Agricultural Systems 194 (2021) 103270

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Review

Cacao-based agroforestry systems in the Atlantic Forest and Amazon Biomes: An ecoregional analysis of land use

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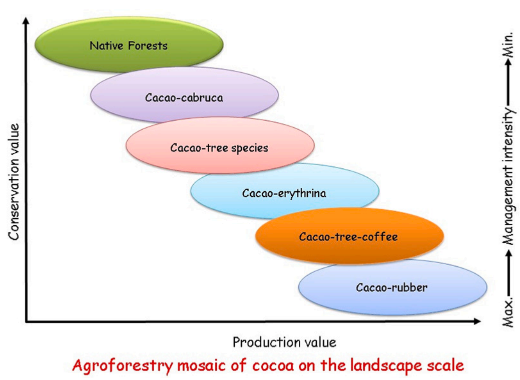
HIGHLIGHTS

- Cacao-based agroforestry systems are considered an important alternative for the sustainable rural development in Brazil.
- We describe cacao agroforestry models, with emphasis on their agronomic, economic and social-ecological as key technologies.
- Cacao agroforestry models constitute an interconnected agroforestry mosaic with natural forests at the landscape scale.
- Cacao agroforestry mosaic is considered an environmentally-friendly agroforestry technique and a climate-smart agriculture.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Mark van Wijk

Keywords:
Agroforestry mosaic
Sustainable rural development
Social-ecological complex
Environmentally-friendly agroforestry
Farming system design
Cacao-cabruca system

ABSTRACT

CONTEXT: Cacao-based agroforestry systems is an appropriate technology as it contributes to improving the standard of living of the population of an agricultural region based on land use without causing undesirable environmental changes. Brazil contributes approximately 5% of world cocoa production. The main cocoa producing states are Bahia and Espírito Santo in the Atlantic Forest biome; and Amazonas, Pará, Rondônia and Mato Grosso in the Amazon biome, with an estimated total planted area of 606,794 ha and about 76,000 rural producers, of which almost 80% are in family farming.

OBJECTIVE: The aim of this review was to describe the various commercially adopted models of agroforestry systems with cacao trees (cacao-AFS), with an emphasis on their agronomic, economic and social-ecological advantages as key technologies for the sustainable rural development of the cacao regions in the Atlantic Forest and Amazon biomes in Brazil.

METHODS: A survey of the literature produced on various models of cacao-AFS was carried out, with an emphasis on farming system design, productivity, profitability, stability, employment and sustainability.

RESULTS AND CONCLUSIONS: Cacao crops provide several social, economic and environmental benefits. The predominant cacao-AFS models in Bahia and Espírito Santo are the cacao-cabruca, cacao-erythrina and cacao-

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https://doi.org/10.1016/j.agsy.2021.103270
Received 10 April 2021; Received in revised form 27 July 2021; Accepted 1 September 2021
Available online 16 September 2021

rubber systems, while the Amazon implements models in mixed and zonal systems with a high diversity of consortium multifunctional species. The social importance of the diversity of cacao-AFS models is to generate new technologies and knowledge, to preserve tree species with a social function (medicinal and fruit species) and to produce food in the systems installation phase. The cacao-cabruca system has the lowest productivity among the cacao-AFS of approximately 180 kg/ha, but with proper shade management and the use of high technology it can achieve much higher productivity. The diversity of cacao-AFS models in the cacao regions characterizes an agroforestry mosaic, forming a forest continuum in relation to conservation and production values. Thus, the mosaic of cacao-AFS can be considered a technology to help preserve and promote biodiversity without harming its commercial production.

SIGNIFICANCE: This study demonstrates that the cacao-AFS mosaic could also be considered an environmentally-friendly agroforestry technique and/or climate-smart agriculture. For this reason, implementing payment for ecosystem services should gain greater relevance as a mechanism to increase added value. This would allow access to niche markets with higher added value by paying for both environmental services and the fine cocoa market.

1. Introduction

Cacao-based agroforestry systems (cacao-AFS) are considered an important alternative for the sustainable development of low input agriculture in Brazil, since these agroecosystems have many sustainability attributes of the natural heterogeneous forest, and can become a socio-economic-ecological component which is appropriate to reduce the anthropic pressure on the original forest cover of the cacao regions (Alvim, 1989a, 1989b; Müller and Gama-Rodrigues, 2012). Thus, cacao-AFS is an appropriate technology as it contributes to improving the standard of living of the population of an agricultural region based on land use without causing undesirable environmental changes. The use of different and multiple species in composing a cacao-AFS reinforces the security in minimizing risks due to fluctuations in the sale prices of consorts (Müller et al., 2012). The cacao tree is traditionally a shade-tolerant plant and can therefore be grown in association with other species under thinned forest (cabruca) (Fig. 1a, b), or under food crops (temporary shading), and other tree species introduced in the area (definitive shading). Thus, the combination of cacao with non-woody species (banana, cassava, etc.) and woody species (erythrina, yellow mombin, rubber, etc.) is excellent proof of the compatibility and complementarity of different species and at the same time sustainability of multistrata production systems (Fontes et al., 2014).

In the international context, Brazil has contributed approximately 4% of world cocoa production since the 2010/2011 harvest, while the American continent (South and Central America) varies between 13 and 16%, Oceania around 13%, and Africa represents approximately 75% of the total amount produced in the world. The main cocoa-producing countries include Côte d'Ivoire, Ghana, Ecuador, Cameroon, Nigeria, Indonesia and Brazil, which represent 89% of the world's cocoa production (ICCO - International Cocoa Organization, 2020). The main cocoa producing regions in Brazil are located in the Atlantic Forest (southern Bahia and northern Espírito Santo) and Amazon (Amazonas, Pará, Rondônia and Mato Grosso) biomes. National production was 259,425 t in the 2019 agricultural year, with Bahia responsible for 44% of national production and Pará for 50%. The production value totaled R $2.5 billion (IBGE/SIDRA, 2019),[1] generating GDP (Gross Domestic Product) of R$24 billion in the production chain. Cacao is planted on 430,051 ha in the Atlantic Forest Biome in the states of Bahia and Espírito Santo, covering 42,940 producers; while the planted area in the Amazon Biome covering the states of Pará, Rondônia, Amazonas and Mato Grosso is 168,799 ha with 33,462 producers (Table 1). It is noteworthy that the cacao-AFS in the state of Pará is mostly produced by family farming and constitutes almost 50% of all cocoa produced in the national territory; it is among the most competitive in the world, especially when considering average productivity (918 kg/ha in dry cocoa beans) and the low production cost (US$750.00/ton produced) of the crop, as verified in most of the municipalities which cultivate the cocoa crop. Such performance associated with the frankly conservationist characteristics of cocoa production in agroforestry systems selects cocoa farming as one of the most interesting agricultural alternatives for sustainable rural development in the Atlantic Forest and Amazon regions, and is already considered as a species for restoring the Legal Reserve of agricultural properties belonging to these regions in the states of Pará, Rondônia and Espírito Santo Santo. In the state of Pará, at least 1.26 million hectares of naturally high-fertility soils in deforested areas outside legally protected and indigenous lands are potentially suitable for cocoa production with low agrochemical inputs, sufficient to make a significant contribution to closing the predicted supply gap (Schroth et al., 2016). Therefore, no new forest clearing is needed to increase cocoa production in the legal Amazon.

Historically, there was a significant drop in cocoa production in Brazil in the late 1980s and mid-1990s, mainly due to the incidence of witches' broom disease in southern Bahia caused by the *Moniliophthora perniciosa* fungus (Pereira et al., 1990, 1996), the reduction of commodity prices, and also due to the occurrence of a long period of water deficit in the south of Bahia (Midlej and Santos, 2012). Brazilian production dropped from 458 thousand tons in 1986 to 170 thousand tons in 2003 (IBGE/SIDRA, 2019). As a result, there was progressive impoverishment in the cocoa region of Bahia where farmers abandoned the cocoa-producing areas and converted them to pastures, and also illegal exploitation of shade trees with high-value wood which compose the cabruca system (Johns, 1999; Marques et al., 2012a, 2012b). However, this negative scenario has been changing as cocoa production has been recovering with planting of clones which are more productive and tolerant to witches' broom, as well as more efficient management practices of inputs (fertilizers and other agrochemicals), combined with the increase in the value of the commodity and cost reduction (Zugaib et al., 2020), resulting in an increase in production of almost 100% in the last 20 years (CONAB—Companhia Nacional de Abastecimento, 2019).

In this modernizing context of the cocoa crop and its expansion, new cacao-AFS models with multifunctional species capable of providing both adequate shade and marketable products which increase revenue have been developed by *CEPLAC* (Executive Committee of the Cocoa Crop Plan) to be used by small and medium producers in all cocoa regions of Brazil (Almeida et al., 2002, 2009, 2014; Brito et al., 2002; Müller et al., 2012; Marques et al., 2012a, 2012b; Marques and Monteiro, 2016). These models are adaptable to new agroforestry technologies and/or to regional ecological conditions based on their structural, functional and socio-economic aspects. In this sense, it is assumed that the advantage of shading for cocoa in all cacao-AFS models is not to provide low light intensity which is considered optimal for the development and production of the plant, but to neutralize unfavorable ecological factors such as: low soil fertility, water stress, protection against winds, and disease and pest incidence (Müller and Valle, 2012). These factors are admittedly more serious in areas without shading

[1] Average exchange rate in 2019 - R$ / US$ = 3.4901; in 2016 = 3.4901; in 2014 = 3.3534

(Alvim, 1989a, 1989b; Johns, 1999). Thus, shading plays a very important role in plant protection in cases where there is no possibility to modernize the crop with modern technologies to correct acidity and fertilization in the case of infertile soils, irrigation to correct water deficiencies, use insecticides and fungicides, or to use varieties with greater productive potential. Accordingly, the use of shading in cacao cultivation must be primarily emphasized from the ecological and economic points of view and not only from the agronomic and physiological points of view. In addition, the use of moderate shading also contributes to greater ecological stability, providing adequate conditions for the reproduction and development of pollinating insects which concomitantly with sexual self-compatibility characteristics of some varieties are some of the main factors responsible for the high productivity of cacao (Müller and Valle, 2012).

Thus, the objective of this review was to describe commercially-adopted cacao-AFS models, with emphasis on their agronomic, economic and social-ecological advantages as key technologies for the sustainable rural development of the cacao regions in Brazil.

2. Agronomic aspects

2.1. Cacao-AFS in the Atlantic Forest biome

Cacao-cabruca, cacao-erythrina and cacao-rubber tree production

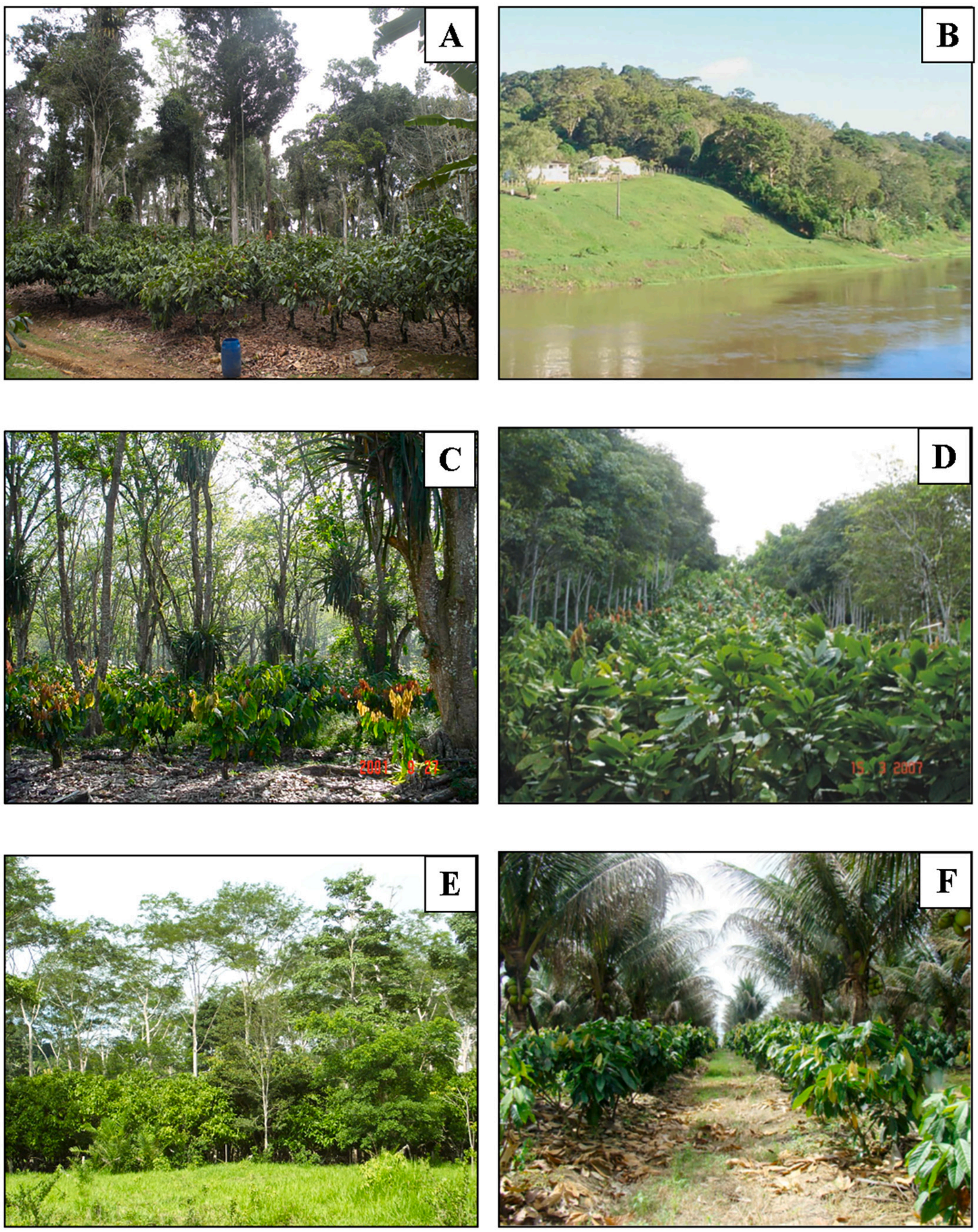

Fig. 1. Cacao-based agroforestry systems in Brazil: (A) Open caçao-cabruca system in Bahia; (B) Closed cacao-cabruca system in Bahia; (C) Cacao-erythirna system in Bahia; (D) Young cacao-rubber in zonal system in Bahia; (E) Cacao-based association with native tree species in Rondônia: paricá (*Schizolobium amazonicum*), mahogany (*S. macrophylla*), ipê-roxo (*Tabebuia heptaphylla*), freijó-laurel (*C. alliodora*), bagassa (*Bagassa guianensis*) and Brazil nut (*Bertholetia excelsa*); (F) Cacao–coconut system in Rondônia.

Table 1
Planted area and number of cocoa producers in Brazil (2019).

States	Planted area (ha)[a]	Number of producers[b]
Bahia	413,052	41,640
Pará	140,549	25,932
Rondônia	9371	5283
Espírito Santo	16,999	1300
Amazonas	1243	1723
Mato Grosso	637	524
Total	581,851	76,402

[a] IBGE/SIDRA (2019).
[b] SisCenex/CEPLAC (2016).

systems predominate in the southern regions of Bahia and northern Espírito Santo. These systems are quite different in the nature and arrangement of the components. The systems used are:

2.1.1. Cacao planted under forest thinning (cabruca)

Cabruca is a cacao cultivation system in intercropping with native forests or dense secondary forest (Fig. 1a, b). It is based on replacing forest strata by a culture of economic interest implanted in the understory in a discontinuous way and surrounded by natural vegetation, and does not cause much harm to the mesological relations with the remaining natural systems. In the cabruca system, the undergrowth is mowed and the smaller trees which offer greater competitiveness to the cacao tree are removed, with only those which can be used as temporary shade for the cacao tree remaining, and even as permanent shade in some situations. After this operation, the tall and sparsely crowned trees are selected for definitive shading and then the rest are felled (Müller and Gama-Rodrigues, 2012).

Unlike other conventional agricultural production models and intensive use of natural resources, the cabruca cacao system does not favor total devastation of forest resources. It allows conservation of the forest remnants inserted in it or those which surround the cultivated areas, as well as the survival of arboreal individuals from the primary forest which have the function of providing environmental comfort to the cacao tree. This led to the formation of ecological corridors which increase the capacity of fauna support for the remaining forest fragments (Fig. 2, Cassano et al., 2014), in addition to maintaining the soil quality at levels close to that of a natural forest; in addition, it conserves water resources when there is high tree density in the riparian zone (Curvelo et al., 2009).

The area planted with the cabruca system in southern Bahia is currently around 250,000 ha. Therefore, it is the production model adopted by almost all producers. The cacao tree density varies from 400 to 900 plants per hectare, depending on the number and the crown size of the trees which affect the shade level. Thus, cabruca can be classified into three levels of shading density based on the number of individuals (ind) of the different tree species existing in the system, and which varies according to microclimate conditions, relief form, the plantation location in the toposequence, the soil quality, and finally the tree architecture and dimensions. Tree density is classified as: (i) low density, when cacao shading is between 25 and 50 ind/ha; (ii) medium density, between 50 and 85 ind/ha; (iii) high density, when it is greater than 85 ind/ha (Lobão et al., 2004). In practical terms, the cocoa farmer classifies the cabruca system based on the shading level into: (i) open cabruca (low tree density, Fig. 1a) and (ii) closed cabruca (medium-high tree density, Fig. 1b). Thus, low cacao density and high shading density concomitant to witches' broom disease have been considered the main limiting factors for low productivity, with average values ranging from 120 to 180 kg/ha under different edaphoclimatic conditions (Zugaib et al., 2020). As a result, this system is very ecologically appropriate, however not economically viable. Cabruca was the planting system used in the formation of cacao plantations in Bahia; however, it is not used in the Amazon region.

2.1.2. Combination of cacao trees with erythrina (clear cutting)

This system starts with cutting and burning the floristic covering of the area. Young cacao trees are initially grown under provisional shade of banana (*Musa* sp.), or other food crops such as cassava (*M. esculenta*) and corn (*Zea mays*), and can also constitute an additional source of income during the installation phase of the crop for about 2–3 years, or until the erythrina plants (*Erythrina* sp.) are providing sufficient shade (Fig. 1c). Banana and cacao trees are planted at a density of 1111 plants/ha and shade trees at a rate of 25 plants/ha. The use of erythrina is mainly due to its ability to fix N_2 in association with diazotrophic bacteria, its fast growth, good height and low dense canopy (Santana and Cabala-Rosand, 1982; Müller and Gama-Rodrigues, 2012; Gama-Rodrigues, 2004).

This production system currently covers an area of approximately 80,000 ha, and was implemented by CEPLAC starting in the 1960s through a broad program to significantly increase cocoa production based on the use of fertilizers, chemical control of insects and diseases and reduction in the level of shading of cocoa to around 25% (Monroe et al., 2016). Thus, the cacao-erythrina system provided greater productivity compared to the cabruca system in the first 20 years of development. However, an absence of pruning the erythrina canopy caused the canopy of these shade trees to close, leading to a shading level similar to that of a closed cabruca. This resulted in decreased productivity in the maturity phase ($>$ 20 years) of the cacao-erythrina system, even with the use of more productive cacao clones which are responsive to fertilization and tolerant to witches' broom (Marques and Monteiro, 2016). This situation brought this production system to an impasse; either the shading level is reduced by pruning the erythrina crowns and/or completely removing some individuals; or the legume is replaced by other tree species of high commercial value such as rubber.

2.1.3. Combination of cacao and rubber trees

Cacao and rubber agroforestry systems have become an increasingly adopted practice by rubber growers in southern Bahia since the 1970s and 1980s, and currently in the northwest region of São Paulo State. The system is very attractive due to the convenience and ease of planting cacao seedlings under very uniform shade provided by the rubber trees, and also due to the epidemic attack of leaf disease (*Microcyclus ulei*) favored by the climatic conditions of the region. With the consequent depletion of many rubber plantations, producers were motivated to adopt an rubber agroforestry system intercropped with cacao which at the time had stimulating prices (Virgens Filho and Alvim, 1988), reaching a planted area of around 4000 ha (Alvim and Nair, 1986). The cacao trees were planted in a single row (450 pl/ha) or double rows (900 pl/ha) at 3 $\times$ 3 m spacing between the rubber tree lines (7 $\times$ 3 m; 473 pl/ha). The system productivity was on average 750 kg/ha of dry rubber and 780 kg/ha of dry cocoa beans. In companies which used high technology, this productivity can reach up to 1625 kg/ha year and 1200 kg/ha year of dry rubber and dry cocoa beans, respectively. The intercropping productivity analyzed by the Land Equivalent Ratio (LER), an index which measures the possibilities obtained in each of the components of the mixed systems in relation to those measured in the respective monocultures, revealed that the properties which used medium technology reached LER values of 2.45, while those which used high technology obtained an LER of 1.41. This means that it would take 2.45 ha and 1.41 ha of rubber or cacao monoculture, respectively, to obtain the production of 1.0 ha of intercropping using medium or high technology, respectively (Virgens Filho and Alvim, 1988).

The estimated area of cacao plantations established under old rubber plantations ($>$ 20 years) in Bahia is currently approximately 11,000 ha out of a total of 30,000 ha of monoculture. However, after some years there has been a record of reduced cocoa productivity due to competition for light (excessive shading), despite rubber trees in the intercropping being benefited by reduced competition with weeds, as well as by the application of fertilizers and other aspects of cacao management (Müller and Gama-Rodrigues, 2012). As a result, two modalities for

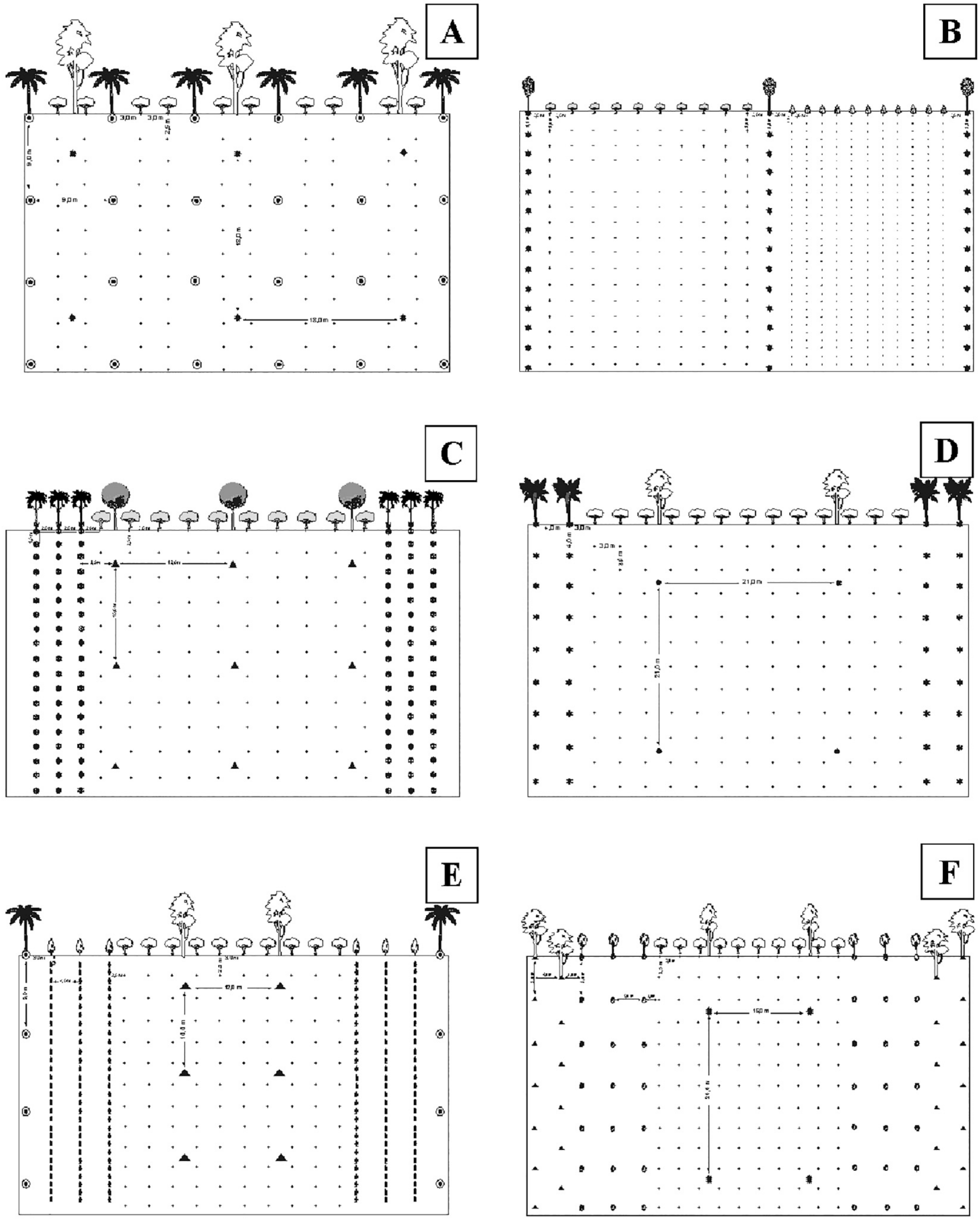

Fig. 2. Schematic diagram showing the spatial arrangement of cacao-based agroforestry systems in Brazil: (A) cacao (+) - coconut (●) – yellow mombin tree (✹) intercropping in Amazonas; (B) cacao (+) – coffee (◗) – teak (❋) intercropping in Rondônia; (C) cacao (+), peach palm (❆) and freijó-laurel (*C. alliodora*) (▲) intercropping in Rondônia; (D) cacao (+) – açaí tree (✱) – yellow mombin tree (✹) intercropping in Amazonas; (E) cacao (+) - coffee (⧫) - coconut (⊙) - andiroba (▲) intercropping in Rondônia; and (F) cacao (+) - soursop (Ⓖ) - andiroba (▲) – yellow mombin tree (✹) intercropping in Amazonas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

establishing AFSs with cacao and rubber trees have been developed since the 1990s within the permanent mixed systems reported by Alvim (1989a, 1989b). The 1st modality is the simultaneous planting of rubber trees in double rows with cacao trees (zonal system). Both the cacao and rubber plantations under this model should be performed in alternating strips or zones, with varying spacing options between the plants within the strips occupied by cacao or rubber trees (Fig. 1d). Alternative (spatial) spacing arrangements vary with plant density in both crops. Normally, the rubber tree is planted in double rows of 3 × 2.5 m, spaced 15 or 17 m apart, with a density of 400 to 440 plants/ha. The cacao tree is planted in quadruple (15 m) or quintuple (17 m) rows between the double rows of the rubber tree at 3 × 3 m spacing; the first row of the cacao tree is planted at 3 m (15 m) and 2.5 m (17 m) away from the rubber tree row, and the stand is fixed at 780 or 830 cacao trees/ha (Marques et al., 2012a, 2012b).

The second modality is planting rubber trees as permanent shade to replace erythrina (continuous system). In this model, the rubber tree must be introduced in simple rows between the lines spaced from each other in order to provide adequate light to the cacao tree (75%). It is recommended that the rubber tree be introduced during the process of renewing the cacao tree by more productive and tolerant to witches' broom clones. The age and renewal stage of the cacao tree may vary in spacing between the rubber tree rows within the same planting area depending on the shape of the area's relief. Thus, the rubber tree spacing can be 15 × 2 m (333 plants/ha), 15 × 2.5 m (267 plants/ha), 15 × 3 m (222 plants/ha) or 18 × 2.5 m (222 plants/ha), while the cacao tree spacing is fixed at 3 × 3 m (1100 plants/ha) (Marques and Monteiro, 2016). The rubber clones must have the basic characteristics of less dense canopy architecture and side branches facing upwards, cup-shaped aspect and regular leaf exchange period in both zonal and continuous models. These rubber tree characteristics make it possible to intercalate food crops of short and semi-perennial cycle between the lines such as beans (*P. vulgaris*), corn (*Zea mays*), manioc (*M. esculenta*), papaya (*C. papaya*), pineapple (*A. comosus*), sugar cane (*Saccharum* sp.), pigeon pea (*C. cajan*), and bananas (*Musa* sp.), among other crops of economic interest, in the immaturity phase of the main crops. This makes these systems suitable for family farming since it enables them to amortize the implementation and maintenance costs in the first three years.

2.2. Cacao-AFS in the Amazon biome

Some cacao-AFS models have been defined for use by small and medium producers in the states of Rondônia, Pará, Mato Grosso and Amazonas based on research developed by *CEPLAC* since the 1990s (Müller and Gama-Rodrigues, 2012; Almeida et al., 2014). These models may undergo adjustments in the future to adapt them to new agroforestry technologies and/or to regional ecological conditions:

2.2.1. Continuous permanent systems

This system uses multifunctional tree species capable of providing benefits such as adequate shading of the cacao tree, maintenance of soil nutrients and support for biodiversity, as well as providing products of economic value for an additional income stream for farmers. In this case, the perennial species which produce fruits, fibers, firewood, wood, latex, palm hearts or oils are planted in regular spacing and arranged continuously in the area. Regardless of whether the tree components are arranged in a continuous or zonal form, performing functions of top shading, side shading, windbreaking or ground cover, young cacao trees are associated with two or more provisional components which provide shade and food, and usually the banana tree.

Banana seedlings of cultivars resistant to *Mal-do-panamá* fungus (*Fusarium oxysporum*), Yellow sigatoka (*Mycosphaerella musicola*) and Black sigatoka (*M. fijiensis*) and/or of the *Terra* variety (known in the north of Brazil as "*banana-de-fritar*" or "*três pencas*"), should preferably be used. This variety is tolerant to the first two diseases and is well received in the regional market. In regions with difficulty in acquiring banana seedlings, provisional shading and use of cassava (*M. esculenta*), pigeon pea (*C. cajan*) or castor bean (*R. communis*) are recommended in a 1 × 1 m or 1.5 spacing × 1.5 m, and properly managed to avoid excessive shade (Mattos, 2001).

Furthermore, provisional side shade species such as corn (*Zea mays*) and cassava (*M. esculenta*) or soil cover species such as beans (*P. vulgaris*) and rice (*Oriza sativa*) can be used in a temporal sequence according to the farmer's preference to take advantage of the light in the lines and to improve the financial performance of the system, thus generating revenues more quickly and during establishment of the crops, however respecting a distance of 0.7 m from the cacao trees. Continuous systems, also called continuous permanent systems, recommended are:

2.2.1.1. Cacao trees with forest species. Cacao trees in the young phase are associated with a kind of temporary shade, usually banana, while the trees of definitive shade formed by different species of regional economic importance grow, such as: paricá (*Schizolobium amazonicum*), mahogany (*S. macrophylla*), ipê-roxo (*Tabebuia heptaphylla*), freijó-laurel (*C. alliodora*), bagassa (*Bagassa guianensis*) and Brazil nut (*Bertholetia excelsa*). The cacao tree is planted in spacing of 3 × 3 m and the shade species from 15 × 15 m to 24 × 24 m (Fig. 1e). This model has been used since 1973 in Rondônia, and totals approximately 9000 ha. This AFS occupies approximately 140,000 ha in the state of Pará.

2.2.1.2. Cacao trees with coconut palms. This system consists of double rows of cocoa trees with a 3 × 3 m spacing established between rows of coconut trees (*C. nucifera*) in 9 × 9 m spacing. The banana tree is implanted among the cacao trees (3 × 3 m) to provide temporary shade and gliricidia (*G. sepium*). This fast-growing tree legume is established along the same lines as the coconut tree. The population densities in this system are: cacao 740 plants/ha, coconut tree 123, banana 740 and gliricidia 247 plants/ha (Fig. 1f).

Experimental results in all cocoa producing regions showed that cocoa cultivation under the shade of coconut trees presented an average productivity of 1250 kg/ha of dried cocoa beans, without the production of coconut declining.

2.2.1.3. Cacao trees with coconut palms and yellow mombin trees. The yellow mombin or *taperebazeiro* (*S. mombin*) was also included as a second component for top shade in the cacao-coco AFS in the State of Amazonas where there are cacao trees in floodplains. This species has great adaptability to flooded areas, rapid vegetative growth, ease of seminal or clonal propagation and high commercial value of the fruit for pulp production.

In this model, the cacao tree is planted in double rows spaced 3 × 2.5 m between rows of coconut trees established at 9 × 9 m in a north-south direction. The provisional shading of the cacao trees is provided by cassava planted in a 1 × 1 m compass and banana trees in the same spacing as the cacao trees. The density is 745 cacao trees/ha, 123 coconut trees/ha and 30 yellow mombin/ha (Fig. 2a). There are approximately 100 ha of cacao plantations implanted using this AFS model in the municipalities of São Sebastião do Uatumã and Itapiranga in the State of Amazonas (Brito et al., 2002).

2.2.2. Permanent zonal systems

Perennial species intercropped with cacao in zonal systems are arranged in a non-continuous manner in the area, thus becoming more efficient than in continuous systems because they enable better light use. They have the important characteristic of facilitating cacao management and shade crops, especially when the latter are arranged in double rows. This allows ample access to harvest the products, making it possible to even fell the plant to use wood or palm heart, reducing the costs of these harvests without causing damage to cacao trees. The adopted zonal models are:

2.2.2.1. Cacao trees with coffee trees. In this system, 10 rows of cacao trees (3 × 2 m) are intercropped with 11 rows of coffee trees (*C. canephora*, 3 × 1 m). Teak (*T. grandis*) trees, an Asian timber species with fast vegetative growth, high economic value and excellent agronomic adaptation in the Amazon region, are established between the areas where the cacao and coffee trees are planted. The teak seedlings planted at a spacing of 2.5 m between plants and 3 m between the cacao and coffee areas. The population density of this model is 947 cacao trees/ha, 1042 coffee trees/ha and 152 teak trees/ha (Fig. 2b).

2.2.3. Mixed permanent systems

Mixed systems are characterized by adopting zonal and continuous systems in the same area for permanent crops. In this case, the species used for shading the cacao tree are arranged continuously in the area, while the main crops are planted in zones. These models are implemented in the state of Amazonas where agriculture in floodplains is significant (Brito et al., 2002; Almeida et al., 2012). The main systems used are:

2.2.3.1. Cacao trees with peach palm trees. This model adopts planting zones of ten rows of cacao trees spaced 3 × 2.5 m apart, alternating with planting zones of three rows of peach palm trees (*B. gasipaes*) in the measure of 2 × 1.5 m. The definitive shade of the cacao tree is provided by freijó-laurel (*C. alliodora*) continuously planted at a spacing of 12 × 10 m in the areas of the cacao tree.

The population density of the system is 1148 cacao trees/ha, 571 peach palm trees/ha and 84 freijó-laurel /ha. Due to the spacing adopted, the peach palm has the objective of producing palm heart (Figs. 2c).

2.2.3.2. Cacao trees with açaí trees in double rows and yellow mombin trees. This model consists of planting 13 rows of cacao trees spaced 3 × 3 m interspersed with two rows of açaí trees (*E. oleracea*) in a 4 × 4 m compass in the north-south direction. A distance of 3 m is maintained among the consort species. Cassava (1 × 1 m) and banana (3 × 3 m) are used as temporary shading for cacao. The cultivation of açaí trees aims at exploiting fresh fruit to produce açaí drink and juices, liqueurs, creams, ice creams and popsicles which are very popular in the Brazilian Amazon. The yellow mombin is used as definitive top shading, established between four plants from the third row of cacao trees and adopting a spacing of 21 × 21 m. Cashew fruit is one of the most sought after and preferred tropical fruits by the population for producing juices and ice creams. The population density of this system is 951 cacao trees/ha, 109 açai trees/ha and 16 yellow mombin trees/ha (Fig. 2d).

This system is recommended for both floodplain and upland areas in the state of Amazonas due to the adaptation of both species to these agrosystems. In the case of establishment in floodplains, it is recommended to use selected cocoa seeds in the region itself in riverside plantations, since most hybrid cacao cultivars do not adapt to this ecological condition (Brito et al., 2002).

2.2.3.3. Cacao trees with coffee, coconut and andiroba trees. This model consists of planting 10 rows of cacao trees (3 × 2.5 m) interspersed with triple rows of coffee trees (4 × 1 m) and a single row of coconut trees (9 m between plants) in the north-south direction. A distance of 3 m is maintained between the rows of coconut and coffee trees; a distance of 2 m between coffee trees and cacao trees; and 13 m between coconut trees and cacao trees. The provisional shading of the cacao tree is formed by cassava and banana trees, and definitive shading constituted by andiroba trees (*C. guianensis*) in 10 × 12 m spacing (Brito et al., 2002).

Andiroba trees are traditionally used for exploiting wood for civil construction (ceilings and frames) due to its physical qualities. Its seeds are also used to extract oil for popular medicinal use with anti-helminthic, healing, anti-inflammatory and febrifugal properties. It is estimated that an adult andiroba tree produces about 200 kg/year of seeds, equivalent to seven liters of oil/year. The population density (plants/ha) of this system is 800 cacao trees, 891 coffee trees, 33 coconut trees and 40 andiroba trees (Fig. 2e). The system is predominantly used on the Madeira River channel.

2.2.3.4. Cacao trees with soursop and andiroba trees. This model comprises a planting area with a double row of andiroba trees (5 m between plants and 4 m between rows), another area with triple rows of soursop trees (*Anona muricata*) in the spacing of 5 × 5 m and ten rows of cacao trees in the 3 × 2.5 m compass in the north-south direction. A distance of 3 m is maintained among the consort species. In this system, the yellow mombin is used as definitive shading of the cacao tree with a spacing of 15 × 20 m. The population density is 800 cacao/ha, 120 soursop/ha, 78 andiroba/ha and 20 yellow mombin trees/ha (Fig. 2f).

Other cacao-AFS models are being tested in the Amazon through specific research actions such as: a) combination of multifunctional fruit and forest perennial species; b) use of agroforestry practices in reintegrating *capoeira* vegetation (Secondary forest) into the production process (Almeida et al., 2009); c) recovery of decayed cacao trees with the use of agroforestry practices; d) cacao-coffee intercropping systems (Müller et al., 2012); and e) cacao-coconut intercropping systems (Cidin et al., 2009). Studies are being conducted by comparing different fruit and forest species spatially interspersed with each other and temporally with short-cycle species (when possible). Edaphic changes resulting from the recycling of nutrients and the incorporation of biomass are monitored in these tests.

3. Economic aspects

The adoption of a specific cacao-AFS model is mainly due to the productivity and profitability achieved. Thus, some economic considerations of AFSs will be presented herein with an emphasis on the yields provided by cacao and the consort species.

3.1. Cacao-cabruca

In this system, if on the one hand the management of cacao conserves the native forest and reduces costs with the use of pesticides (biological buffer), on the other hand local producers currently suffer from economic barriers, low productivity and impossibility to commercialize the wood resulting from pruning and/or removing native trees. The highly fluctuating prices of the crop also make producers look for alternatives to cocoa cultivation. Therefore, *CEPLAC* implemented the Cabruca Technical Management Project (*PTMC*) to reverse this scenario, implementing the shading adaptation (shading reduction) with pruning or suppression of some specimens of perennial woody species, high planting density, replacing unproductive cacao trees and those susceptible to witches' broom, and performed area fertilization (Lobão et al., 2004). The productivity in the first year after implementing the Cabruca Technical Management Project (*PTMC*) was multiplied by 3.0 (103 kg/ha to 300 kg/ha) in a pilot area of 1.9 ha in the municipality of Barro Preto, Bahia; furthermore, the observed increase in productivity after the 7th year of using the *PTMC* was 14 times compared to the initial productivity (103 kg/ha up to 1445 kg/ha). It was possible to at least double the current average yields of cabrucas with 40-55% shading on 26 farms through the judicious use of mineral fertilizer and other intensification practices compatibles with C stocks in the large trees of up to 65 Mg ha^{-1} (Schroth et al., 2016).

On the other hand, the current legal restrictions for the management of tree species to reduce shading, limited access to credit, a high dependence on fertilizers and other agrochemicals with a high risk of environmental pollution, and the instability of the price paid to the producer generates a high degree of uncertainty about the sustainability of cocoa production in the cabruca system in the long term. A similar question already occurred with cocoa producer in implementing the cabruca modernization policy by eliminating 50–70% of shade trees and the use of high technology in the 1960s and 70s (Johns, 1999).

Therefore, a complementary alternative to increase the financial profitability of producers could be an environmental valuation of the cacao-cabruca system for the purpose of rural credit (Zugaib et al., 2016). These authors reported that the economic indicators for a 20-year crop cycle considering increasing productivity from 300 kg/ha (1st year) to 1050 kg/ha (7th to 20th year) revealed that the productive model is both viable with payment for environmental services, as well as without it (Table 2). Thus, economic results significantly improve by including payment for environmental services through indirect use (carbon) and option (water) values. In addition, the economic value of wood as an

Table 2
Some financial indicators on cocoa production of the cacao-cabruca system, Bahia, Brazil.

	IRR	NPV (R$/ha)[b]	Payback	B/C
No environmental assets	19%	7747	7 anos	1.27
With environmental assets[a]	55%	26,112	4 anos	1.60

IRR, NPV e Payback for direct, indirect and option values.
IRR = Internal Rate of Return; NPV = Net Present Value, B/C = Benefit/cost. Discount rate 8.75% p.y.
[a] Average aboveground carbon stocks (57.5 Mg ha^{-1}) in the large shade trees.
[b] Average exchange rate in 2016 - R$ / US$ = 3.4901. Adapted from Zugaib et al. (2016).

environmental timber asset which will remain after shading in a 1.4 ha cacao-cabruca model was estimated at R$100,526.93 (Zugaib et al., 2016). Thus, this economic asset should be considered by the financial system as a legal guarantee for financing for cocoa producers in Bahia.

3.2. Cacao-rubber tree

In addition to the study by Virgens Filho and Alvim (1988) which showed the economic viability of the cacao intercropping under old rubber plantations, recent studies have also reported favorable economic indicators for the cacao-rubber intercropping in a zonal system (Cotta et al., 2006; Sanches, 2019). In addition to products of intercropping species (dried cocoa beans and latex), the carbon stock in the tree biomass (107 MgC/ha), particularly of rubber trees, would accredit the cacao-rubber intercropping as a promising activity in generating Reduced Emission Certificates for a 34-year cycle (393 RECs/ha), making this cacao-ASF model more economically attractive (Cotta et al., 2006). The sensitivity analysis for the net present value (NPV), with a discount rate of 10% p.y, showed that the interest rate was the cost variable which most affected the viability of the intercropping. A 20% decrease corresponded to a 49% increase in the viability of this production system. In turn, a 20% increase in the price of RECs increased the viability of the intercropping by only 8.5%. This is because the revenue from the RECs represents a smaller amount when compared to the total investment cost; as a result, when interest is incurred, the income of the RECs is less affected than the project costs. When considering the REC, the price of rubber and cocoa beans may be reduced up to 76% and 72%, respectively, and the value of the labor cost an increase of up to 78%; even so, the intercropping would still remain viable. The study also highlighted the social relevance of this intercropping, since the labor cost was responsible for 61% of the total cost of the intercropping, evidencing its significant contribution to generating employment and income in rural areas.

Sanches (2019) reported that both the cacao-rubber intercropping and the cabruca system were economically viable, but the cacao-rubber intercropping showed better financial results (Table 3) due to the diversification of revenue sources - dried cocoa beans, latex and banana (temporary shade). It is noteworthy that the cacao density was 833 plants/ha in the intercropping, while it was 1000 plants/ha in the cabruca; however, the intercropping presented higher productivity per plant (2.2 kg/plant) than the cabruca (1.5 kg/plant) in the production stabilization phase (from the 6th year onwards). The sensitivity analysis of price *versus* cocoa productivity showed the cacao-rubber tree intercropping was less sensitive than the cabruca system. A 20% reduction in productivity corresponded to a 36% decrease in IRR (Internal Rate of Return) in the cabruca system, while the decrease in the cacao-rubber tree intercropping was only 18%. For both cacao-SAF models, the sensitivity analysis also showed that the cost of maintenance and harvesting is the most sensitive, with labor representing about 70% of this cost in relation to the cost of the investment phase and administrative costs. However, the cacao-rubber tree intercropping was also less sensitive than the cabruca system. These results reinforce what has already been discussed in topic 3.1, which is efficient agricultural intensification is necessary in the cabruca system in order to increase productivity together with payment of the environmental benefits to increase the economic viability of this production system (Also see topics 3.4 and 4).

Table 3
Financial indicators for the cacao-rubber and cacao-cabruca systems, Bahia, Brazil.

Indicator	Cacao-rubber	Cacao-cabruca
Average revenue (R$/ha)[a]	15,805	10,698
Average COE (R$/ha)	6571	5754
Gross Margin (R$/ha)	9234	4943
Payback (years)	14	19
IRR (%)	15.4	12.3
NPV (R$/ha)	11,738	2156

Average Revenue = Average Revenue for the 30 years analyzed ● Average COE = Average Direct Cost of the 30 years analyzed ● Gross Margin = Average Revenue - Average COE ● IRR = Internal Rate of Return ● NPV = Net Present Value. Discount rate 10% p.y.
[a] Average exchange rate in 2019 - R$ / US$ = 3.9451. Adapted from Sanches (2019).

3.3. Cacao-AFS in the Amazon region

Cacao productivity in Rondônia varied according to the AFS models implemented in 5 ha modules (Table 4). The estimated yield of dried cocoa beans was higher in the cacao-forest species intercropping, followed by the cacao-peach palm (−2.5%), cacao-teak (−23%), and cacao-coffee (−32%) intercrops. The productivity of peach palm and coffee can be considered satisfactory for family farming in the Amazon region (Almeida et al., 2014).

In the case of roundwood productivity for intercropping cacao-forest species, cacao-coffee, and cacao-peach palm AFSs, it was estimated that it was feasible to use 80% of the implemented original shading stand after 25 years of cultivation due to losses due to diseases, pests, winds and other factors. The average productivity for the remaining stand for the mixture of forest species was 1.6 m^3 of roundwood/tree. In these circumstances, it was estimated at 56.3 m^3 of roundwood/ha for the intercropping of cacao-forest species, 25.6 m^3 of roundwood/ha for cacao-coffee, and 46.1 m^3 of roundwood/ha for cacao-peach palm. Furthermore, an average yield of 1.9 m^3 of roundwood/tree and 183.9 m^3 of roundwood/ha was estimated for teak (*T. grandis*), which participates in the cacao-coffee intercropping. On the other hand, the estimated cumulative average yield in the cacao-teak intercropping in rows was 278.3 m^3 of teak roundwood/ha at the age of 20. It was also estimated that the mixture of forest species for the top shading of cacao trees in this intercropping would have an average yield of 40.8 m^3 of roundwood/ha.

Considering only the stabilization year (6th year) of the cacao-AFS

Table 4
Estimated productivity levels for consortium species in different cacao-based agroforestry systems, Rondônia, Brazil.

Age (years)	Cacao – Forest species	Cacao - Peach palm		Cacao - Coffee		Cacao - Teak
	Dried cocoa beans (kg/ha)	Dried cocoa beans (kg/ha)	Peach palm (bunches/ha)	Dried cocoa beans (kg/ha)	Coffee (kg/ha)	Dried cocoa beans (kg/ha)
1	–	–	–	–	–	–
2	–	–	420	–	–	–
3	200	195	840	135	240	155
4	400	390	1380	270	480	310
5	800	780	1380	550	900	615
6	1200	1170	1330	820	1800	925

Adapted from Almeida et al. (2014).

models (Table 4), it appears that all models presented satisfactory economic indicators (Table 5). There was a wide variation from R$5349.46 to R$11,642.21 for the variable gross margin/ha/year, with a higher value for the cacao-coffee AFS. This latter situation obviously resulted from the best prices practiced in the commercialization region of the products of these consort species. The cacao-coffee AFS had the highest maintenance cost/ha/year, followed by the cacao-peach palm AFS, and with relatively close values for the cacao-teak and cacao-forest species AFS. The higher maintenance cost for cacao-coffee AFS was due to the fact that both crops are labor intensive, especially in the harvesting and processing activities, which together accounted for 38.4% of the costing expenses. The greatest demand for labor in this AFS occurs in the fruiting period, since the coffee harvest season in the region coincides with the fruiting peak of the cacao tree (Almeida et al., 2014).

Regarding the availability of resources obtained by the four cacao-AFSs, the cacao-peach palm intercropping presented a higher modular net margin/year (1 module = 5 ha) equivalent to 8.4 times that of cacao-teak, 2.3 times of cacao-forest species, and 1.1 times cacao-coffee. Its value of R$29,264.92/year represented a monthly income of about 3.4 living monthly wages for the rural producer (Table 5). In turn, the cacao-forest species intercropping enabled revenue of 1.48 living wages/month, while the cacao-coffee intercropping generated revenue of 2.95 salaries. The lowest revenue was provided by the intercropping of cacao-teak equivalent to 0.40 living wages/month. However, as cocoa and coffee are some of the main commodities in the tropical region of the world, the prices of both cultures in the national and international markets favor intercropping cacao-coffee, added to the social importance due to its high demand for labor.

However, considering the exploitation and commercialization of roundwood at the end of the 25-year production cycle for the cacao-forest species, cacao-coffee, and cacao-peach palm intercrops; and 20 years for cacao-teak, the modular net margin values could significantly increase (Table 6). The cacao-coffee intercrops stand out with an estimated value of R$341,584.00, with profit from the sale of teak timber and the mixture of forest species; and cacao-teak, including the sum of the sale of timber, a mixture of forest species and teak for a total of R $465,212.00. These results show that although the cacao-teak intercropping presented the lowest revenue, which was 0.40 living wages/month since only the dry cocoa production was considered, it could present the best profitability when taking into account the possibility of commercializing the timber at the end of the production cycle.

Müller et al. (2012) analyzed the agronomic and economic viability of AFSs with cacao and seven-year-old coffee trees in two intercropping zones in band and perimeter, involving four models which varied according to the area occupied (in%) by the main consorts of cocoa and coffee: model-1 (38:62); model-2 (50:50); model-3 (68:32) and model-4 (15:85). The banana tree was used as a temporary shade for the(Jackson et al., 2012; Lobão and Valeri, 2009; Moço et al., 2009; Schroth et al., 2011, 2016a,b; Tomich et al., 2005) cacao tree, and the peach palm tree as definitive shade. The productivity of the intercropped species varied between 207 and 482 kg/ha for cacao, between 358 and 2362 kg/ha for coffee, and between 452 and 3160 bunches/ha for peach palm. The values

of the Land Equivalent Ratio (LER) ranged from 3.3 to 5.1. All the tested models showed economic viability, with models 2 and 3 standing out above the others in both the cost/benefit ratio (CBR) and net present value (NPV), as well as for the internal rate of return (IRR) (Table 7). These results showed the strong influence that a given AFS model has on the agronomic and economic viability of cacao-coffee system and other types of intercropping in a family farming module.

Table 6
Revenue generated by the sale of timber produced in modules of 5.0 ha of cacao-based agroforestry systems.

AFS models	Forest species	Timber volume (m^3)	Timber average price/m^3 (R$)[d]	Total price (R$)
Cacao – Forest species	Mixture[a]	282	153[b]	43.146
Cacao - Peach palm	Mixture	231	153	35.343
Cacao - Coffee	Mixture	128	153	19.584
	Teak	920	350	322.000
Cacao – Forest species	Mixture	204	153	31.212
	Teak	1.240	350[c]	434.000

[a] Mixture of species of regional importance (angelim-pedra, *Hymenolobium petraeum*; bandarra, *S. parahyba*; cambará, *Gochnatia polymorpha*; cumaru, *D. odorata*; cupiúba, *Goupia glabra*; garapa, *Apuleia leiocarpa*; ipê-roxo, *Handroanthus impetiginosus*; jataí, *T. angustula*; oiticica, *Licania rígida*; pau-d'alho, *Gallesia integrifólia*; tauari, *Couratari tauari*; among others).
[b] Estimated average price paid to the rural producer, on the property, regardless of the species.
[c] Estimated average price paid to the rural producer, on the property, considering values practiced in Ji-Paraná, Rondônia and Alta Floresta, Mato Grosso.
[d] Average exchange rate in 2014 - R$ / US$ = 3.3534. Adapted from Almeida et al. (2014).

3.4. Valuation of the above- and belowground carbon stocks as an ecosystem service in cacao-AFS

Global climate change, which affects the entire planet, requires concentrated global action to mitigate the emission of greenhouse gases (GHG) and reduce global warming. The Brazilian government created the *ABC* Plan (Low Carbon Agriculture) which aims to ensure continuous and sustained improvement of management practices which reduce GHG emissions, and in addition which increase the fixation of atmospheric CO_2 in the plant-soil system of the various sectors of Brazilian

Table 7
Economic indicators of the cacao-coffee system, Rondônia, Brazil.

Indicator[a]	M1[b]	M2	M3	M4
	Models			
BCR	2.6	4.1	4.1	2.4
NPV (R$)[c]	8900	19,268	17,788	4644
IRR (%)	31	47	46	29

[a] BCR = Benefit/Cost Ratio; NPV = Net Present Value; IRR = Internal Rate of Return. Discount rate 8% p.y.
[b] Proportion of cacao and coffee trees (%): M1 (38:62); M2 (50:50); M3 (68:32) and M4 (15:85).
[c] Average exchange rate in 2014 - R$ / US$ = 3.3534. Adapted from Müller et al. (2012).

Table 5
Revenue generated (R$)[a] in modules of 5.0 ha of cacao-based agroforestry systems (AFS) in the year of production stabilization, Rondônia, Brazil.

AFS models	Gross margin/ha/year	Maintenance cost/ha/year	Net margin/ha/year	Modular net margin/year	Living wages/month
Cacao – Forest species	6959	4394	2565	12,826	1.48
Cacao - Peach palm	10,908	5065	5852	29,264	3.37
Cacao - Coffee	11,642	6508	51,34	25,671	2.95
Cacao - Teak	5349	4658	691	3457	0.40

[a] Average exchange rate in 2014 - R$ / US$ = 3.3534. Adapted from Almeida et al. (2014).

agriculture (MAPA - Ministério da Agricultura, Pecuária e Abastecimento, 2012). Within this context, AFSs present themselves as a sustainable activity which enables generating Reduced Emission Certificates (RECs) to be traded on the carbon credit market (Wise and Cacho, 2005). Commercializing credits resulting from reducing and/or sequestering carbon will be a new and important revenue source for producers aware of the opportunities generated by sustainable businesses, in turn stimulating a reduction of emissions and carbon sequestration in rural areas.

In this sense, what would be the revenue source provided by the cacao-AFS when considering the values of stored carbon (above- and belowground)?

Brazil has approximately 600,000 ha of cacao trees planted, almost all of which are under AFS. When analyzing the case of the State of Pará in the Amazon region, since 1996 the Regional Superintendence of *CEPLAC* imposes in its guideline that new plantings should be exclusively done in anthropized areas. Thus, it appears that with the State Program for the Expansion of Cocoa, approximately 100 thousand hectares of degraded areas have already been recovered, which added to the 50 thousand hectares established up to 1996 total 150 thousand hectares. This planted area corresponds to approximately 150 million cacao trees, and in addition 6.6 million trees of native species to the Amazon used as permanent shade for cacao trees. There is no doubt that cacao cultivation is fully environmentally friendly and also one of the best options for recovering environmental liabilities. If we account for the carbon volume stored only in the aboveground biomass using a value of 46 t of fixed carbon per hectare (Schroth et al., 2015), we will reach approximately 25.2 million tons of CO_{2eq}, which is the unit used in the carbon credit market (Valdetaro et al., 2011), which at a price of €18.41/t (price per tonne of CO_{2eq} at the lowest price of 2019), would total approximately €464 million. In this scenario, the economic benefit generated by the carbon credit shows that producing deforestation free cacao (environmental benefits) would enable the livelihoods of thousands of land owners, especially family farmers, as well as their workers and share-croppers in this part of the Brazilian Amazon (Schroth et al., 2016).

Additionally, the cacao-AFSs in the southern region of Bahia occupy 440,000 ha: 250,000 ha of cacao-cabruca AFS, and 190,000 ha of cacao-erythrina and cacao-rubber AFSs. When considering the values of 87 t C/ha (cacao-cabruca) and 46 t C/ha (cacao-erythrina and cacao-rubber) of carbon stored in aboveground biomass, respectively, we reach a total of 111.6 million CO_{2eq}, which would total €2.1 billion.

When adopting cacao-AFSs (Cacao-erythrina, cacao-cabruca and cacao-rubber) when taking into account carbon credit and accounting for the carbon stock in the soil (up to 40 cm deep for an area of 1 ha) over 20 years, there was an increase of approximately €2870 in profitability. In addition, the economic viability of these cacao-AFSs calculated by the net present value (NPV) demonstrated that there was an increase of approximately 56% in NPV when considering the carbon stored in the soil. These results show that incorporating carbon credits into the economic valuation of these production systems will be an option to make this activity more profitable (Hespagnol, 2020). Thus, the cacao-AFSs in southern Bahia have a potential financial addition in the sale of carbon credits of approximately €1.3 billion.

4. Social-ecological aspects

Does the diversity of cacao-AFS models as a path to poverty reduction lead towards sustainable rural development of the cocoa regions in the Atlantic Forest and Amazon biomes? This answer is initially very complex and uncertain since the integrated management of natural resources to achieve this goal requires innovative practices, institutions and policies, in which only research to understand specific problems will not provide a satisfactory solution. In this sense, cacao-AFSs must be understood as socio-ecological systems with multiple value chains at the landscape scale, which start with the production of cocoa and intercropping species (perennial species and annual crops) for the marketing of their multiple products. Thus, the entire spectrum of agroforestry solutions must contribute to rural livelihoods and sustainable multifunctional landscapes.

The social importance of establishing a diversity of cacao-AFS models is in generating a great amount of permanent employment and fixation of workers and their families in the field in face of the impossibility of mechanizing most of their agricultural practices. It is estimated that cocoa cultivation generates employment for every 2.5 ha during its production cycle (Almeida et al., 2014). Based on this estimate, Brazilian cocoa cultivation currently has the potential to generate around 232,740 direct jobs, of which 45% would be allocated in the cacao-cabruca system. Labor normally represents more than 60% of production costs (Sanches, 2019), but is this a problem or a solution? It would be an apparent 'problem' for rural producers concerned with reducing production costs, but it would be a 'solution' to the socioeconomic problems caused by unemployment. This topic is still an ongoing debate among the various sectors which compose the cocoa production chain in Brazil. In addition, another social importance of the diversity of cacao-AFS models is to generate new technologies and knowledge, preserve tree species with a social function (medicinal and fruit species) and to produce food during the installation phase of the AFSs (Müller and Gama-Rodrigues, 2012), which makes these systems suitable for the proposal of family farming in order to guarantee a greater diversity of food supply for domestic consumption, as well as to boost the local commerce of small towns and villages, thus increasing food security and improved nutrition for the populations of the cocoa regions.

On the landscape scale, the existence of different cacao-AFS models constitutes an interconnected agroforestry mosaic with various types of forests in its surroundings. The existence of cacao-cabruca, cacao-erythrina and cacao-rubber AFSs (in mixed and zonal systems) surrounded by the natural forest at the farm level is common in the southern region of Bahia (Monroe et al., 2016), forming a forest continuum in relation to conservation and production values (See graphical abstract). It is necessary to consider that the different land use forms are like links in a continuum and interdependent in terms of ecosystems and sustainable use. Each link provides multiple, but not identical, values. In this agroforestry mosaic, the nature and extent of its overlaps with other forest types depend on factors which include the choice of intercropped species and the intensity and nature of other management practices (Gama-Rodrigues, 2004). It is recognized that the cabruca system makes cacao an ideal crop for biodiversity- or wildlife-friendly farming (Schroth et al., 2011), which gives it the highest conservation value compared to other cacao-AFSs. However, the conservation value of each cabruca site is strongly influenced by the size and biodiversity levels of the forest fragment connected to it in the landscape. A high percentage of forest cover in the landscape, the diversity of species (flora and fauna) recorded in cabrucas is greater when compared to an agroforestry landscape with little representation of forests (Cassano et al., 2014). Cabrucas in landscapes with small forest fragments and a history of high exploitation by selective logging can constitute the main reserve of native tree species diversity in the cacao-AFS mosaic (Lobão et al., 2009). Therefore, in these landscapes it is expected that the conservation value of cabrucas tends to be high, since each tree constitutes a habitat or a source of food for other biological groups (flora and fauna) (Cassano et al., 2014). On the other hand, there may be little variation in the conservation value of a cacao-AFS mosaic when only specific biological groups are considered. Closely interconnected natural forests, cabrucas and cocoa-erythrina consortia exhibit similar organism density and species richness for soil and litter invertebrates (Moço et al., 2009). In this overall context, the expected linear relationship between conservation and production values in a cacao-AFS mosaic (See graphical abstract) may also turn out to be a convex relationship (cabrucas with higher conservation values than natural forests) or even a constant relationship (variation of production values for the same conservation value) in other agroforestry landscapes. A mixed landscape mosaic offers a reasonable compromise between profitability and environmental objectives (Tomich et al., 2005). Thus, the cacao-AFS mosaic can be considered a technology to help preserve and promote biodiversity (ecological intensification), without harming its commercial production (agricultural intensification), and can therefore enhance economic and ecological resilience of cocoa regions in Brazil. In this context, the cacao-AFS mosaic could also be considered an environmentally-friendly agroforestry technique and/or climate-smart agriculture. For this reason, implementing payment for ecosystem services should gain greater relevance as a mechanism to increase added value of cocoa production, making farmers less vulnerable to fluctuations of commodity or input markets (Jackson et al., 2012). This would enable entering niche markets with higher added value such as the special/fine cocoa market (premium or gourmet chocolates).

5. Conclusions and future outlooks

In view of the diverse social, economic and environmental benefits of cacao-AFSs in Brazil, future research actions must prioritize improving the production system sustained in the integration of resources and production factors, and in the interactions between the soil-plant processes, emphasizing the role of biological processes in nutrient cycling and pest and disease control in order to minimize the need for agricultural inputs and maximize their efficiency, thereby enabling a marked reduction in production costs and their potential for environmental pollution. The effectiveness of cacao-AFS mosaic management strategies at the farm and landscape scales depends on the farmer's knowledge, as well as the knowledge of the local community, local and national NGOs, the private sector, and local and federal government agencies that cacao-AFSs are socio-ecological systems. Both ecological and agricultural intensification must be understood as "two sides of the same coin", without having to decide between two management alternatives ("heads or tails") to improve productivity and sustainability performance.

In this context, Brazilian cocoa cultivation is able to (at least partially) meet some Sustainable Development Goals (SDGs) of the United Nations (UN) Agenda 2030, specifically: i) SDG 2 - *End hunger, achieve security food and nutrition improvement and promote sustainable agriculture*; ii) SDG 15 - *Protect, recover and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, stop and reverse land degradation and stop biodiversity loss*.

Authors' contributions

All authors contributed to the conceptualization; formal analysis; writing - original draft; writing - proofreading and editing.

Ethics declarations

Conflict of interest: The authors declare no competing interest.
Funding: Not applicable.
Ethics approval: Not applicable.
Consent to participate: Not applicable.
Consent for publication: Not applicable.
Availability of data and material: Not applicable.
Code availability (software application or custom code): Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103270.

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