



# Contribution of cacao agroforestry versus mono-cropping systems for enhanced sustainability. A review with a focus on yield

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**Abstract** The demand for cocoa has increased over the past years following the growth of cocoa-based products linked to the rise in living standard in highly populated countries. Cacao industry is therefore currently facing the dilemma of producing more cacao while ensuring its sustainability. Cacao monocrops and agroforestry systems (AFS) are two contrasting ways to produce cocoa, yet their impact on yields, contribution to farmer livelihood, cocoa quality remains understudied. Therefore, we reviewed existing literature comparing (1) monocrop cacao farming systems with (2) simple or (3) complex AFS. We found 19 comparisons of the cocoa yields in

monocrops and simple AFS and 20 comparisons of monocrop and complex AFS. Three main research findings derive from this work. First, in about one third of cases, cacao trees yield more (or equally) in AFS than in monocrops. However, when considering only simple AFS, cacao trees yield more or equal to cacao monocrop in 52% of the cases. Second, cocoa AFS yields an average of 14% less than cacao monocrop. Yet, on average simple AFS yielded 2% less than cacao monocrops. Finally, there are too little elements to draw conclusions about the nexus between cocoa quality and cacao tree cultivation system.

**Keywords** Economic performance · Intensification · Agroforestry · Monoculture · Quality · Trade-offs

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## Introduction

Cocoa production has been continuously increasing in the last two centuries, both in quantity and geographically. In 1961, the surface of harvested cocoa was about 4.4 million ha, while since 2018 it has exceeded 12 million ha (FAOSTAT 2021). From a yield perspective, in 1964 1.52 million tons of cocoa were produced, 78% of which in Africa, while in 2018 world production reached 4.78 million tons (ICCO 2021), with 76% coming from Africa, confirming the African continent's leading position, Ivory Coast and Ghana representing over 60% of the world supply (ICCO 2021).

Increasing global cocoa demand in the new millennium has triggered farmers in developing countries to expand cacao cultivation. The unprecedented increase of production over the past 10 years, growing from 3.63 to 4.78 million tons (ICCO 2021), has induced dramatic deforestation where native forest almost disappeared in some countries such as Ivory Coast (Higonnet et al. 2017) and Ghana where 80% of the native forests have disappeared since the introduction of cacao (Cleaver 1992). In the coming years, consumption rates are expected to continue with the rise in living standards of highly populated emerging countries (India, China and Brazil in particular) (ICCO 2018). Several papers have been reflecting on the negative impacts of the growing demand for cacao on land use and biodiversity conservation (Kelley 2018; Ruf and Zadi 1998).

In its natural habitat, the cacao tree (*Theobroma cacao* L.) grows in the lower strata of the Amazonian forest and is adapted to low light environment. During its domestication process, it has been cultivated under a variety of AFS where light, local air temperature, humidity and wind movement inside the plantation are regulated by higher plant strata, directly affecting photosynthesis, growth and yield of cocoa (Somarriba and Lachenaud 2013; Rice and Greenberg 2000). Cacao-based AFS range from traditional complex multistrata systems gathering up to 10 cultivated plant species on the same plot (Deheuvels et al. 2014), to planted simple systems where one or two plant species are cultivated in association with the cacao trees (Rice and Greenberg 2000). However, since the 1950s, cacao tree cultivation has also been implemented in monocrop systems, with no associated crop and no light regulation service from any higher plant stratum. Cacao monocrops allow the cacao trees to produce at their full potential (Aso-maning et al. 1971). In several contexts, the intensification of the cocoa yield has been promoted on large scale under cacao monocrop systems based on improved varieties or clones. These high cocoa yielding systems always rely on high labor costs and high inputs requirements, especially chemical fertilizers, herbicides, fungicides and pesticides (Wood and Lass 1987). Heavily promoted by agricultural and research extension services (Ruf and Zadi 1998), monocrops have rapidly expanded (Gockowski and Sonwa 2011).

The adoption of cacao monocrop systems has triggered a heated and still ongoing debate about

their advantages and disadvantages in comparison with cacao AFS (Lennon et al. 2021). In the recent years, several publications have analyzed cacao AFS for different ecosystem services, such as biodiversity conservation (Jezeer et al. 2017; Cuni-Sanchez et al. 2016), nutrient cycling (Middendorp et al., 2018), control of erosion, maintenance of soil fertility, carbon sequestration and storage (Mortimer et al., 2018). Despite a rising number of publications in recent years addressing the sustainability and performance of agroforestry systems (Andres et al. 2016; Schneider et al. 2016), there is currently a gap in a paired comparison of cacao AFS with monoculture systems on a global scale, addressing yield and quality performance impacting directly farmers' economic livelihood.

To date, only Niether et al. 2020 have conducted a review comparing productivity, sustain to farmers' incomes, soil chemical and physical properties for cacao monocrop and AFS on a global scale, while more literature is available on a local scale (e.g. Deheuvels 2012; Schneider et al. 2016). Nevertheless, the meta-analysis carried out by Niether et al. (2020), did not take into consideration structure and plant diversity of AFS (e.g. number of associated species and their density) which can be crucial in determining the cocoa yields, thus possibly the economic sustainability of the farming system (Somarriba and Lachenaud, 2013).

This review considers literature on comparative yield performance in cacao monocrop versus two cacao AFS (simple—where cacao trees are associated with a maximum of three shade species, and complex—where cacao trees are associated with four or more shade species). Moreover, we aim to investigate whether different cacao cropping systems may affect cocoa sensorial quality. We discuss the respective impacts of the different cacao cropping systems, in the attempt to provide an overview of the current knowledge on comparative analysis of cacao AFS versus cacao monocrop around the world.

## Material and methods

### Literature selection

This review covers literature using the following combinations of keywords: yield AND cacao (or

cocoa) AND zero shade; yield AND cacao OR cocoa AND full sun; yield AND cacao OR cocoa AND monocrop; yield AND cacao OR cocoa AND agroforestry. We gathered 146 articles in English by using the Google Scholar and Web of Science engine in the month of June 2021. After the screening, twelve articles were selected as relevant to our research questions, based on the following characteristics:

- They include simultaneous data on monocrops and AFS
- They clearly describe the cacao cropping systems and do not include shade trees in the cacao monocrops
- They include precise data regarding cacao yield in kg of dried beans/ha
- They include tree density in both monocrop and AFS
- They report measured data, thus excluding yield projections and models.

To address the research question about cocoa quality we looked for the following combinations of keywords: “cocoa quality” AND “zero shade”; “cocoa quality” AND “full sun”; “cocoa quality” AND monocrop; “cocoa quality” AND ‘agroforestry’ by using the Google Scholar and Web of Science engine in the month of June 2021. We found 135 publications in English but none of them clearly addressed our research question, except for a poster by Douady et al. (2015) which was not complete enough to be included. Yet, from the screening, we selected ten publications relevant to our research question.

#### Global typology of cacao cropping systems

Several scholars have attempted to identify global typologies of cacao cropping systems. Rice and Greenberg (2000) proposed a simplified model based on three typologies including (1) “Rustic cacao system” which is a cropping system under thinned primary or older secondary forest; (2) “Planted shade systems” represent a polyculture cacao cropping systems; and (3) “technified cacao” corresponding to cacao monoculture.

More recently, Somarriba and Lachenaud (2013) offered a comprehensive classification based on six typologies. Those consist of (1) cacao monoculture; (2) cacao cropping systems with specialized shade

trees (e.g. *Inga*, *Erythrina*, *Gliricidia*, and *Albizia*); (3) cacao cropping systems with other crops (e.g. *Hevea brasiliensis*, *Cocos nucifera*, *Elaeis guineensis*, Musaceae); (4) cacao cropping systems with mixed level of shade; (5) cacao cropping systems under thinned forest (e.g. *cabruca* in Brazil), and (6) successional cacao cropping system.

For the sake of the comparison of cacao cropping systems analysed in different geographical contexts, this review considers three categories: cacao monocropping; simple AFS systems and complex AFS systems.

In *Cacao monocrop systems* cacao is grown under full sun. This system is widespread in Ivory Coast, Ghana, Ecuador, Peru, Malaysia and Indonesia (Belsky and Siebert 2003; Schneider et al. 2016; Schroth et al. 2004) using hybrid or clones and high inputs.

*Cacao AFS* include a wide variety of plants and trees including fruits and timber. Some of them are characterized by fast-growing shade species (one or more) like *Cordia alliodora*, *Erythrina* spp., *Gliricidia sepium*, *Cassia* spp., and *Inga* spp. In other cacao cropping systems, the cacao trees are associated with fruit trees and timber species (Gama-Rodrigues et al. 2010). This system is common in Central and South America but also in some African countries, e.g. Cameroun, Nigeria and Ivory Coast (Jagoret et al. 2011; Oke and Odebiyi 2007), where farmers manage their cacao farms also by preserving some of the forest species present when the cacao farm was established, while eliminating others and introducing fruit species into the system. Thus, we identified Simple agroforestry systems (SAFS) where cacao trees are associated with a maximum of three (shade) species and Complex agroforestry systems (CAFS) where cacao trees are associated with four or more (shade) species per plot. Average plot size was 3.47 hectares, yet data from 3 case studies were incomplete.

We proposed this classification in order to maximize the articles included in the review while distinguishing two main nuances of AFS. We are aware that in current scientific literature, the term cacao agroforest is used loosely to denote all kinds of shaded cocoa systems, from very simple, monospecific, one single strata shade canopy (Smiley & Kroschel 2008) to species-rich, structurally complex rustic cacao system (e.g., Jagoret et al. 2011; Ruf 2011).

## Definition of cocoa quality

The International Cocoa Organization (ICCO), a worldwide recognized inter-governmental organization defines cocoa quality based on the flavor. Yet, other organizations such as CAOBISCO include several other factors such as proper fermentation and drying, absence of foreign odors, moisture level. Nevertheless, “the International Standards for the Assessment of Cocoa Quality and Flavour” has been working for years on improving the definition of fine or flavor cocoa based on the concept of terroir, yet a full agreement has yet to be reached. Therefore, the definition of cocoa quality is still not univocal and remains controversial. To partially overcome this issue, a combination of several factors such as genetic origin and morphological features of the plants as well as chemical characteristics of the cocoa beans) are considered to fit cocoa into the categories of “fine or flavor” or “bulk” (according to ICCO). Specifically, fine or flavor cocoa is characterized by “fruit (fresh and browned, mature fruits), floral, herbal, and wood notes, nut and caramel notes as well as rich and balanced chocolate bases” (ICCO 2018).

## Results

Our search obtained 12 articles of which five were conducted in Africa, and especially in Ghana ( $n=3$ ), four in Asia (with 3 from Malaysia) and three in Latin America. The articles were published between 1971 and 2019. The articles contained 19 comparisons of the cocoa yields in monocrops and SAFS and 20 comparisons of monocrops and CAFS.

### Cacao yields in monocrop systems

Cacao in the analysed monocultures yielded on average 823 kg/ha but greatly vary between 2854 kg/ha with amelonado progenies in Ivory Coast (Koko et al. 2013) and 210 kg/ha in Malaysia with the PBC123 hybrid (Vanhove et al. 2016). Nevertheless, cacao tree density largely varies between 625 trees per hectare in Bolivia (Schneider et al., 2016) to 1766 in Ghana (Blaser et al., 2018). Thus, productivity per tree is 0.77 kg of dried cocoa beans/tree but ranges between

2.69 kg of dried cocoa beans/tree (Abou Rajab et al. 2016) and 0.19 kg of dried cocoa beans/tree (Vanhove et al. 2016).

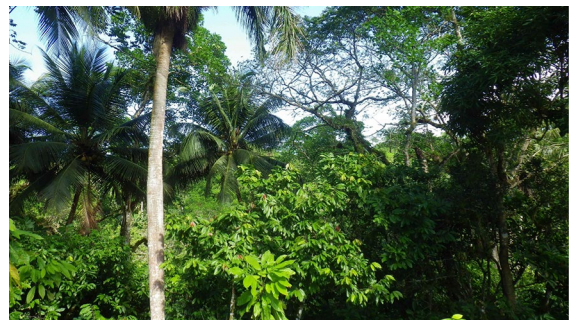
### Simple and complex agroforestry systems

Average cocoa yields in analysed SAFS was about 804 kg/ha ranging from 207 kg/ha in Nigerian cacao AFS with *Terminalia ivoriensis* (Egbe and Adenikinju 1990) and 2000 kg/ha with *Gliciridia sepium* in Indonesia. Even more than in monocrops, density of cacao trees can be as low as 278 trees/ha in Panama (compared to 833 trees/ha of the intercropped Musa AAB see Ramirez et al. 2001) and as high as 1178 trees/ha in Ghana (Blaser et al. 2018), yet the average was 872 cacao trees/ha and 300 associated trees/ha. Productivity per cacao tree was 0.97 kg on average.

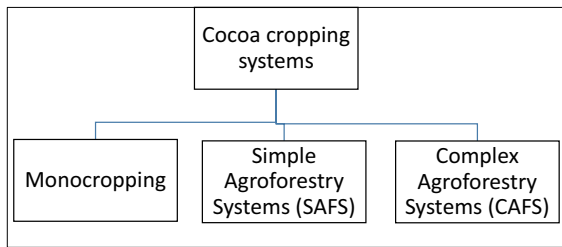
The analysis of the selected CAFS revealed that the average cocoa yield was 495 kg/ha (ranging between 105 kg/ha in Schneider et al. (2016) and 1600 kg/ha in Abou Rajab et al. (2016). Density greatly varied between 625 cacao trees/ha in Bolivian systems (Schneider et al. 2016) and 2166 cacao trees/ha in Ghana (Blaser et al. 2018). The average tree density in CAFS was 1246 cacao trees/ha and 231 associated trees/ha (including any other tree but cacao). Productivity per cacao tree was 0.4 kg on average (Figs. 1 and 2).

### Comparison of cacao monocrops and simple AFS

The 19 comparisons of monocrops and SAFS reveal that in nine cases, cocoa yields were lower (up to -71%) in SAFS than in monocultures, in 37% of the cases, AFS yield more cocoa per tree than



**Fig. 1** Complex cacao agroforestry system in the Loma Sotavento farm, Dominican Republic (Source: O. Deheuvels, CIRAD)

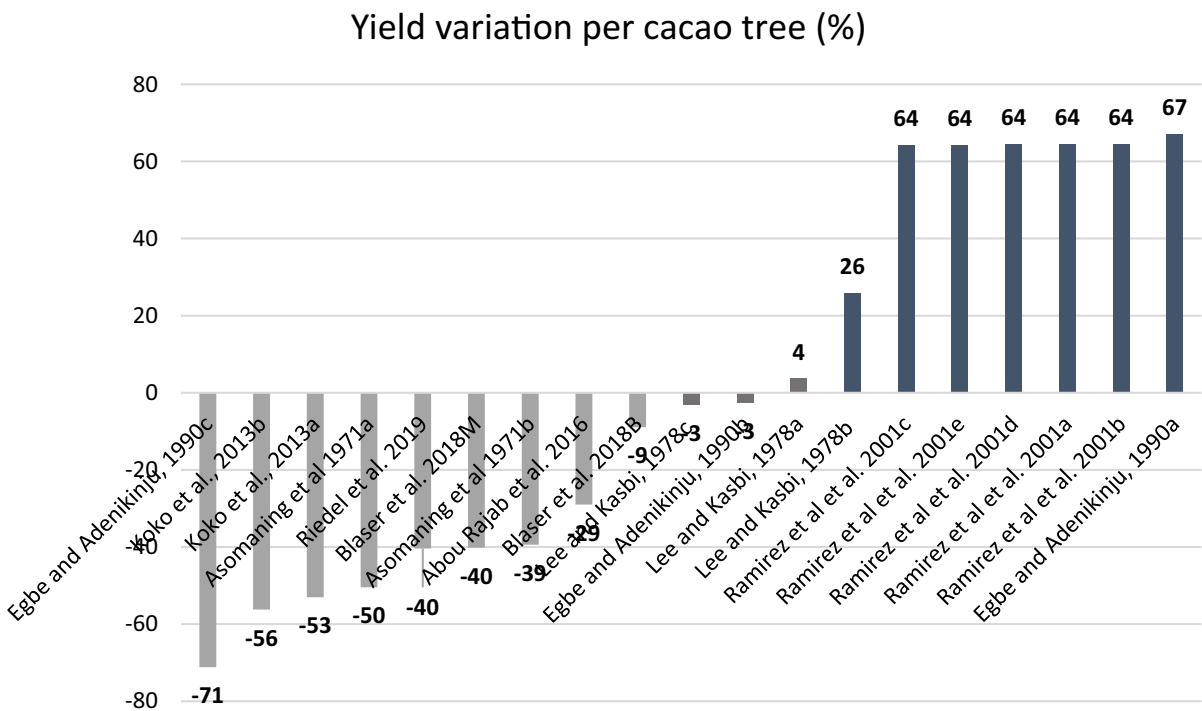


**Fig. 2** Cocoa cropping systems classification used for the sake of this article (adapted from Rice and Greenberg, 2010 and Somarriba and Lachenaud 2013). SAFS=0–3 species; CAFS > 3 species

in monocrops (7 cases), and in 15% there is only a limited difference ( $\pm 5\%$ ) (Fig. 3). However, the average SAFS yielded 2.3% less than cacao monocultures. The most productive SAFS were associated with *Elaeis guineensis* (Egbe and Adenikinju 1990; Lee and Kasbi, 1978), and *Musa* AAB and *Cordia alliodora* (Ramirez et al. 2001).

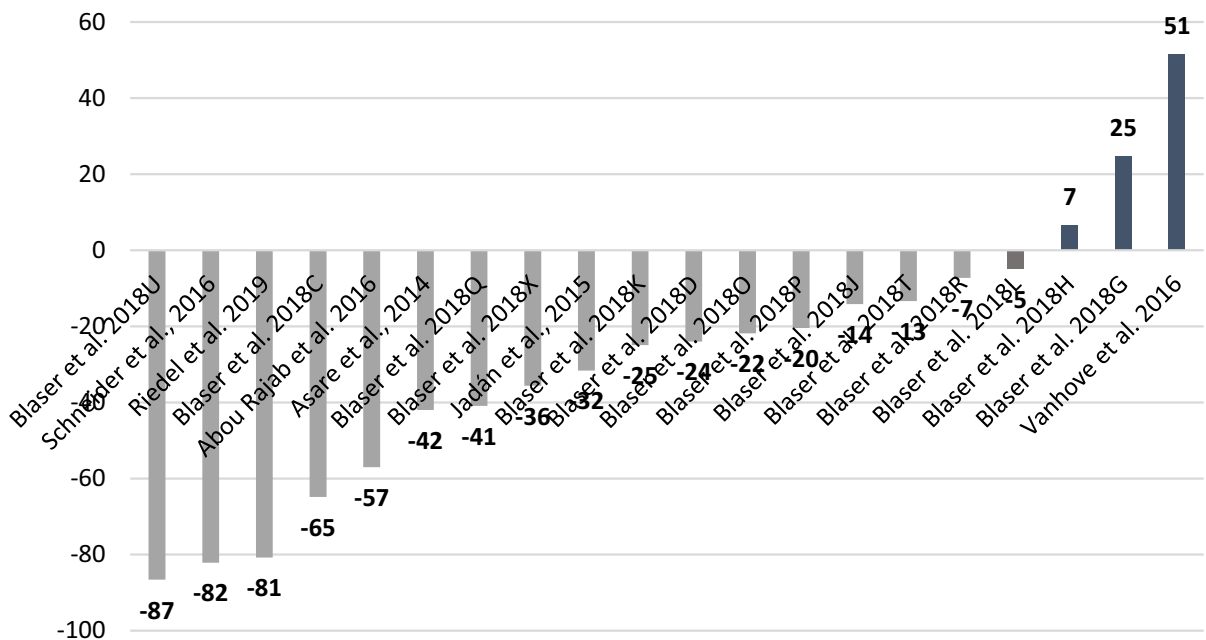
Comparison of cacao monocrops and CAFS systems

The 20 comparisons of monocrops and CAFS reveal that in 80% of the analysed cases, cocoa yields were lower (up to  $-87\%$ ) in CAFS than in monocrops, in 15% of the cases, AFS yield more kg of dried cocoa beans per tree than in monocrops, and only one case showed a limited difference ( $-5\%$ ) (Fig. 4). The average CAFS yielded 40% less than cacao monocrops. The most productive CAFS compared to its monocrop, the case reported by Vanhove et al. (2016), was associated with perennial shade species (*Peltophorum pterocarpum*, *Gliricidia sepium*, *Durio* sp., *Erythrina fusca* and *Parkia speciosa*, *Cocos nucifera*). Also the comparison G in Fig. 4 by Blaser et al. (2018) reporting  $+25\%$  of cocoa yield under monocrop included a limited number of associated species ( $n=4$ ). On the contrary, in several other cases a limited number of associated species did not lead to an increase in cocoa production per tree (e.g. Blaser comparisons C, Q, K intercropped with four species). Nevertheless, the least productive CAFS were intercropped with a high number of species ( $n=11$  and  $76\%$  of shade cover, Blaser et al. 2018—U) and cultivated in highly

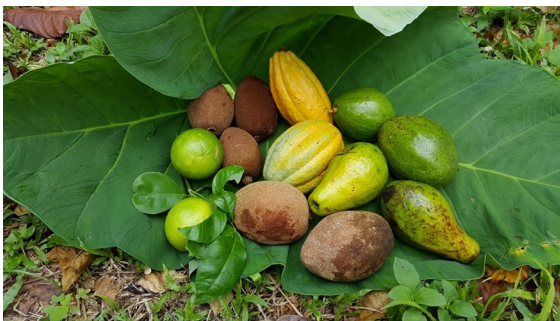


**Fig. 3** Yield variation per cacao tree (kg dry cocoa beans/ha) in cacao mono and simple agroforestry systems

## Yield variation per cacao tree (%)



**Fig. 4** Yield variation per cacao tree (kg dry cocoa beans/ha) in cacao mono and complex agroforestry systems



**Fig. 5** Diversity of harvested crops from a diversified cocoa-based agroforestry system in Loma Sotavento, Dominican Republic (photo: Pierre Costet)

diversified successional agroforestry systems (Schneider et al. 2016) (Fig. 5).

Globally, out of the 39 comparisons of cacao monocrop and (simple and complex)AFS, 25 cases (64%) cacao cultivated in AFS reported lower cocoa yields per tree, 10 cases (26%) AFS reported higher cocoa yields per tree, and 4 cases (10%) shown limited difference. On average cocoa cultivated in AFS yielded 14% less than that of monocultures.

#### The contribution of cropping systems to cocoa sensorial quality

We found no studies on the impact of cropping systems on cocoa sensorial quality, with few exceptions analyzed here. Cocoa quality is determined by a complex composition of cocoa bean flavors and depends on cacao genotype and environmental factors such as soil, light quality, elevation and post-harvest processes (Kongor et al. 2016; Oliva-Cruz et al. 2021). It clearly appears that the genotype strongly contributes to determine the chemical composition of the bean. For instance, Motamayor et al. (2008) identified 10 genetic clusters of cacao with each a typical sensorial profile (see also Seguire and Meinhardt 2014; Kongor et al. 2016). However, the sensorial profile can be further modified by pre and postharvest processes to influence flavors, we could not find any evidence of a direct effect of cropping systems (e.g. shaded systems) on cocoa aromatic quality.

A few articles address the cocoa aromatic quality issue in Ecuador. Herrmann et al. (2015) found that the Ecuadorian cacao variety CCN-51, widely grown in Ecuador and Peru, usually cultivated in

monocropping systems and considered a non-aromatic variety, weak in flavor. Yet, Huamanchumo de la Cuba (2013) reported that CCN-51 beans from Peru were considered fine or flavor quality at important European cocoa fora. Scott et al. (2016) argued that a possible reason for this controversy is due to the fact that CCN-51 variety is cultivated under agroforestry systems in the highly ecologically diversified Amazonian area, thus in a different way than in other zones where this variety is mainly cultivated as monocrop.

Another cacao variety is “el Nacional”, characterized by a floral aroma given by a combination of factors including crop systems and farming practices (Gockowski et al. 2011). Indeed, Franzen and Borgerhoff Mulder (2007) reported that Ecuadorian farmers consider the traditional shade-grown “el nacional” superior to cocoa grown in monocrop in respect to flavor complexity.

Araujo et al. (2014) proposed a Cacao Quality Index to better understand what affects cacao quality. It is based on variables such as fat, acidity, phenols, caffeine, theobromine, pH, sugars as well as macro and micronutrients. Such index can be adjusted according to the goal of the stakeholder (being it a cacao farmer, cacao consumer, or an industry). However, the relation between cocoa flavor complexity and cacao cropping system is still unclear and not extensively explored (Kongor et al. 2016).

## Discussion

Three main research findings derive from this work. First, in one out of three cases, cacao trees yield more (or equally) in AFS than in monocrops. However, when considering only SAFS, cacao trees yield more or equal to cacao monocultures in 52% of the cases. Second, AFS cocoa yields an average of 14% less than cacao monoculture. Yet, on average simple AFS yielded 2% less than cacao monocultures. Finally, in line with Vaast et al. (2016) no studies have been published on the effects of shade on the size of beans, cocoa chemical composition and quality. Indeed, the nexus between cocoa quality and cacao tree cultivation is still terra incognita and there are too little elements and publications to draw conclusions.

Before discussing these findings, we emphasize that they should be read with caution because of a

limited number of studies, which have addressed the comparison of monocrop and AFS cacao, reporting relevant data (yields, density, system description). This study would have benefitted from the calculation of the LER (Land Equivalent Ratio) index, which compares the yields obtained by crops cultivated in AFS and monocrops. Yet, in most of the studies, the absence of data regarding yields of the crop associated to cocoa did not allow the calculation of LER. Similarly, the study would have benefitted from an in-depth socio-ecological comparison to provide a more holistic perspective on the comparison of monocrop and agroforestry cocoa systems, yet not enough data about associated crops and their relevance for farmer economic and social livelihood were reported in the articles.

Finally, we could not consider in our analysis the respective effect of management practices such as pruning, fertilizing or weeding due to the lack of homogeneous data.

Cacao yields per tree are found to be lower in complex than in simple AFS

Our results show that in half of the in-pair comparisons cacao yields less in simple AFS than monocrops. However, the proportion increases to two thirds when considering also the cacao CAFS. This is in line with previous findings, for instance in Bolivia, Armengot et al. (2016) recorded that CAFS yielded less than other agroforestry systems. Similarly, in Costa Rica, Deheuvels et al. (2012) found that cocoa yield per tree was higher in simple cropping systems with a dominance of *Musa* than in complex cropping systems characterized by high crop diversity. However, Kieck et al. (2016) found that plant diversity did affect cocoa yields, yet, the pod size was positively correlated to the diversity of the cacao cropping systems.

The yields variation in complex and simple AFS could be the result of inter-specific competition for water, light and mineral elements due to the variable density of trees associated with cacao trees expecting higher income per area from fruits and cacao (Jagoret et al 2017).

Cacao trees cultivated in SAFS yield on average as much as cacao monocultures

Cacao monocrop often produces more cocoa than AFS (e.g. Armengot et al. 2016). More specifically, the recent review by Niether et al. (2020) reveals that cocoa yield in AFS is on average 75% of the monocrop cocoa production. However, sometimes monocrops have higher yields than AFS due to productive genotypes (e.g. Belsky and Siebert 2003; Gockowski et al. 2013) and/or intensive management practices such as NPK fertilizer and pesticides application (Amujoyegbe et al. 2016).

Abou-Rajab (2016) also remarks that associated plant under AFS does not impede high cocoa yields (e.g. 2000 kg/ha/year). Indeed, the primacy of monoculture in regards to yields does appear not to be adamant, as others, (e.g. Andres et al. 2016; Tschardt et al. 2014) found that AFS cocoa yielded more than monocrops. Moreover, publications focused on cocoa yields do not take into consideration the income derived by the associated species, which, in turn, are important to economically compensate the difference in cocoa yields (Armengot et al. 2016). AFS produce cumulative yields from different kind of products, ranging from edible fruits for human and animal consumption to firewood, timber wood, leaves and bark also used for medicinal purposes (Cerda et al., 2014). They also provide a range of ecosystem services that interact through tradeoff relationships (Deheuvels 2012; Jagoret et al. 2017).

In addition, cacao AFS may produce lower yield on an annual basis but can be more productive in the long-term due to the longer production cycle compared to monocrops (e.g. Clough et al. 2009; Rice and Greenberg 2000). Nunoo and Owusu (2017) reported much shorter life cycles for cacao in monocrop versus AFS (i.e. 15–20 versus 80–100 years) which can be due to the better microclimate including more constant temperature and higher humidity (Heming et al. 2022). The reason for lower cocoa yields in intercropping systems are possibly due to the resource competition with associated crops (Blaser et al. 2018). For instance, several scholars agreed that the competition with light is a factor limiting (cocoa) yields in AFS (Blaser et al. 2018; Schneider et al. 2016; Wartenberg et al. 2018). Yet, recently Blaser-Hart et al. (2021) found that competition for light in cocoa AFS is higher among low-canopy trees than

among elevated-canopy trees. This finding could be used in designing cocoa AFS with lower impact on cocoa yields. Another important competed resource is water and nutrient (Heming et al. 2022 and references within; Mortimer et al. 2018). Yet, choosing appropriate shade tree species (e.g. those occupying different soil levels) at suitable densities could limit such competition (Köhler et al. 2014). An accurate management for pruning, cleaning, or fertilization may compensate such competition. Nevertheless, when external inputs are not available on smallholders' farms, cacao AFS may be the better alternative for maintaining cocoa productivity over time (Andres et al. 2018). Indeed, high yielding cacao varieties often require intensive management practices that include higher external inputs and higher costs in order to best express their genetic potential (Hütz-Adams et al. 2016).

It is generally acknowledged that AFS contribute to biodiversity conservation (Schroth and Harvey 2007). On the contrary, monocrops provide very little benefits in term of biodiversity conservation (Perfecto and Vandermeer 2008) and can lead to less resistance to pests (Franzen and Borgerhoff Mulder 2007). Curiously, Tondoh et al. (2015) found a higher abundance of earthworms in monocrops due to the appearance of species adapted to degraded lands.

#### Implications of cacao cropping systems for farmer economy

Cocoa yield plays a crucial role to guarantee farmers' economic livelihood as cocoa is mainly produced by smallholders (Cerda et al. 2014; Notaro et al. 2020). However, the recurrent fluctuations of cocoa prices on the world market, is a major cause of economic instability for smallholders. This can be partially overcome by promoting a complementary stable production from associated plant species. Indeed, Jagoret et al. (2017) highlighted that the productivity of a cacao AFS include yield deriving not only from cacao but also from associated species, which are rarely taken into account when analyzing the profitability of the cacao cropping system. This diversification strategy provides a comparative advantage for smallholders, maximizing opportunities by lowering specific yields and improving overall productivity. This is a key common strategy for farmers who cannot afford the high



input levels in labor and external costs linked with monocropping providing higher short-term cacao yields (Jumiyati et al. 2018). Compared to monocrop systems, AFS were found to have a higher return on labor, and a lower environmental impact, and improving energy efficiency of the system (Armengot et al. 2016).

AFS may enhance overall ecological resilience (Mbow et al. 2014) and farm household economic resilience (Kiewisch 2015) by incorporating a diversity of associated species providing a combination of ecosystem services such as light and water regulation, pests and diseases control, pollinators' communities regulation, soil quality enhancing, and creation of a favourable microclimate (Mortimer et al. 2018). They generate a significant additional revenue from selling a diversity of products reducing farmers' financial risk (Notaro et al. 2020; Jagoret et al. 2019; Ramírez et al. 2001). Cerda et al. (2014) mentioned the possibility of selling fruits at local markets, although their lower economic value compared with cocoa cannot easily fulfil families' financial needs.

A carefully designed AFS with different seasonal fruiting patterns can ensure an all year around production (Cerda et al. 2014). Moreover, the production of domestically consumable food providing additional income is an important motivation for the adoption of AFS by cocoa producers (Gyau et al. 2014). Association with other plant or trees provides a higher diversity of marketable products, particularly in case of a lower harvest or lower cacao prices on the market (Notaro et al. 2020).

The economic viability of cacao-based cropping systems depends on their ability to generate a stable income, despite price and yield seasonal volatility. High diversification and underpinned benefits of stable incomes and ecosystem services is only possible when the market access is developed enough to ensure the marketing of small amounts of certain products (Ruf 2011). Then, creation of local markets or export must be encouraged by national policies, services and infrastructures (Jagoret et al. 2014). This poses problems to farmers in remote areas with often-low developed road infrastructures far from city market or potential exports, for dry fruits for instance. Also, Delgado Vargas (2013) mentioned that farmers feel the need of increasing their knowledge on cacao crop management in order to improve their systems and their productivity, yet access to education,

agronomic training and market information is not always possible.

Previous studies suggested that certification processes can add value to cocoa but also to associated products in diversified AFS. However, the diversity of crops in cacao polycultures needs to be supported by implementing economic incentives such as organic or fair-trade certifications (Asare et al. 2014). Indeed, the increasing adoption of certification schemes (such as Rain Forest Alliance) may be another factor leading to the decision to support AFS (Gyau et al. 2014). Such certification schemes are meant to promote the adoption of AFS to improve the overall sustainability performance by building recognizable labels to differentiate such cocoa in the global markets (Folefack and Darr, 2021). However, much of the certified cocoa is currently sold as bulk due to the lack of local market (Amiel and Laurans 2019).

Nevertheless, the short-term higher income of monocrops is a very appealing aspect for farmers to shift to this cropping system (Ruf 2011). Indeed, AFS based on cacao require some years (depending on the included species) to provide marketable timber and fruits.

AFS require farmers to deal with complex systems gathering several cultivated plant species and hence inducing innovative crop management. As cocoa production is mostly a family business, creating multigenerational bonds between the family members to ensure the transfer of this knowledge and a good understanding of their system will benefit its well-functioning (Delgado Vargas 2013). This process can be fostered by making cacao cultivation should be attractive for young generations of farmers. This can be achieved by improving its image and increasing the income generated by highly biodiverse and agro-ecological cropping systems.

Oteng Yeboah et al. (2012) and Vebrova et al. (2014) showed that local knowledge on trees and crops and their interactions are often transmitted from one generation to another. The knowledge of ecological interaction is crucial for the management of complexity to ensure economic viability of AFS. Smith Dumont et al. (2014) reported that in Ivory Coast some technical recommendations created barriers to farmer innovation, while Sanial and Ruf (2018) found that in the same country, top-down technical recommendations without co-creation of knowledge were unsuccessful. Eliciting farmers' traditional knowledge

and promoting extensive knowledge exchange and transfer are seen to unfold the full potential of the complex systems (Delgado Vargas, 2013).

## Conclusions

Our review found that, on average, simple cacao AFS do not yield much less than monocrops, yet they provide both ecological and economic advantages (and possibly social too, not analysed in this review). We thus agree with Saj et al. (2017) that well management cacao AFS can exhibit sustainable yields impacting farmers' economic livelihood.

In line with the recent findings of Saj et al. (2017) and Jagoret et al. (2019) in Cameroon, this review shows that cacao AFS have a high potential to provide a positive viable long-term perspective, although this is site specific and has to be assessed, farm by farm. Site-specific features are key factors to be considered by farmers who want to improve or convert their cropping systems towards sustainable AFS. As stated by Gyau et al. (2015), the composition of simple and complex AFS should be tailored according to location, market access, income-level but also cultural values and availability of technical assistance. By finding the right balance of complexity, farmers can achieve the potential benefits from the whole complex system in terms of income.

To comply with the increasing demand for cocoa, many factors must be considered: cocoa price volatility, effect of climate change, yield and quality variability, soil fertility and potential risk of pest and disease. The challenge is then to find an equilibrium between ecological, economic and social aspects of cocoa production and processing.

Beyond our main focus on yield comparison in different types of cacao AFS, an important factor is also the management and agronomic aspects of the systems, as well as social and ecological aspects. but which could not be sufficiently analyzed and documented in our review with the limited number of publications relating these aspects while also indicating the yields. However, some indications can be given here. From an agronomic perspective, it is important to improve the crop management such as regular pruning, grafting and a good cultural planning which can reduce pest incidence. From a social perspective, a better integration of scientific and technical

knowledge to the local ecological knowledge of the farmers, taking into account their cultural values, is required. Moreover, more efforts should be put in fostering intergenerational knowledge transmission about (cacao) a AFS management. From an economic perspective, it is needed to reduce financial risk and preserve food security at household level. We therefore propose to combine such agronomic, social and economic perspectives, the analysis of market accesses and its long-term economic evaluation on market opportunities and constraints to define the site-specific optimum complexity for an overall sustainable cocoa production.

Overall, we support the promotion and application of simple cacao AFS as they could still hold comparable cocoa yields while providing alternative income opportunities in case of negative market cocoa price fluctuation, natural calamities etc. We suggest to promote an intergenerational agroecological knowledge exchange especially for those areas where cacao has been cultivated for long time.

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## Declaration

**Conflict of interest** The authors declare that they have no conflict of interest.

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