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INFLUENCE OF SOCIO-TECHNICAL NETWORKS ON THE DIVERSITY OF CACAO AGROFORESTRY SYSTEMS IN NORTHEASTERN PARÁ, BRAZIL

INFLUÊNCIA DAS REDES SOCIOTÉCNICAS NA DIVERSIDADE DE SISTEMAS AGROFLORESTAIS DE CACAU NO NORDESTE DO PARÁ, BRASIL

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ABSTRACT

This article analyses the influence of the socio-technical networks associated with agroforestry systems (AFS) on the diversity of cacao agroforestry systems (CAFS) in the Eastern Brazilian Amazon, in the municipalities of Irituia and Tomé-Açu. Fieldwork was carried out through semi-structured interviews, participatory activities and agrarian diagnostics. Three types of CAFS were identified: Group 1 was "market-oriented"; Group 2 was related to "food sovereignty"; and Group 3 was "syntropic". The socio-technical networks appeared fragmented: an institutional network in Tomé-Açu focused on cacao intensification, while an agroecological network, predominantly in Irituia, pertained to cooperatives and local associations. Group 1, as part of the institutional network, uses intensive techniques. The second and third groups adopt alternative strategies: Group 2 uses crop diversification and certified markets, while Group 3 focuses on syntropic agriculture to regenerate degraded land. Connecting these networks could facilitate knowledge and practice exchanges, contributing to more resilient and sustainable production systems.

Keywords: cacao; family farming; participatory research; agrarian system theory; socio-technical system theory; Brazilian Amazon rainforest.

RESUMO

Este artigo analisa a influência das redes sociotécnicas associadas aos sistemas agroflorestais (SAFs) sobre a diversidade dos sistemas agroflorestais cacaueiros (SAFCs) na Amazônia Oriental, nos municipios de Irituia e Tomé-Açu. O trabalho de campo foi feito por entrevistas semiestruturadas, atividades participativas e diagnósticos agrários. Três tipos de SAFCs emergiram da análise: Grupo 1 "orientado para o mercado"; Grupo 2 "soberania alimentar"; e Grupo 3, "sintrópico". As redes sociotécnicas aparecem fragmentadas: uma rede institucional em Tomé-Açu, voltada para a intensificação do cacau, e uma rede agroecológica, predominante em Irituia, vinculada a cooperativas e associações locais. O grupo 1, inserido na rede institucional, adota técnicas agrícolas intensivas. Os grupos 2 e 3 empregam estratégias alternativas: o grupo 2 prioriza a diversificação de culturas e mercados certificados, enquanto o grupo 3 se concentra na agricultura sintrópica para regenerar áreas degradadas. Uma melhor articulação entre essas redes poderia facilitar a troca de conhecimentos e práticas, contribuindo para sistemas de produção mais resilientes e sustentáveis.

Palavras-chave: cacau; agricultura familiar; pesquisa participativa; teoria dos sistemas agrários; teoria dos sistemas sociotécnicos; Amazônia brasileira.

1 INTRODUCTION

Agroforestry systems (AFS) are defined as "*a land use consisting in associating trees with agriculture or livestock farming in order to obtain production or useful services to living organisms*" (Torquebiau, 2022), where the integration of trees is deliberate (Nair; Kumar; Nair, 2021). This combination offers a promising approach to restore ecosystem services of degraded agricultural landscapes, as it increases biodiversity of farmer plots, limits disease spread and soil erosion and provides economic benefits through diversified production (Niether *et al.*, 2020; Young, 2017). Globally, AFS are seen as a response to contemporary challenges and as a means to improve the livelihoods of small-scale and family farmers by promoting locally adapted diversification strategies aiming at reducing input dependency and strengthening food sovereignty (Jamnadass *et al.*, 2013; Ollinaho; Kröger, 2021; Torquebiau, 2022).

In the Brazilian Amazon, the expansion of AFS reflects the consolidation of agroecological practices, particularly in the state of Pará (Souza *et al.*, 2021). *Theobroma cacao* L., a shade-tolerant species with high market value (Braga; Domene; Gandara, 2019), plays a central role in this process. Integrating cacao trees (*Theobroma cacao*) into AFS is considered as an efficient measure to restore degraded lands and support family farmers' livelihoods. In Pará, satellite data show that cacao plantations contribute to the recovery of degraded areas within family farms (Venturieri *et al.*, 2022).

Legally recognized as a native species contributing to ecological restoration, cacao has become a strategic choice for farmers, supported by a favourable regulatory framework. Under the Brazilian Forestry Law (n°12.651/2012), cacao can play a key role in restoring Permanent Protection Areas (PAA) and Legal Reserves (LR). Recently, in the State of Pará, the program PROSAF, led by the state institution Ideflor-Bio, has been promoting cacao-based environmental restoration. Such practices are not new, as the Executive Committee of the Cacao Farming Plan (CEPLAC) of Pará has been supporting cacao agroforestry systems (CAFS) since the 1970s, but these recent programs have encouraged expansion of such systems.

Pará recently became Brazil's leading state in cacao bean production (In April […], 2024), with 80% of the production located along the *Transamazônica Highway*[1]. Today, CAFS competes with full-sun cacao monoculture, which has been expanding in the Transamazonian region (Folhes; Serra, 2023).

1 In the Transamazonian region, 149,396 tons of cacao seeds were produced in 2023.

Though it provides faster short-term high yields (Niether *et al.*, 2020), intensive monoculture of cacao often depends heavily on agrochemicals and monoclonal varieties, increasing vulnerability to pests, diseases and environmental disturbances (Andres *et al.*, 2016). Despite incentives from public policies and CEPLAC Pará, family farmers face limited access to technical assistance for CAFS management, improved and locally adapted varieties and fair markets.

Moving beyond the farmer's perspective, multi-level sociotechnical networks analysis provides an effective approach to understand the establishment of CAFS and the diversity of practices and visions they embody (Rodríguez *et al.*, 2023). In this respect, our study addresses the following question: how does the configuration of sociotechnical networks influence the diversity of cacao agroforestry systems in Pará? Specifically, the study aims at (i) comparing the adoption of CAFS throughout the agrarian history of the municipalities; (ii) identifying the configuration of the socio-technical networks involved in the adoption of CAFS; (iii) analysing synergies and constraints within these networks. To understand these dynamics, this study combines the agrarian systems approach, which links agrarian history to social, economic and ecological dimensions of agricultural landscapes (Cochet, 2011), and the socio-technical approach, which focuses on technological innovations and stakeholder networks (Casagrande *et al.*, 2023). Through this combined perspective, we analyse how historical trajectories and the stakeholders network shape the adoption of CAFS. The research focuses on two emblematic municipalities of Northern Pará, Tomé-Açu and Irituia, which differ in land-use history, restoration incentives, and cacao development within AFS.

2 METHODOLOGICAL PATHS

2.1 ANALYTICAL FRAMEWORK

The diffusion of CAFS, including practices, knowledge, and both agricultural and plant materials, relies on a complex and dynamic network of stakeholders. To examine these processes, this study adopts an analytical framework which draws on the theories of Agrarian Systems (AS) and Socio-Technical Systems (STS) (see Methodology section) to combine concepts of agricultural innovation, stakeholder networks, and technology diffusion:

• The AS approach (Deffontaines; Osty, 1977) adopts a systemic perspective that analyses the farm as a whole and its components, acknowledging the complexity of rural dynamics and socio-economic contexts (Gautier; Benjaminsen, 2012). It distinguishes three interdependent levels of organization that structured the collection of field data (table 1) and guided the development of the CAFS typology.

Table 1 – Study variables in relation to the agrarian system conceptual framework

Concepts	Variables	Collected data
Agrarian system (territory)	Agrarian landscape Territorial stakeholders	IBGE data Plant propagation system stakeholders Agricultural advisory stakeholders
Production system (family farm)	Diversity of farming systems	Composition of production systems
Cropping system (CAFS)	Technical itinerary Varietal sequences	Agricultural practices Total number of varieties and cacao varieties Plant propagation type Stakeholders involved in CAFS

Source: authors' elaboration based on Cochet *et al*. (2002).

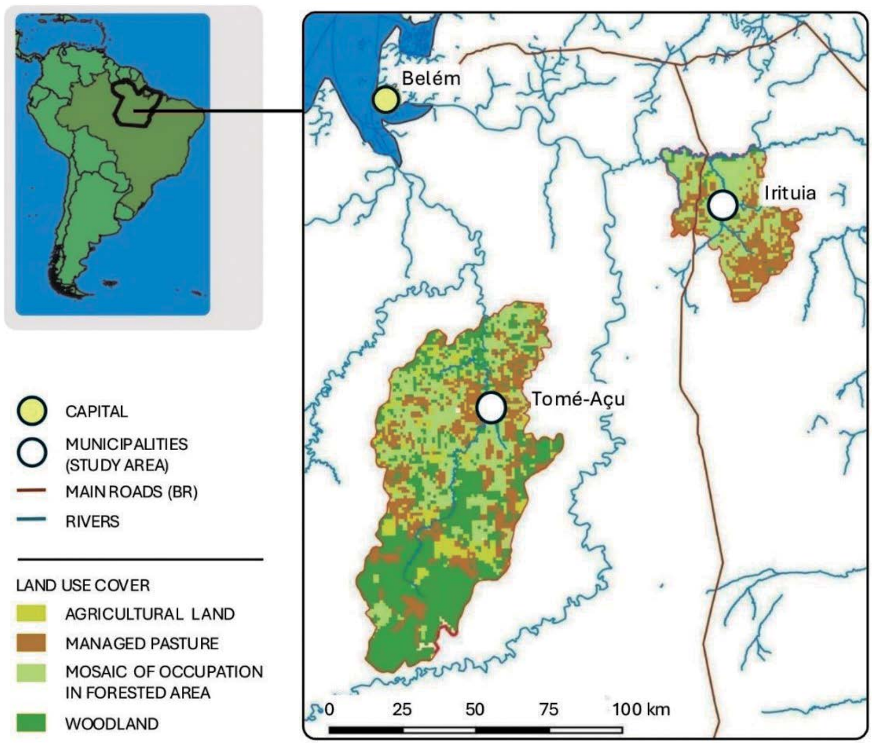
• STS is defined as "a set of stakeholders interacting around technologies, resources, infrastructures, and rules" (Angeon *et al*., 2024). AS can be considered as a type of STS, as they integrate technical, social, and institutional dimensions (Jonet, 2015). Frameworks inspired by STS theory are particularly useful for analysing the diffusion and adoption of technologies such as CAFS, by identifying barriers and enabling factors. The socio-technical diagnostic method (Casagrande *et al*., 2023) was applied in this study to assess how the STS influences the adoption of agricultural practices that support ecological restoration.

The study focuses on stakeholder networks that directly or indirectly interact with family farmers and have influenced the adoption of CAFS by family farmers. These systems were grouped according to their similarities and differences, reflecting distinct networks shaped by specific drivers and lock-in mechanisms. However, this research does not attempt to capture the entirety of the broader socio-technical system, nor does it explore the consumer–market dimension, which would require further investigation (Geels, 2004).

2.2 STUDY AREAS AND AGRARIAN HISTORY WITHIN THE TWO MUNICIPALITIES

The study was conducted in Irituia and Tomé-Açu, in Northeastern Pará (Figure 1). The contrasting contexts, along with their proximity and accessibility, justified their selection. Tomé-Açu is characterized by a well-developed cacao agro-industry and its integration within CEPLAC's cacao genetic material distribution network. Irituia is known for its distinctive forest restoration dynamics, to which AFS have contributed (Sousa, 2023), and for its active agroecological networks. Both municipalities have followed the deforestation trends observed in Pará and in the Brazilian Amazon between 1985 and 2022 (Browder; Pedlowski; Summers, 2004).

Figure 1 – Location and land use of the study areas



Source: the authors (made with QGIS 3.34.9, IBGE (2022)).

Tomé-Açu's distinct history of Japanese immigration shaped its agricultural trajectory, in particular with black pepper (*Piper nigrum*) expansion. In the 1970s, a fusariosis outbreak on black pepper monocultures led to crop diversification, such as the development of AFS (Homma, 2016).

The agrarian history of Irituia is divided in three major agricultural periods (Braga; Navegantes-Alves; Coudel, 2020; Sablayrolles; De Assis, 2020). The latest marks the emergence of AFS, as of 2009. Prior to this, there were *quintais* (Moraes *et al.*, 2022), a traditional form of agroforestry close to the family farmer's homes (Braga; Navegantes-Alves; Coudel, 2020).

The diffusion of AFS involves diverse stakeholders: public institutions such as EMATER (State Technical Assistance and Extension Enterprise), research institutes like EMBRAPA (Brazilian Agricultural Research Corporation) or Ideflor-bio (Forest and Biodiversity Development Insitute of Pará), and private companies (Albuquerque, 2017; Sablayrolles; De Assis, 2020).

In both municipalities, cooperatives supported AFS dissemination. A comparison shows that the Tomé-Açu Mixed Agricultural Cooperative (CAMTA) is geared towards international agro-industrial production, while the Irituia Family Farmers Agricultural Cooperative (Cooperative of Irituia) focuses on local and regional markets (Table 2).

Table 2 – Comparison of CAMTA and of the Cooperative of Irituia

	CAMTA	Cooperative of Irituia
Year of creation	1929	2011
Members	172 cooperators, linked to 1000 farmers	32 family farmers
Productions	Pulp (4000t): açai (750t), cacao seeds (600t)	Pulp (7.8t), jambu (3.3t)
Market	Local / international	Local / regional

Source: Albuquerque (2017), Campos *et al*. (2022), Moraes *et al*. (2022) e Silva, Kato e Martins (2019).

CAMTA (1929) provides technical assistance to family farmers from seedlings production in CAMTA'S nursery, to the processing of goods. CAMTA and Japanese descendants (*Nikkei)* have contributed to certify the Agroforestry Systems of Tomé-Açu (SAFTA) (Futemma; De Castro; Brondizio, 2020), now promoted to restore degraded lands (Albuquerque, 2017). CAMTA's link with Japan led to the development of a high-quality cacao market. In 2019, Tomé-Açu was the first municipality in Pará to obtain a Protected Geographical Indication (PGI) for cacao beans enabling exports to Japan (Cruz *et al*., 2021).

The Cooperative of Irituia (2011) provides municipal schools with local produce from family farming, supported by federal programs (Resque *et al.*, 2023). It promotes agro-ecological AFS and access to organic certification (OPAC) and markets. By 2019, 73% of members were involved in organic farming (Silva; Kato; Martins, 2019). Compared to CAMTA, it faces greater challenges in accessing markets and technical support.

In this context, cacao farming for production purposes began earlier in Tomé-Açu, whereas it is emerging in Irituia (Table 3).

Table 3 – Temporal comparison of cacao farming in the municipalities

	Tomé-Açu		Irituia	
Year	1990	2023	1990	2023
Cacao farming area (ha)	3 195	3770	0	15
Share of cacao farming areas in the municipality (%)	37	7.69	0	0.36
Share of Pará production (%)	5.6	1.9	0	0.005

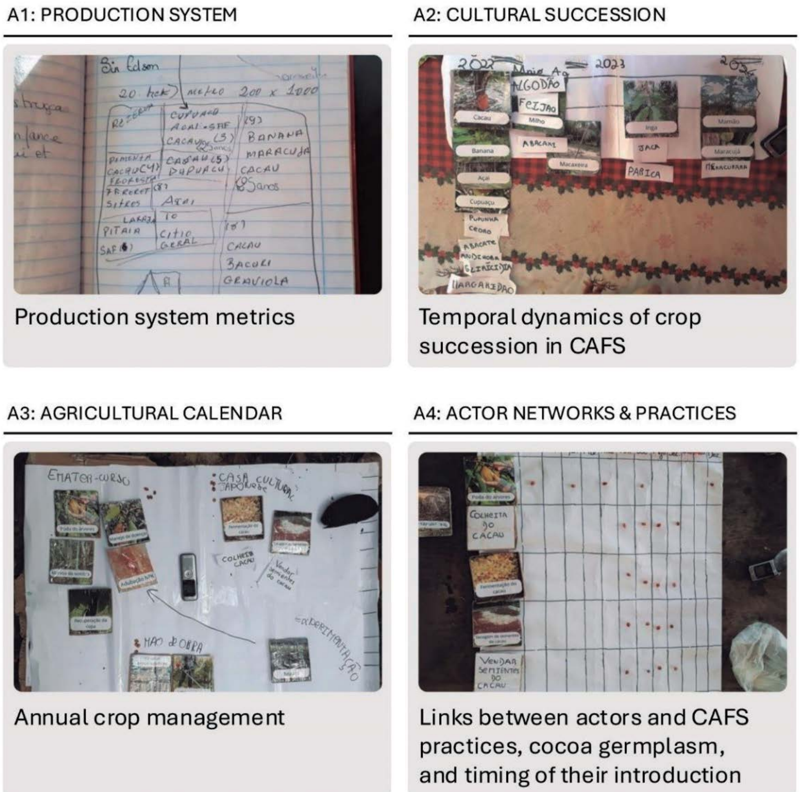
Source: IBGE (2017).

In Tomé-Açu, with CEPLAC's support and seedling distribution in the 1970s, cacao farming in AFS expanded during high international demand. Thus, cacao farming and CAFS development in Tomé-Açu followed Pará's trend. In contrast, commercial cacao production in Irituia is more recent, and although underrepresented in official statistics (Table 3), has been currently driving transformations in local production systems.

2.3 DATA COLLECTION AND ANALYSIS

Data was collected over a one-month field survey combining: (i) participant observation (Olivier De Sardan, 1995); (ii) in-situ walking interviews conducted across farming production systems; and (iii) participatory research tools (Figure 2) based on the Participatory Rural Appraisal approach (Chambers, 1994; Gastaldi, 2022). These were structured according to Cochet's methodology for spatio-temporal characterization of agrarian systems (Cochet *et al.*, 2002) and adapted to the local context during an initial phase of participant observation. CAFS were defined as a crop with a mix of species, including *Theobroma cacao*, and at least one species creating shading.

Figure 2 – Participatory research tools used during field survey



Source: authors.

The corpus of interviews included 20 family farmers practising CAFS, 7 in Tomé-Açu and 13 in Irituia, and 6 key stakeholders involved in SST of AFS and CAFS. Family farmers were initially selected prior to fieldwork and subsequently expanded using snowball sampling, as trust was an important factor in gaining access to farmers and stakeholders. Analytical representativity was sought through diversified interaction across different networks, and inclusion of key stakeholders. Field observation completed the interviews, including activities led by IVISAM (Syntropic Life Institute in Amazonia) and the SAFTA project.

All interviews with family farmers and notes from the field were recorded in a table divided in three main categories: (i) history and trajectory of the production systems, (ii) cacao production within AFS and (iii) limits and perspectives of production. Interviews were then structured in a typology based on an empirical core aggregation approach (Grémy; Le Moan, 1977), as is common in human and social sciences. Each variable is supported by

PRA and interviews analysis. Retained variables are (i) the land used for crop transition, (ii) the farmer's objective in establishing the studied plot, (iii) orientation of practices, and (iv) cacao varieties used.

Finally, the socio-technical network was built following the methodology from Casagrande (Casagrande *et al.*, 2023). Stakeholders and family farmers were categorized based on their main area of activity (production, technical support, cacao germplasm dissemination), focusing on two key networks: spread of cacao germplasm and practices/knowledge dissemination around CAFS. Areas were: (i) production; (ii) technical support and dissemination of knowledge; (iii) dissemination of cacao genetic material, including hybrid seeds, seedlings and clonal varieties. Flows between stakeholders were identified based on interviews and data from A4.

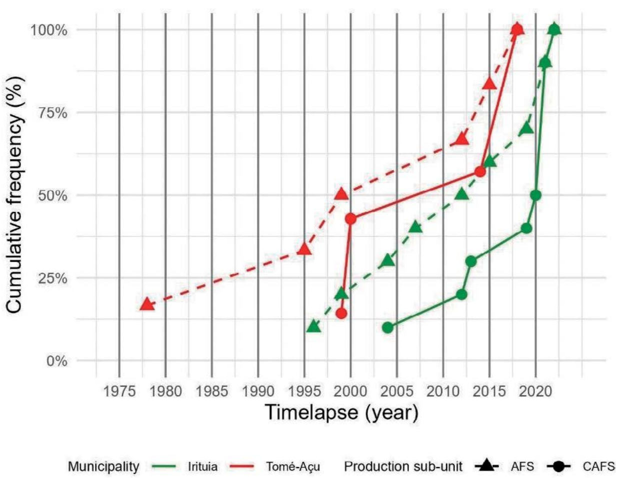
3 RESULTS AND DISCUSSION

3.1 DIVERSITY OF AGROFORESTRY SYSTEMS

3.1.1 Temporal evolution of cacao agroforestry systems

Among the farmers interviewed, agroforestry systems (AFS) emerged earlier in Tomé-Açu than in Irituia, reaching its midpoint in 1998 and 2008 respectively (Figure 3). In both municipalities, recent generations included cacao from the beginning, thus reflecting its increasing integration into AFS.

Figure 3 – Introduction of agroforestry systems and cacao agroforestry systems in the studied production systems, in Irituia and Tomé-Açu. Cumulative frequency of production systems averaged every five-year interval.



Source: authors, based on field surveys.

Cacao agroforestry systems (CAFS) also began earlier in Tomé-Açu. CAFS were disseminated by the *Nikkei* community and CAMTA through the SAFTA and SAF-dendê models (Futemma; De Castro; Brondizio, 2020). Half of farmers interviewed in Tomé-Açu had previously worked on Nikkei's farms, which subsequently influenced their agroforestry practices.

In Irituia, the midpoint was reached in 2020, thus highlighting slower initial development. Farmers who implemented CAFS prior to 2020 were generally older (above 50), while those who used them afterwards belong to a younger generation (30-40). AFS has expanded after 2009 as an extension of *quintais* (Braga; Navegantes-Alves; Coudel, 2020). The creation of the Cooperative of Irituia (2011) and of the IVISAM (Syntropic Life Institute in Amazonia) association (2018) likely supported this development. The Cooperative has promoted and strengthened agroecological practices (Sablayrolles; Da Silva, 2021).

Fieldwork has highlighted the role of IVISAM, scarcely documented, in the dissemination of CAFS and agroecological practices. Its creation as a social initiative in Irituia contributed to and encouraged the expansion of syntropic CAFS through a network of family farmers. Inspired by Ernst Götsch's philosophy (1984), syntropy is a niche agricultural model which relies on interactions to foster regeneration through species diversification, soil restoration and successional processes, while avoiding fire, heavy machinery, and pesticides (Götsch, 1997), as an alternative to conventional models:

> Syntropy is a form of agroforestry system, but more complex than what you may have seen in Tomé-Açu…they have few plant species and use chemical fertilizers. Syntropic farming is a bit more complex: we work with greater plant diversity, and with soil cover. It is an imitation of the forest (Family farmer, founder of IVISAM, G3, Irituia).

In both municipalities, cooperatives are pivotal in the flows of knowledge, finance, and agricultural materials which shaped the diversity of AFS models. Across Pará, the integration of crop diversification with the spread of AFS reflects transformations in agrarian and socio-technical systems, driven by agroecological approaches in national and state policies (Da Cruz Rodrigues; Mesquita; De Medeiros, 2019). Since the 1970s, cacao networks have promoted CAFS and genetic material through the diffusion of the hybrids from CEPLAC. These networks influence CAFS diversity by facilitating the circulation of agricultural practices, the supply of seedlings and inputs, and the exchange of technical knowledge.

3.1.2 An empirical typology of cacao agroforestry systems

To assess the influence of sociotechnical networks, CAFS were analysed through a typology. Variables used to construct the empirical typology differentiated three CAFS groups (Table 4).

Table 4 – Typology of CAFS based on key determining variables

	G1market-oriented	G2 food sovereignty	G3 syntropic
Municipality	Tomé-Açu	Tomé-açu & Irituia	Irituia
Family farmers (n)	6	5	7
Land use before transition	Slash-and-burn (33%), black pepper (17%), açai (17%)	Slash-and-burn (33%), *quintais* (16%), degraded land (16%)	Slash-and-burn (33%), pasture (50%)
Purposes according to the farmer	Cacao benefits (33%), restoration (33%), diversification (33%)	Diversification (80%), restoration (20%)	Restoration (85%), diversification (15%)
Orientation of practices	Intensification	Empirical	Syntropic
Cacao varieties	*Cacau comun,* hybrid, clonal varieties	*Cacau nativo*, *cacau comun, Nikkei*	Hybrid varieties, *Nikkei*

Source: authors, field work

Before implementing the studied CAFS, the previous main land uses were slash-and-burn (35%), monocultures of açai, banana and black pepper (17.65%) and pasture (17.65%).

Farmers had multiple purposes in adopting CAFS, among which three main categories:

- Product diversification, particularly with fruit, enables food security and diversification of incomes. Farmers expressed the difficulty they used to have in feeding their families, which led them to use diversification;

- Cacao benefits relate to cacao's positive interactions with other economically important species;

- Restoration of land that has been degraded, often because of conventional farming practices. AFS are seen as a means of reforestation or soil restoration, or both.

Regarding practices, 25 main categories were documented (A3). Additional practices emerged through interviews and participation in agricultural activities. Eleven practices are shared by half of the farmers. Some practices are group-specific, like chemical fertilization in G1. Since this is explicitly rejected by G3, it highlights how certain practices are controversial and may reflect values that influence farmers' approach to farming.

Farmers identified cacao varieties including old local varieties known as *cacau comun*, CEPLAC hybrids, seeds from the *Nikkei* community, and improved clonal varieties such as CCN51, PS1319, BN34, and PH17. Field survey showed that farmers know the origin of cacao seeds better than the variety, often naming the supplier.

3.1.3 Profiles of the identified CAFS groups

Group 1: market-oriented CAFS

G1 CAFS prioritize cacao production for the market, using intensified practices aimed at boosting crop yield: chemical fertilisation (66%), pesticides (66%) and tree grafting (33%).

The first CAFS was planted 24 years ago. All the farmers in this group previously worked in *Nikkei* farms before establishing their own, which is a common pattern in Tomé-Açu (Futemma; De Castro; Brondizio, 2020). Cacao is grown with other crops such as açai (*Euterpe oleraceae*, 2 farmers), palm oil (2 farmers, as of 2018) or woody species (1 farmer). Açai and cacao are frequently grown together because they occupy complementary strata: açaí provides shade for cacao while cacao helps maintain soil humidity. As one farmer explained: "I had the idea to cultivate cacao to create a microclimate for açai trees. It creates a cover on the ground… we were losing a lot of water." (family farmer, G1, Tomé-Açu). Cacao varieties include hybrids from CEPLAC and, more recently (within the past five years), clonal varieties.

Group 2: food sovereignty CAFS

G2 CAFS are marked by experimentation and the use of traditional knowledge, focusing on food diversification.

G2 comprises one CAFS in Tomé-Açu and four in Irituia. The first CAFS date back to 21 years, after a farmer brought cacao seeds back from *Nikkei* farms in Tomé-Açu. The intended purpose was food diversification to improve livelihoods. Farmers frequently emphasized the importance of AFS in household security: "It's the best way to get out of poverty" (Family farmer, G2, Irituia). Initially, they had limited institutional support, no cooperatives, internet nor training: they relied on family and neighbours. Practices included selective cutting in secondary forest (*capoeira*) or extending *quintais*. Their experience reflects a shift from past deforestation to a current focus on restoration. Not only did the practices change, but also the mindset of farmers:

> There used to be more people killing trees and setting fire… The point of view on these practices evolved. With the help of cooperatives, today's preoccupations and the intensification of climate change. There didn't used to exist so many ways to learn, but now there is the cooperative. […] I was a destroyer, and I changed my vision. If you make monoculture nowadays, it is going to be a problem (Family farmer, G2, Irituia).

Cacao plays a secondary role and includes cacao hybrids from CEPLAC (1 farmer, Tomé-Açu), native cacao (1 family farmer) and cacao from the *Nikkei* community (3 family farmers, Irituia and Tomé-Açu). One farmer in Irituia produces chocolate and seeks OPAC (Organic Certification).

Group 3: syntropic CAFS

This group uses syntropic practices in CAFS to restore degraded land, like pastures.

G3 CAFS have expanded within the past five years, following the creation of IVISAM. Farmers have joined forces around shared values for land restoration: "I tested this system to restore the soil. As you can see, there is a river and people were burning close by, polluting the river. So, I made this system so that people wouldn't burn anywhere near it". (Family farmer, G3, Irituia).

The idea of care, for land, humans and plants, is central. It echoes permaculture core values which are: "caring for nature, people and sharing equitably". Common practices include organic fertilization with nitrogenous plants, soil cover and banning chemical inputs. Diversification and plant interactions is intended to compensate for the use of chemical inputs. For example, trees of *Gliricidia sepium* generates organic matter and fixes nitrogen. Urucu (*Bixa Orellana* L., 1753) is used as a potassium recycler. This syntropic approach therefore calls for experimental and technical knowledge of plants, and of the wider system. Cacao seedlings were purchased from the Nikkei community. Hybrid seedlings were obtained from CEPLAC. CAFS are recent, and not yet productive, but valued for their economic potential.

3.1.4 Contribution of cacao to the production systems

The contribution of cacao to production systems is variable: G1 family farmers highlighted the importance of productivity and mainly focus on cacao; in G2, cacao is used as a traditional native species, among many others; and in G3, it supports economic viability of the whole system. Hence, *Theobroma cacao* was identified as an emblematic species for the three groups.

One possible explanation for the integration of cacao in AFS over time (figure 3) lies in the challenge of restoring productive areas (Tavares *et al.*, 2024). Moreover, cacao can contribute efficiently to the economic viability of production systems. While family farmers both focus on food security and market (Almeida; Ferreira; Coudel, 2023), CAFS help combine both. More specifically, in 2024, prices of fermented dried cacao beans rose from R$ 15 per kilogram to R$ 45 (field survey).

However, fluctuations in the international market can equally encourage or lead to abandonment and replacement of a dominant crop, as in G1 CAFS. Developing resilient markets focused on product quality can help mitigate these impacts by setting fair prices for farmers (Somarriba *et al.*, 2021).

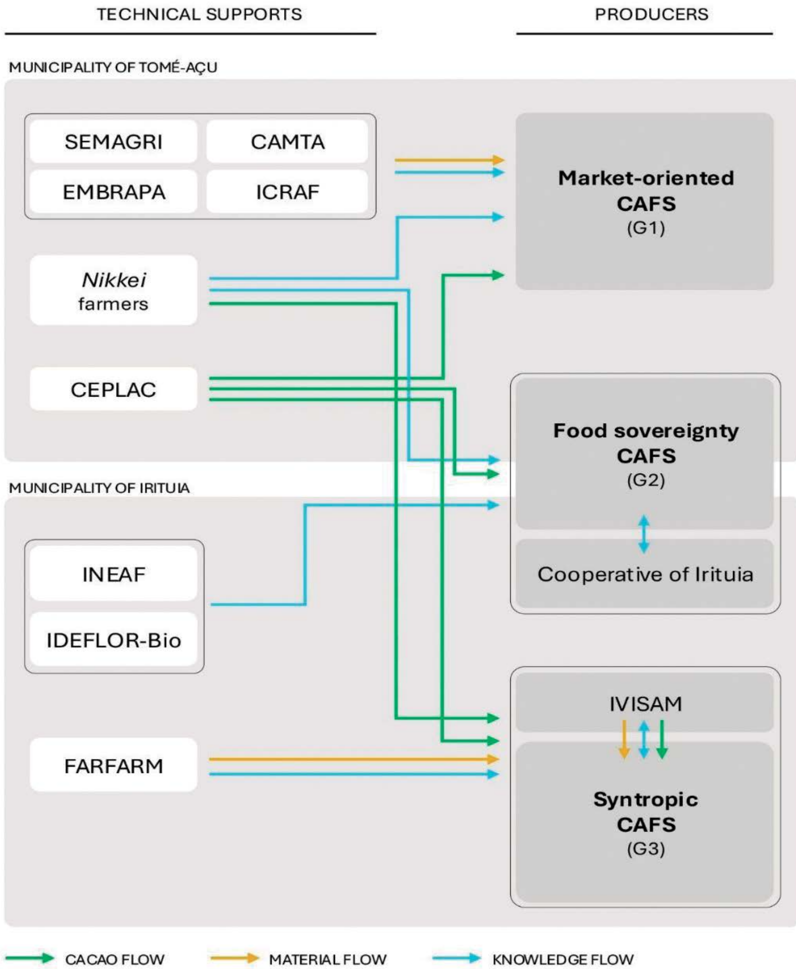
Thus, CAFS can take a variety of forms, shaped by the values, needs and strategies of farmers, which determine their practices. These perceptions and representations are clearly embedded in the local context. For this reason, a focus on the networks related to agroforestry systems can provide a better understanding of the factors that encourage CAFS implementation.

3.2 SOCIO-TECHNICAL NETWORKS RELATED TO CAFS

3.2.1 The socio-technical networks of cacao agroforestry systems

The two municipalities are part of a complex socio-technical system (SST) involved in disseminating agroforestry systems (AFS). Two interconnected subsystems are apparent (Figure 4): in Tomé-Açu, the network focuses on intensifying cacao production within AFS, while in Irituia, it is more oriented toward family production. Together, they contribute to the diversity of cacao agroforestry systems (CAFS). These networks are distinct and exhibit few direct links.

Figure 4 – Socio-technical networks involved in CAFS farming, by group



Source: authors, field work

Knowledge exchange, agricultural practices and cacao seed flows do however occur from Tomé-Açu to Irituia, via CAMTA and some farmers of the *Nikkei* community. These flows have facilitated the introduction of CEPLAC hybrid cacao seeds into Irituia.

Both municipalities are subject to national regulations and institutions, as well as state-specific rules in Pará. They operate within a multi-actor and multi-sectoral network supporting national and regional agroecological systems engaged in CAFS dissemination while also sustaining cacao production. This network includes public institutions, research centres, private enterprises, and local organizations.

The network includes the following stakeholders, classified by business area:

- **Producers**: Family farmers, cooperatives and associations are central to implementing AFS. G2 is connected to the Cooperative of Irituia through partnerships, including access to OPAC[2]. Both G2 and G3 are associated with IVISAM. CAMTA also plays a key role in Irituia and for G1 by promoting AFS and supporting cacao expansion.

- **Municipal agricultural departments (Secretaria de Agricultura, SEMAGRI):** each municipality has an office, which provides technical support, manages nurseries and facilitates access to agricultural projects. They serve as intermediaries between family farmers and external stakeholders. Some key producers, such as the founder of IVISAM, have played a key role by working as coordinator of SEMAGRI, and established contact with local farmers through this position.

- **Research and technical institutes**: Institutions like Ideflor-bio (Forest and Biodiversity Development Institute of Pará) provide technical support. Research institutes such as ICRAF (International Centre for the Research on Agroforestry), CEPLAC (Executive Committee of the Cacao Farming Plan, under the Ministry of Agriculture), and EMBRAPA (Brazilian Agricultural Research Corporation) support family farmers in developing AFS. For example, Ideflor-bio supports family farmers linked to the cooperative through several projects, such as *Tijolo verde*. CEPLAC also produces hybrid seeds selected for productivity, quality and disease resistance. They distribute the seeds via a mapping system: Tomé-Açu maintains a local sub-unit, whereas Irituia is not encompassed within this framework.

- **Private enterprises**: FARFARM provides technical support, inputs, seeds, and technical knowledge to farmers in Irituia. They aim to develop regenerative AFS for organic cotton production, produced in the first three years of the AFS. Subcontracted out by VEJA, a fair-trade footwear company, it facilitates market access for farmers.

3.2.2 The role of socio-technical networks in the diversity of CAFS

The diversity of CAFS in Tomé-Açu and Irituia emerges from differentiated and fragmented networks, whose stakeholders interact with family farmers and provide access to resources (plant material, knowledge,

2 It was established through a project led by the Federal University of Pará (UFPA) and the Institute of Family Farming (INEAF).

and markets) and agricultural trajectories. While synergies reinforce these networks, tensions reveal divergent and sometimes contradictory visions.

G1 is part of an intensification network in Tomé-Açu, influenced by the Japanese-Brazilian and SAFTA models. It has been shown to benefit mid- and small-scale farmers by adapting it to their local context (De Castro; Futemma, 2021). This network encompasses an institutional framework composed of CEPLAC Pará, EMBRAPA, ICRAF, CAMTA and SEMAGRI of Tomé-Açu.

Divergent visions among stakeholders have been observed, for instance in the promotion of tree grafting for cacao. While CEPLAC has expressed concerns about this practice, in connection with a controversy surrounding the Transamazonian, detailed in Folhes and Serra (2023), CAMTA and EMBRAPA collaborate to disseminate grafting techniques for cupuaçu, cacao, and other species to family farmers. This dissemination is likely facilitated by the presence of EMBRAPA's experimental fields and of CAMTA's tree nurseries (De Menezes *et al.*, 2009; Gurgel *et al.*, 2014; Pereira; Dos Santos; Alves, 2009). Controversies in socio-technical networks are common and reveal tensions (Belmin *et al.*, 2018), which may point the need for clearer regulation regarding cacao innovations and "best" practices.

The other subsystem is enhanced in G2 and G3, mostly in Irituia, strengthened by local initiatives, cooperatives, associations, with institutional support from stakeholders such as Ideflor-bio. By supplying materials in Irituia through the project *Tijolo verde*, Ideflor-bio aimed at promoting reforestation of degraded lands, contributing to environmental recovery, food security and income generation for family farmers.

It contributes actively to the transformation of production systems and to the reduction of chemicals, by reinforcing the adoption of organic and syntropic practices, based on empirical practices. The impact of the network on the reduction of chemicals is crucial, since the global trend in farming goes towards chemical inputs increase (Kongor; Owusu; Oduro-Yeboah, 2024), as is more prevalent in G1. In Brazil, agrochemicals are widely used, with a 690% increase in pesticides sales from 2009 to 2020 in the Amazonian region (Gaboardi; Candiotto; Panis, 2023). However, AFS, as part of agroecological agriculture, should help reduce family farmers' dependence on chemicals and enhance food sovereignty (Ollinaho; Kröger, 2021; Souza *et al.*, 2021).

According to farmers, these networks have facilitated their adoption of diversification practices. G2's connection with the cooperative suggests an intent to access diversified markets, adopt agroecological practices and eventually join OPAC. The latter can support a variety of products, not just cacao, serving as a means to benefit from agroecological practices, which are often challenging to implement, due to regulatory constraints (Sablayrolles; De Assis, 2020). In the northeastern part of Pará, cooperatives have been identified as crucial social organisations for marketing family farming products (Da Cruz Rodrigues; Mesquita; De Medeiros, 2019).

Traditional collective working groups (*mutirão)* are organised by IVISAM and allow farmers to co-construct knowledge and practices, reinforcing reciprocal ties (Yalu; Matous, 2024). Reviving this collective tradition enables the implementation of AFS in one to two days and facilitates hands-on learning of syntropic practices. It symbolizes the integration of traditional and technical knowledge. As one family farmer pointed out: "According to me, these groups are impulses because people share their energy and their strength. That's what drives the process forward. They are remnants of the past; farmers used to work a lot with these groups" (family farmer, G3, Irituia).

G2, and particularly G3, engaged in community-based processes, which likely support the adoption of organic farming (Bravo-Monroy; Potts; Tzanopoulos, 2016). Both groups are heterogenous with nearly equal representation of men and women, thus highlighting the importance of these networks for inclusiveness, since usually, in Latin America, cacao farming is typically male-dominated (Ingram *et al.*, 2016; Kouassi *et al.*, 2023).

As a result of the fragmented socio-technical networks, family farmers in Irituia face difficulties in accessing resources linked to the cacao network, as they are not included in CEPLAC's mapping. This can lead to inequalities among farmers. Indeed, the economic contribution of cacao to production systems can be higher than that of other products, as has been shown in Central America (Cerda *et al.*, 2014). Intermediaries in the *Nikkei* community act as bridges between the two subsystems, enabling farmers to access the formal plant material distribution system, and consequently, CAFS. For example, IVISAM has been purchasing cacao seedlings from a *Nikkei* farmer for G3 participants. However, these plant materials are likely uncertified offspring of CEPLAC hybrids, resulting from uncontrolled crosses with other cacao trees and potentially offering lower quality and productivity than the original selected hybrid varieties.

Thus, fragmentation of the network is reflected in the diversity of CAFS. This fragmentation reveals the coexistence of multiple, and sometimes contradictory, speeches among the stakeholders involved in the SST of CAFS. To ensure the sustainability of CAFS, which are still developing and remain fragile, reciprocal cooperation in the multi-level and multi-actor network is essential (Rodríguez *et al.*, 2023).

The dynamics observed in Irituia and Tomé-Açu are therefore part of a broader SST linked to the dissemination of AFS and CAFS dissemination. They operate within a wider regional context where cacao cultivation is not always integrated into AFS. In the Transamazonian region, STS associated with full-sun monoculture puts pressure on the CAFS-oriented systems (Folhes; Serra, 2023), which highlights even more the need to consolidate and strengthen these networks.

4 FINAL CONSIDERATIONS

In this article, we have studied the influence of sociotechnical networks on the diversity of cacao agroforestry system (CAFS) models in family farming in Irituia and Tomé-Açu, combining agrarian systems and socio-technical approaches. Three distinct CAFS models have been identified, reflecting different strategies among family farmers, across municipalities with contrasting agrarian histories: (i) intensification of cacao production; (ii) diversification of crop systems and integration into fair markets; and (iii) restoration of degraded lands, using cacao as a crop with substantial economic significance.

The configuration of socio-technical networks appeared as crucial in shaping CAFS. The fragmented nature of these networks has led to the emergence of two multi-level stakeholder subsystems across the municipalities, which condition access to cacao germplasm, knowledge and technical assistance. On the one hand, an institutional cacao network, more prominent in Tomé-Açu, supports the intensification of cacao production. On the other hand, cooperative and associative networks, mainly observed in Irituia, promote agroecological practices. Hence, both agrarian histories and network configurations shape the diversity of the systems.

These dynamics highlight the central role of institutional networks in providing access to seeds and technical assistance, as well as the importance of reciprocal learning networks built around co-produced knowledge, as illustrated by Tengö *et al*. (2014), in spreading agroecological and syntropic practices. Even if the three groups operate within relatively close-knit networks, synergies may reinforce the networks. The presence of intermediary stakeholders bridging these networks reflects the importance of facilitating the circulation of technologies and practices developed within each group.

Strengthening such exchanges could enhance both the economic viability or the environmental sustainability of their respective systems.

A limitation of this study lies in its focus on a single sub-unit within each production systems at a given point in time and space. However, even a single production system may include multiple AFS and CAFS connected to different networks. It is therefore essential to recognize that agrarian systems are dynamic and continuously evolving, rather than fixed entities.

This study therefore shows the value of combining the agrarian systems and socio-technical approaches to better understand the dissemination of CAFS and AFS. The field of socio-technical systems studies remains underdeveloped, though it could significantly contribute to a deeper understanding of agrarian dynamics and to the consolidation of agroecological networks supporting AFS. As Rodríguez *et al.* (2023) emphasises, the opportunity for stakeholders to construct coherent speeches around AFS is essential to strengthen the networks. Moreover, the growing competition from the technological trajectory of cacao monoculture in the Transamazonian region (Folhes; Serra, 2023), coupled with the weakening of CEPLAC's direct contact with farmers, reinforces the need to consolidate and sustain agroforestry-based cacao cultivation across Pará.

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