actions for monitoring, enforcement, and combating deforestation and illegal burning has, in turn, intensified the excessive exploitation of natural resources, as evidenced by the renewed upward trend in deforestation rates observed in the Amazon and Cerrado biomes over the past decade.

In summary, this analysis identified a broad set of public policies aimed at promoting structural changes in the Brazilian economy that foster the adoption of sustainable agricultural systems. However, for this agenda to achieve its established objectives and targets, improved coordination from the government is essential to ensure that different actions are aligned towards a common goal: the transformation of the Brazilian production system across various economic sectors with the aim of promoting sustainability.

6. Gaps in the current knowledge related to economic assessment of sustainable agricultural systems



The findings of the systematic literature review reveal the current paucity of information about economic and financial analysis of the ICLFs as well as AFs within both the Amazon and Cerrado biomes. Some structural characteristics contribute to elucidating this general scenario:

- It is quite difficult to collect economic information infield studies, especially longitudinal datasets necessary for conducting economic viability analyses on integrated systems in the Brazilian Amazon and Cerrado biomes. Farmers, in general, are unwilling to disclose their economic information. They are afraid that the Brazilian internal revenue service and institutions responsible for environmental governance could use this information. Consequently, the majority of identified studies predominantly rely on annual data points, such as revenue and production costs.
- Longitudinal studies conducted within actual farming contexts encounter a multitude of challenges, such as: i) market

risks; ii) commercial risks; iii) economic risks, and iv) insufficient farmers' management and planning skills and capacity, particularly small and medium farmers who lack the means to hire private technical and management assistance. These challenges are exacerbated when examining agricultural systems incorporating forest components, given the persisting research gaps concerning forest management within integrated systems, particularly regarding the management of native tree species. The predominant use of eucalyptus trees as a forest component is because its management practices are well known; it is a fast growth species and has a well stablished and growing global market demand for wood, fiber and energy production.

- Due to the scarcity of available economic data, the majority of studies rely on controlled experiments or case studies conducted on-farm scale. This approach restricts the extrapolation at the landscape level and evaluation of real commercial farming challenges adopting of integrated systems.
- The literature review identified substantial variability in the methodological approaches of economic analysis. The absence of standardized protocols for data collection and analysis constrains a more robust comparison of economic performance across diverse agricultural systems.
- Given the limited availability of economic data, numerous studies tend to evaluate individual components as isolated subsystems, such as profitability of crop subsystems or productivity of livestock subsystems. However, this approach overlooks the fundamental characteristic of integrated systems, namely, the synergistic interactions among all subsystem. A comprehensive and integrated approach allows to share some of the fixed costs among the different productive activities carried on the same land and using the same machines and infrastructure, in such a way that it has positive impact on efficiency of use of natural capital (land, water, climate) and manufactured capital (infrastructure) and on profitability and sustainability of integrated systems.

7. Final Remarks

Sustainable agricultural systems, (Integrated Crop-Livestock-Forestry and Agroforestry Systems), are recognized for their substantial economic, social, and environmental potential benefits, positioning them as viable instruments for both public and private policies aimed at promoting a transition from conventional to sustainable agricultural practices in the Amazon and Cerrado biomes. The broad array of configurations and variations inherent in sustainable agricultural systems allows for their adoption by diverse socioeconomic demographics of farmers, regardless of variables such as farm size, geographic location, product specialization, or other structural characteristics.

Despite research and development efforts aimed at fostering the adoption of sustainable agricultural systems in Brazil, including collaborative initiatives with the private agricultural sector, federal research and extension programs often encounter challenges in effectively reaching farmers, particularly small and medium-sized scales. While existing research predominantly focuses on improving agronomic and economic farm outcomes and subsequently disseminating this knowledge, such efforts may not yield desired changes in the adoption of sustainable agriculture if underlying structural barriers remain unaddressed and farmers are not sufficiently convinced.

Moreover, this study corroborates the prevailing perception among farmers regarding the lack of information about the economic results of ICLF and Agroforestry Systems. In this regard, this study significantly contributes by presenting representative case studies from both systems that can serve as initial frameworks for constructing a research agenda aimed at evaluating the economic performance of sustainable agricultural systems in the Amazon and Cerrado biomes.

Despite being highlighted in national and international commitments as crucial instruments for advancing the sustainability of Brazilian agriculture, and despite the existence of a considerable number of public policies with tailored actions aimed at fostering the adoption of sustainable agricultural systems, this study underscores the imperative for enhancements and adjustments to ensure that these systems can effectively contribute to Brazil's agricultural production growth and, simultaneously, enhance the well-being of Brazilian society and consolidate Brazilian agriculture sector at the forefront of knowledge regarding production associated with natural resource conservation.

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ANNEX

Annex 1: Set of the most common (animal and vegetal) species found in ICLF and AF systems in Brazilian Amazon and Cerrado biomes.

(continue)

Crops		Pastures		Animals		Forest (Timber trees)		Forest (Fruit trees)	
Soja	*Glycine max*	Capim/ forrageira	*Panicum maximum* cv. Mombaça	Aves	*Gallus gallus domesticus*	Mogno	*Swietenia macrophylla* King/Meliaceae	Castanha do Brasil	*Bertholletia excelsa* H.B.K. / Lecythidaceae
Milho	*Zea mays*	Capim/ forrageira	*Panicum maximum* cv. BRS Tamani; Zuri; Paiaguás; Quênia	Suinos	*Sus scrofa domesticus*	Mulateiro	*Calycophyllum spruceanum* (Benth.) Hook. f. ex K. Schum./ Rubiaceae	Pupunha	*Bactris gasipaes*
Arroz	*Oryza sativa* (BRS Primavera; Realce; IAC 201...)	Braquiaria	*Braquiária brizantha* (Piatã, Marandu, Zuri, Tamani)	Bovinos	*Bos taurus*	Ipê	*Tabebuia serratifolia*	Açai	*Euterpe oleracea*
Sorgo	*Sorghum bicolor* (BRS 310; BR501)	Braquiaria	*Braquiária decumbens* (*B. decumbens*)	Caprinos	*Capra hircus*	Bordão de Velho	*Samanea tubulosa* (Benth.) Barneby & J.W. Grimes/ Fabaceae	Cacau	*Theobroma cacao*
Milheto	*Pennisetum glaucum*	Braquiaria	*Braquiária ruziziensis* (*B. ruziziensis*)	Ovinos	*Ovis aries*	Cedro-doce	*Bombacopsis quinata* (Jacq.) Dugand/ Malvaceae	Cupuaçu	*Theobroma grandiflorum*
Algodão	*Gossypium* spp.	Braquiaria	*Braquiária humidicola* (*B. humidicola*)			Taxi-branco	*Tachigali vulgaris* L.F. Gomes da Silva & H.C. Lima	Bacuri	*Platonia insignis*

Annex 1: Set of the most common (animal and vegetal) species found in ICLF and AF systems in Brazilian Amazon and Cerrado biomes.

(continue)

Crops		Pastures		Animals	Forest (Timber trees)		Forest (Fruit trees)	
Girassol	*Helianthus annuus*	Braquiaria	*Braquiária mutica* (*B. mutica*)		Paricá	*Schizolobium parahyba* var. amazonicum (Huber ex Ducke) Barneby/Fabaceae	Murici	*Byrsonima crassifolia*
Mandioca	*Manihot sculenta*	Nabo forrageiro	*Raphanus sativus*		Cumaru	*Dipteryx odorata* (Aubl.) Willd. /Fabaceae	Banana	*Musa* spp
Abóbora	*Cucurbita moschata*	Feijão forrageiro/ lab-lab	*Dolichos lablab*		Seringueira	*Hevea brasiliensis*	Manga	*Mangifera indica* L
Alface	*Lactuca sativa*	Feijão forrageiro/ caupi	*Vigna unguiculata L. Walp*		Andiroba	*Carapa guianensis* Aubl./ Meliaceae	Goiaba	*Psidium guajava*
Rúcula	*Eruca vesicaria* ssp.	Sorgo forrageiro	BRS 506; BRS 511		Gliricídia	*Gliricidia sepium* Kunth/ Fabaceae	Laranja	*Citrus sinensis*
		Milheto Forrageiro	ADR-701; ICMH 356		Teca	*Tectona grandis* L.f./ Lamiacea	Limão	*Citrus limon*
					Eucalipto	*Eucalyptus* sp./Myrtaceae	Abacaxi	Ananas comosus

Annex 1: Set of the most common (animal and vegetal) species found in ICLF and AF systems in Brazilian Amazon and Cerrado biomes.

Crops	Pastures	Animals	Forest (Timber trees)		Forest (Fruit trees)	
			Mogno-africano	Khaya ivorensis A. Chev./ Meliaceae	Baru	Dipteryx alata
			Pinus	Pinus sp.	Pequi	Caryocar brasiliense Cambess.
			Aroeira	Astronium urundeuva (M. Allemão) Engl.	Cajuzinho-do-cerrado	Anacardium humile A.St.-Hil.
			Jatobá	Hymenaea courbaril L.		
			Carvoeiro	Tachigali vulgaris L.G.Silva & H.C.Lima		
			Acácia	Acacia mangium		

Source: (Balbino et al., 2011; Macedo, 2001; Schembergue et al., 2017; Skorupa and Manzatto, 2019)

Annex 2: Safra Plan 2023/2024: Main Rural credit lines for ICLF and AF adoption.

Credit line	Beneficiaries	Production system	Loan maximum value	Interest rate	Payment deadlines
Pronaf Bioeconomy	Small farmers	ICLF and SAF, including the recovery of PPA, RLA and degraded pastures	R$ 210 thousand	4% year	Up to 20 years, with a grace period up to 8 years
Pronamp	Medium farmers	ICLF for recovery of degraded pastures	R$600 thousand to R$1.5 million, depending on the investment	8.0% year	Up to 8 years, with a grace period up to 3 years, depending on the investment
ABC Integration	Large farmers and farmers association (unions and cooperatives)	ICLF and SAF	R$5 million	6.0% year	Up to 12 years, with a grace period up to 8 years.
FCO Green	Small, medium and large farmers and farmers association (unions and cooperatives)	ICLF and SAF, including the recovery of PPA, RLA and degraded pastures	R$2 million	Up to 7.46% year	Up to 20 years, with a grace period up to 12 years.
FNO Rural Green	Small, medium and large farmers and farmers association (unions and cooperatives); and traditional populations in the Legal Amazon	ICLF and SAF	According to the farmer's profile	7.6% pa to 11.15% year, depending on the investment	Up to 20 years, with a grace period up to 10 years.

References:
Banco do Brasil, 2024. Linhas de investimento. URL https://www.bb.com.br/site/agronegocios/investimentos (Accessed in: 03.25.24)
BNDES, 2024. Restauração ecológica. URL https://www.bndes.gov.br/SiteBNDES/bndes/bndes_pt/Galerias/Convivencia/Restauracao_Ecologica/linhas_financiamento.html. (Accessed 03.02.24).

Annex 3: Systematic Literature Review Approach

The research methodology encompasses a systematic investigation of the research process, encompassing aspects ranging from initial planning to the sequential execution of steps leading to result reporting (Creswell and Poth, 2017; Sehrawat et al., 2023). This section presents the methodological framework employed in conducting the systematic literature review, highlighting the research design, the methodologies for data collection, and the analytical approaches utilized.

Research Design

This step adopts a qualitative approach characterized by the examination of subjective aspects inherent in social phenomena and human behavior. The research design is constructed through the observation of natural behaviors, theoretical framework development, expert insights, and interviews, facilitating subsequent descriptive and scientific interpretation (Hernandez-Sampieri et al., 2014; Yin, 2015).

Data collection

To ensure the validity, consistency, robustness, and reliability of the systematic literature review, information was extracted from peer-reviewed scientific databases using Boolean logical operators and keywords. The following scientific databases were consulted:

- **Web of Science** *(WoS) (https://www.webofscience.com)*
- **Scopus** *(Elsevier) (https://www.scopus.com)*
- ***Google Scholar*** *(https://scholar.google.com.br/?hl=pt)*

In the *Web of Science* database, the search was conducted using the "*topic*" information set. For *Scopus*, the search encompassed the "*article title*," "*abstract*," and "*keywords*" information sets. Conversely, in *Google Scholar*, the search was based solely on the "*keywords*"

information set. Given the operational challenges associated with retrieving data from the *Google Scholar* database, the software *Publish or Perish* was utilized, available at the following link: https://harzing.com/resources/publish-or-perish. It is important to note that information sourced from Embrapa, as well as reports, periodicals, and working papers from institutions or organizations addressing the subject matter of this project, categorized as "gray literature," was included in the *Google Scholar* database search. These scientific databases are recognized worldwide as the most relevant for multidisciplinary studies (Chadegani et al., 2013; Kar et al., 2022).

Search formulas

The search formulas, comprised of keywords and decision rules incorporating potential synonyms, alongside Boolean logical operators utilized in the aforementioned scientific databases, are described as follows:

a) Keywords set

1 - Crop: *crop / harvest / agriculture / farm*
2 - Livestock: l*ivestock / farm animal / husbandry / pig / sow / boar / piglet / fattening pig / cattle / cow / bull / beef / cattle / dairy-cattle / ovis-aries / capra-hircus / chicken / hen / rooster / laying-hen / broiler / chick / duck / goose / poultry*
3 - Forest: *forest / woodland*
5 - Integration: *integration / sinergy*
6 - Cerrado biome: *Cerrado*
7 - Amazon biome *Amazon*

The keyword set was derived through iterative simulations and recursive analysis of findings from the selected scientific databases. At this stage, a broader keyword list was selected given the study's scope, which encompasses not only economic and financial aspects but also addresses factors such as barriers, incentives, and benefits associated with the adoption of sustainable agricultural systems. Additionally,

the study explores recommendations and proposals aimed at enhancing the efficacy of public policies related to environmental impacts within the agricultural sector.

Furthermore, it is important to highlight that employing search engines in references, such as the one outlined here, inherently involves the characteristic that a larger number of keywords may result in a more restrictive search. Hence, to mitigate the risk of excluding potentially relevant references, we initially utilized a comprehensive search engine (*Keyword set*), followed by a systematic manual evaluation aligned strictly with the project's scope, as outlined below:

- barriers, obstacles, limits, difficulties for adoption
- incentives, credit, subsidies, benefit for adoption
- technical assistance, training, courses, access to information, technical reference units
- public policy, ABC Plan, ABC+ Plan, National Climate Change Policy, Conference of the Parties (COP 15), Paris Agreement,
- GHG emissions, deforestation, land use, land saving effect, sustainable agricultural systems, sustainable livestock, agroecology, regenerative agriculture
- income, revenue, profit, viability indicators, NPV, IRR, profitability index, payback,
- cost, expense, disbursement, investment
- large farmers, monoculture, monocropping, large scale,
- small farmers, family farming

b) Search formulas

i. SCOPUS

("crop*" OR "harvest*" OR "agri*" OR "farm*") AND TITLE-ABS KEY ("Livestock*" OR "farm*animal*" OR "Husbandr*" OR "pig" OR "sow" OR "boar" OR "piglet" OR "fattening pig" OR "cattle" OR "cow" OR "bull" OR "beef" OR

“cattle*” OR “Dairy-cattle*” OR “ovis-aries*” OR “capra-hircus*” OR “Chicken*” OR “hen*” OR “rooster*” OR “laying-hen*” OR “broiler*” OR “chick*” OR “duck*” OR “goose*” OR “poultry”) AND TITLE-ABS-KEY (“forest*” OR “woodland*”) AND TITLE-ABS-KEY (“integrat*” OR “Sinerg*”) AND TITLE-ABS-KEY (“cerrado*” OR “Amazon*”)

ii. Web of Science

“crop*” OR “harvest*” OR “agric*” OR “farm*” (Topic) AND “Livestock*” OR “farm*-animal*” OR “Husbandr*” OR “pig” OR “sow” OR “boar” OR “piglet” OR “fattening pig”, “cattle” OR “cow” OR “bull” OR “beef” “cattle*” OR “Dairy-cattle*” OR “ovis-aries*” OR “capra-hircus*” OR “Chicken*” OR “hen*” OR “rooster*” OR “laying-hen*” OR “broiler*” OR “chick*” OR “duck*” OR “goose*” OR “poultry” (Topic) AND “forest*” OR “woodland*” (Topic) AND “integrat*” OR “Sinerg*” (Topic) AND “cerrado*” OR “Amazon*” (Topic)

iii. Google Scholar using the software Publish or Perish

Search in Portuguese

“colheita*” OR “agríc*” OR “fazenda*” AND “Pecuária*” OR “fazenda*-animal*” AND “floresta*” AND “integração” OR “Sinergia *” AND “cerrado*” OR “Amazônia”

Search in English

“crop*” OR “harvest*” OR “agric*” OR “farm*” AND “Livestock*” OR “farm*-animal*” OR “Husbandr*” AND “forest*” OR “woodland*” AND “integrat*” OR “Sinerg*” AND “cerrado*” OR “Amazon*”

Literature selection: inclusion and exclusion procedures

In addition to selecting the scientific databases (*Scopus, Web of Science and Google Scholar*), other criteria were applied to delineate the search and, consequently, the literature

selected. Initially, studies published before 2010 were not considered. The year 2010 was selected due to its significance in reflecting a relevant shift in Brazilian government initiatives aimed at promoting the adoption of sustainable agricultural systems. Specifically, in December 2009, the National Policy on Climate Change (PNMC) was enacted, with Article 12 explicitly outlining Brazil's commitments to mitigate greenhouse gas (GHG) emissions. Furthermore, to meet the targets outlined in the PNMC, Article 11 mandates the formulation of sectoral plans for key economic sectors such as transport, energy, industry, health, and agriculture (Brasil, 2010).

In 2010, the Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low Carbon Economy in Agriculture (ABC Plan) was introduced. This public policy is primarily aimed at reducing greenhouse gas (GHG) emissions in agriculture by enhancing the efficiency of natural resource utilization, increasing the resilience of production systems and rural communities, and facilitating the agricultural sector's adaptation to climate change (Brasil, 2012).

In addition to the period criteria, operational criteria, namely duplicity and relevance to the project's subject, were employed for the inclusion and exclusion of information (Figure 7). Initially, the search formulas yielded 631 documents from the three databases. Subsequent application of the selection criteria resulted in a final list comprising 253 documents, which will be utilized for subsequent activities.

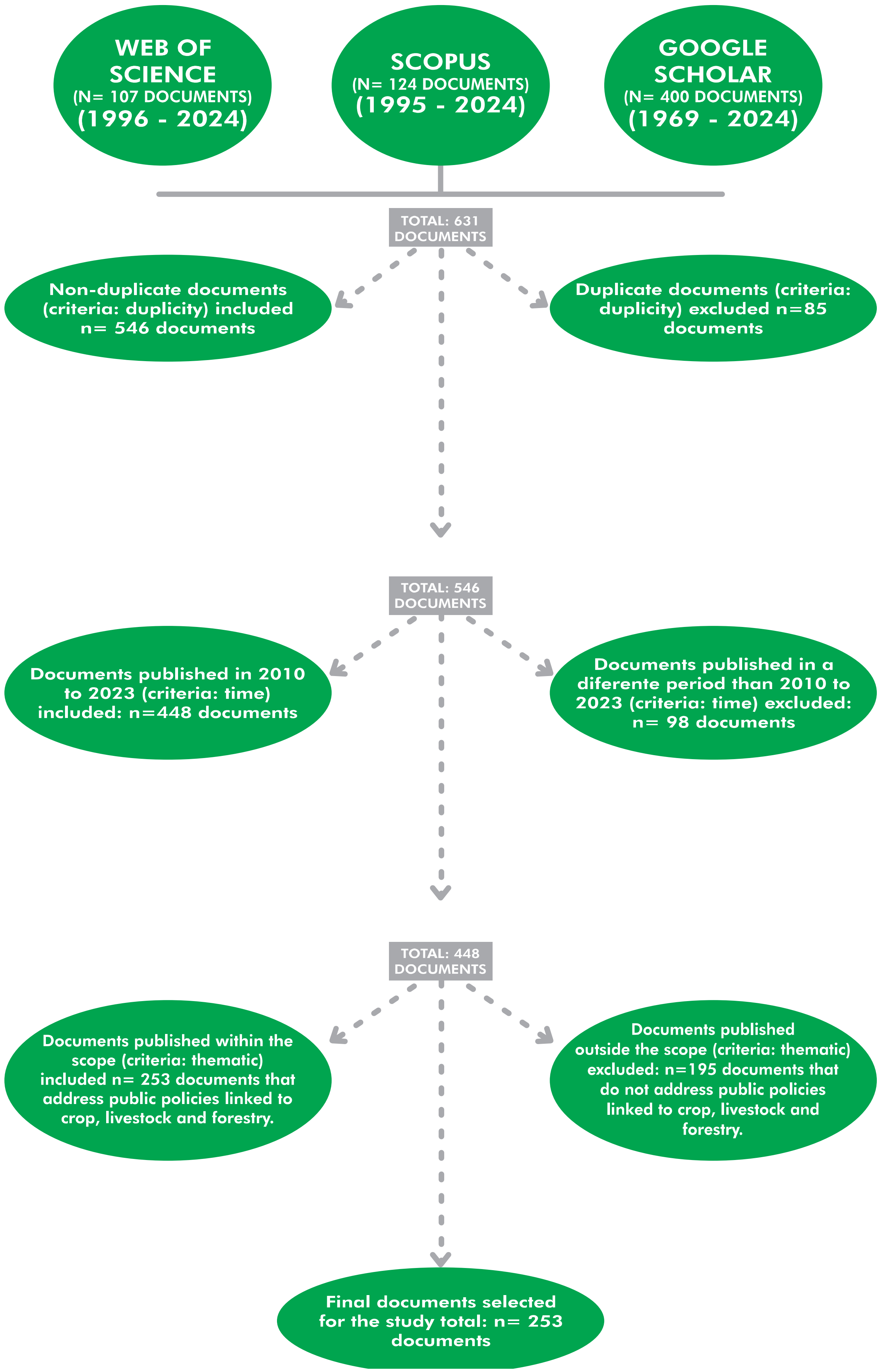

Figure 7: Inclusion and Exclusion criteria.

To identify material relevant to the project, an initial evaluation was conducted based on both the titles and abstracts. In cases where a decision regarding inclusion or exclusion could not be reached based solely on the title or abstract, the full text was analyzed.

After an initial analysis of the selected articles, the following data were manually extracted into an Excel spreadsheet for utilization in the analytical phase: authors, title, journal name, year of publication, conceptualization of crop/livestock/forest, abstract, keywords, DOI, environment analyzed, country or region, existing gaps, findings, sample, main theory, hypotheses, unit of analysis, method, future research, and limitations. Over this dataset, the next step of this project involved applying the ROSES protocol (RepOrting standards for Systematic Evidence Syntheses) to process the systematic literature review.

Analytical procedures from the article's selected data

To conduct the data analysis, it is proposed to carry out a lexical analysis in accordance with the requirements outlined in the ROSES protocol (RepOrting standards for Systematic Evidence Syntheses), specifically designed for studies within the areas of conservation and environmental management (Haddaway et al., 2018; Haddaway and Macura, 2018; Shaffril et al., 2021). This protocol is recommended by the Collaboration for Environmental Evidence (CEE) guidelines (Fitzpatrick et al., 2022) and has been extensively utilized in recent systematic literature review studies (Reisch et al., 2021; Shaffril et al., 2021; Nisa et al., 2022; Thayer et al., 2022; Barragan-Jason et al., 2023; Weir and Dahlhaus, 2023).

The ROSES protocol serves as a guide for designing, ensuring, and managing the quality of bibliometric analyses and systematic literature reviews in accordance with the CEE guidelines (Haddaway et al., 2018; Haddaway and Macura, 2018). Its transdisciplinary adaptation offers numerous benefits, particularly in defining research objectives and developing systematic search strategies that focus on the essential aspects required in the initial and intermediate stages of systematic literature reviews. These

include searching, screening (determining inclusion and exclusion criteria), data extraction, and critical appraisal, all of which contribute to constructing the final database to be considered (Haddaway et al., 2018; Chakraborty et al., 2021; Shaffril et al., 2021).

The ROSES protocol will be included in the report's annex, as can be found at the following link: https://www.roses-reporting.com/systematic-review-protocols. In addition to the ROSES protocol, advanced methodologies utilizing data analysis software were implemented to provide support and tools for comprehending the complex relationships between the selected studies (Hair Jr. et al., 2017). In this context, lexical analysis software such as IRAMUTEQ, through the RStudio platform, along with the support of VOSviewer and BIBLIOMETRIX software, were used to highlight the current state of the art of the subject under investigation.

The utilization of these software tools facilitated the generation of valuable insights, including the consolidation of results categorized by biome, area size, and producer profile. Moreover, they aided in understanding the existing gaps related to current knowledge regarding the adoption, incentives, and barriers of Integrated Crop-Livestock-Forest Systems and Agroforestry Systems. Additionally, they helped identify potential challenges that may arise from the adoption of sustainable agricultural systems within the Amazon and Cerrado biomes.