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RESEARCH ARTICLE

Competitive yields in organic and agroforestry cacao cropping systems: results from 15 years of a long-term systems comparison trial in Bolivia

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Abstract
Cacao production is facing challenges of low productivity due to low soil fertility and climate change. Agroforestry and organic farming are potential sustainable and climate-resilient alternatives, but they are often associated with lower yields compared to monocultures and conventional farming. Despite their potential, empirical data on the long-term productivity of cacao cultivated in complex agroforestry systems and under organic management remains limited. Expanding this evidence base is essential to inform the development of agricultural practices and policies that advance environmental sustainability and food security. To fill this gap, we present 15 years (2008–2022) of data on cacao production and associated crops of a unique long-term trial comparing five cacao cropping systems in Bolivia: organically and conventionally managed monocultures, diverse agroforestry systems under organic and conventional management, and successional agroforestry systems without external inputs. We collected data on yields along with detailed information on the design and agronomic management from the beginning of the trial. All systems achieved competitive cacao yields in the mature phase. Organic and conventional systems had similar cacao yields, while agroforestry systems reached 56% of monoculture yields. Total system yields of the agroforestry systems were up to 6.9 times higher than monocultures. In the successional agroforestry, 22 crops were harvested, with short life cycle crops contributing to one-third of total production. This study shows that staple food crops and fruit trees as well as high-value crops (coffee, ginger, curcuma) can be successfully combined with cacao, and that agroforestry designs can be adapted over time by adding or eliminating crops to meet new goals or market opportunities. Extensive research has highlighted the positive contributions of agroforestry and organic farming to the delivery of ecosystem services. This study provides empirical evidence that it is possible to design and implement systems that reconcile environmental sustainability with productive performance.

Keywords Crop diversification · Long-term trial · Monoculture · Organic agriculture · Successional agroforestry · Dynamic agroforestry · Syntropic agriculture · *Theobroma cacao* · *Coffea arabica* · *Musa* spp

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1 Introduction

Although cacao originates from Central and South America, it has been cultivated across the tropics for over 100 years (Cilas and Bastide 2020). The five countries with the highest production volume in 2022 were Côte d'Ivoire, Ghana, Indonesia, Ecuador, and Cameroon, accounting for 79% of total cacao production (FAOSTAT 2024). Productivity per hectare at the farm level is generally low, with an annual mean of 533 kg ha^{-1} for the above-mentioned countries in 2022. Reasons for low productivity are degraded soils, pests and diseases, extensive management, and overaged plantations

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with poor yielding varieties (Wessel and Quist-Wessel 2015; Blaser et al. 2018).

Increasing demand for cacao, together with low productivity, has led to the expansion of production areas, driving partly the deforestation in tropical regions (Clough et al. 2009; Vaast and Somarriba 2014; Kalischek et al. 2023). At the same time, initiatives for intensification and renovation of existing plantations focus on mineral fertilization, irrigation, and enhanced genetic material, often in monocultures, or reducing shade tree density in existing agroforestry systems (Vaast and Somarriba 2014; Wainaina et al. 2021). High cacao yields from intensely managed plantations have been reported (e.g., up to 4150 kg ha^{-1} year^{-1} in Latin America (Barrezueta-Unda 2019)). However, negative effects for biodiversity and the environment of such approaches have been demonstrated (Wainaina et al. 2021; Pérez-Neira et al. 2023). Additionally, external inputs are costly and may be difficult to access for smallholders, who are producing >80% of the cacao worldwide (Vaast and Somarriba 2014; Kenfack Essougong et al. 2020).

Cacao agroforestry, i.e., the combination of cacao with shade trees and other perennial crops on the same surface, is seen as an alternative for more sustainable and climate-resilient cacao production (Ten Hoopen et al. 2019). Agroforestry systems have the potential to diversify crop production and thereby income and nutrition for farming communities, while providing ecosystem services such as increasing soil fertility and enhanced biodiversity (Cerda et al. 2014; Vaast and Somarriba 2014; Naoki et al. 2017; Marconi and Armengot 2020; Niether et al. 2020; Amponsah-Doku et al. 2022). Additionally, agroforestry systems have less negative environmental impacts and store more carbon compared to monocultures (Niether et al. 2020; Pérez-Neira et al. 2023). This has led to growing interest in, and promotion of, agroforestry by an increasing number of value chains and public actors (Vaast and Somarriba 2014; Critchley et al. 2022). Organic production, which prohibits the use of external synthetic inputs, is another management alternative which provides benefits in terms of soil fertility, environmental impact, ecosystem services, health, and social aspects in comparison to conventional farming (Te Pas and Rees 2014; Lorenz and Lal 2016; Reganold and Wachter 2016; Sarkar et al. 2021; Mahmood et al. 2024). The combination of organic management and agroforestry practices may further improve sustainability indicators (Pérez-Neira et al. 2023; Willmott et al. 2024).

Organic agriculture and agroforestry are usually associated with lower yields compared to conventional farming and monocultures (Connor 2008; Seufert et al. 2012; Ponisio et al. 2015). Overall, a yield gap of −19% has been estimated when comparing organic and conventional farming (Lorenz and Lal 2016). However, this is crop- and context-specific. For instance, a lower yield gap has been reported for perennials, such as coffee, banana, apple, or alfalfa (Seufert et al. 2012). In the tropics and subtropics, yields under organic management have in some cases even exceeded those under conventional management by as much as 26% (Te Pas and Rees 2014). However, for cacao production, there is still limited knowledge about how organic and conventional systems compare. Some previous studies in Ghana have reported similar or even higher cacao yields under organic farming compared to conventional production (Asigbaase et al. 2021; Schader et al. 2021; Kofi Doe et al. 2023). The variability in reported outcomes underscores the importance of conducting more comparative studies on organic and conventional cacao production.

In agroforestry systems, cacao yields are generally estimated to be 25% lower compared to full-sun monocultures (Niether et al. 2020). However, there is a wide variety of cacao agroforestry systems practiced worldwide, ranging from very simple systems with only a few trees or species per hectare up to highly diverse tree species combinations and specific management practices, like successional agroforestry systems (Andres et al. 2016; Sonwa et al. 2019; Niether et al. 2020). Shade trees can be trees kept when clearing rainforest, deliberately planted or managed from natural regeneration. Additionally, shade trees can either be managed through pruning or not. The type of agroforestry system, number, diversity, and arrangement of associated species and shade canopy management may have a strong influence on cacao yields, apart from cacao management, genetic material, and its age (Saj et al. 2017; Blaser et al. 2018; Mattalia et al. 2022; Esche et al. 2023; Somarriba et al. 2024). Additionally, yields from selected associated crops and timber trees may contribute substantially to nutrition and income, which increases food security and sovereignty as well as economic resilience of farmers and farming communities (Cerda et al. 2014; Jacobi 2016; Wainaina et al. 2021). Total system productions have been shown to be on average 10 times higher in agroforestry systems than in monocultures (Niether et al. 2020).

Cacao yields are highly variable through the life cycle of a plantation. In Latin America, cacao trees usually start producing 3–4 years after planting and enter into full production after 8–10 years (De Almeida and Valle 2007). The economic life of a cacao plantation is around 30–40 years, with the highest yields achieved at the age of 15–25 years (Somarriba et al. 2021). Additionally, some associated crops in agroforestry systems such as fruit or timber trees may only enter into production when cacao is mature or even aging (Ramírez-Argueta et al. 2022). On the contrary, other crops, especially annuals, can be harvested before the cacao trees enter into production (Jagoret et al. 2012). Acquiring data on the scale of these different cycles of cacao production is essential to identify barriers and action levers of

Fig. 1 Aerial view of the SysCom long-term trial in Bolivia. The trial includes four repetitions of 5 different cacao cropping systems as well as a secondary forest (Fallow) of the same age as a control for ecological studies. The different systems have been indicated for one of the four blocks. In between the research plots of 48 m × 48 m (5.5 ha), simple agroforestry systems are implemented (3.5 ha). Picture: Marco Picucci, FiBL.

sustainable cacao-based cropping systems and contribute to their increased adoption.

Research in cacao agroforestry systems often relies either on data from farmers' fields with varying varieties, ages, environmental, and socio-economic conditions with little information on management practices, or on controlled experiments with relatively simple designs (i.e., cacao in combination with 1–2 timber species) with scarce examples of diversified agroforestry systems (Mattalia et al. 2022; Ramírez-Argueta et al. 2022). The SysCom long-term trial in Bolivia, initiated in 2008, compares 5 different cacao cropping systems in one site (Fig. 1): two monocultures, under conventional and organic management, two diverse agroforestry systems under conventional and organic management, and a successional agroforestry system without external inputs. Previous studies in the same trial reported results on productivity from the first years, i.e., up to 2014 (Armengot et al. 2016; Schneider et al. 2017). Cacao yields in conventional systems were higher than in the organic ones in the monocultures but not in agroforestry systems. Additionally, total system yields, including all associated crops, were higher in the agroforestry systems compared with the monocultures.

This study shows for the first time the production of cacao and associated crops in five cacao cropping systems over the first 15 years of the SysCom long-term trial, from its implementation until entering full cacao production. It addresses the following questions: Are yields under organic management and agroforestry systems comparable to those under conventional farming and monocultures? How does this depend on the age of the plantation? How do the design and management of agroforestry systems influence total system yields across different phases? Is it possible to achieve long-term competitive cacao yields without external inputs?

2 Material and methods

2.1 Site description

The study was conducted in a long-term trial situated at the Sara Ana Centre for Research and Training, in Alto Beni, Bolivia, on a terrace of the Alto Beni River at approximately 380 m a.s.l. (15°27′36.60__S, 67°28′20.65__W, https://maps.app.goo.gl/rqAYJWBC6urzCSP96). Sara Ana's climate is humid tropical with a unimodal rainfall pattern. The dry season, characterized by months with less than 100 mm of rainfall, typically lasts from May to October, while the rainy period occurs between November and April. The average annual rainfall over the past 10 years (2013–2022) is 1635 ± 83 mm, with an average annual temperature of 27 °C (Supplementary material 1). The recorded temperature extremes were 9 °C in June 2022 and 42 °C in November 2020. Soils belong to the reference soil groups of Lixisols and Luvisols.

2.2 SysCom Bolivia long-term trial

The long-term trial in Bolivia is included in a larger international program, Farming System Comparison in the Tropics, SysCom (https://systems-comparison.fibl.org/index.html), with the main aim of providing scientific data on the performance of organic and conventional agriculture in the tropics. The long-term trial was set up in 2008 and compares 5 cacao production systems (treatments), i.e., conventional monocultures (MON-CON), organic monocultures (MON-ORG), conventional agroforestry systems (AFS-CON), organic agroforestry systems (AFS-ORG), and successional agroforestry systems without external inputs, under organic management (AFS-SUC). The systems selected for comparison include the use of synthetic inputs to maximize cacao yields (MON-CON) and more traditional production systems under shade, including other crops in addition to cacao (agroforestry systems). The agroforestry systems designed encompass agroecological principles, according to Thapa et al. (2024) (see detailed management below). The organic systems were included to test the potential of organic agriculture compared to conventional farming. This gradient of management intensity of the systems (MON-CON, MON-ORG, AFS-CON, AFS-ORG, AFS-SUC) allows the generation of data in the framework of transition to more sustainable food production. The trial was designed in a randomized complete block design with four repetitions. Plot size is 48 m × 48 m, with a net plot of 24 m × 24 m (24 m × 32 m for cacao, covering 48 cacao trees) for data collection, leaving a border of 2–3 lines of cacao trees to avoid edge effects.

2.2.1 Cacao and general management

The spacing of cacao is 4 m × 4 m, according to practices in the region. In all plots, a mixture of 12 cacao varieties was planted between November and December 2008. Varieties initially included 4 locally selected clones, 4 international clones, and 4 full-sib families from crosses between the international clones and the IMC 67 (Armengot et al. 2023). Due to very low yield of the latter, they were grafted in 2018 with the best performing individual from each crossing (Armengot et al. 2023).

A detailed overview of main management practices is summarized in Supplementary material 2. In all cropping systems, cacao was pruned one to four times per year, and pruning residues were spread below the cacao canopy. Pest and disease management was done by cultural measures in all systems. Every 2 weeks, cacao pods were checked, diseased pods cut and left on the soil surface below the cacao canopy. Witches' broom was controlled by phytosanitary pruning, and mealy bugs as well as leaf cutting ants were controlled manually. Only in 2 years, there were single applications of insecticides in the conventional systems to control leaf cutting ants. Fertilization of cacao was initiated in November 2010, with mineral fertilizer (Blaukorn BASF, Germany, 12–8–16-3 N-P2O5-K2O-MgO split in two doses) in MON-CON and AFS-CON and locally made compost with crop and vegetation residues, hens' slurry, and sawdust for MON-ORG and AFS-ORG. Agroforestry systems received 50% of the amount of fertilizer of the monocultures (Schneider et al. 2017). From 2016 on, compost application in AFS-ORG was stopped. Weeding in conventional systems was done with herbicides (2–5 applications per year), brush-cutters, and machete. In the organic systems, including AFS-SUC, herbicides were not applied. In AFS-SUC, in early years, so-called selective weeding was applied with machete: this practice included removal of climbing weeds and pruning and mulching of other spontaneous vegetation and deliberately integrated biomass species (i.e., pigeon pea, common jack-bean, or achiote). In MON-ORG and AFS-ORG, a perennial soybean cover crop was sown. It fully covered the soil during the first years, but it progressively disappeared, being replaced by a mix of spontaneous herbaceous cover in MON-ORG and further reduced due to shade and litter in AFS-ORG (Marconi et al. 2022).

As described above and in Supplementary material 2, in this trial, despite the different management between systems, an effort was made to apply good agricultural practices in all systems, in line with agroecological recommendations. For instance, the regular formation and phytosanitary pruning of cacao trees as well as the biweekly removal of pods for pest and disease control allowed for fairly low incidence levels in all systems, rendering the use of chemical pesticides unnecessary (Armengot et al. 2020). In all systems, pruning residues and opened cacao pods were left in situ to contribute to soil fertility. Conventional systems employed a combination of mechanical and chemical weed control, while organic systems included a perennial cover crop to reduce mechanical weed control.

2.2.2 Temporary shade, agroforestry design, and associated crops

Temporary shade to cacao was provided by plantain in all systems, planted between April and December 2008 with a density of 4 m × 4 m. Plantain was removed from all the systems at the end of 2011.

The three agroforestry systems, AFS-CON, AFS-ORG, and AFS-SUC, included further shade and associated species, following two different logics: AFS-CON and AFS-ORG were designed to represent market-oriented agroforestry systems, focusing on fewer crops and including only a few fruit trees for self-consumption, plus fast-growing leguminous shade trees for biomass production. Timber trees were not prioritized, i.e., planted at low densities, due to missing market and high competition from illegal logging in natural forests in the region. AFS-SUC systems combined a multitude of crops, with crops both for self-consumption and the local market. AFS-SUC systems followed the logic of successional agroforestry, which is synonymous with dynamic or syntropic agroforestry. This concept aims at maximizing the diversity and density of crops and biomass species, to protect soil against erosion and to suppress weeds, with regular pruning of weeds, biomass species, and later on the shade canopy to increase nutrient cycling and enhance the positive interactions between species and environmental services (Jacobi et al. 2014; Andres et al. 2016; Naoki et al. 2017; Dos Santos et al. 2021).

Apart from plantain, in both AFS-CON and AFS-ORG, shade trees were planted in April 2009, according to a fixed design maintained up to the mature phase (Supplementary material 3). The shade trees could be classified into four groups: timber and latex trees (32 m × 16 m), fruit trees (16 m × 16 m), palms (irregular, 69 ha^{-1}), and leguminous trees with regular pruning for biomass (8 m × 8 m). The initial design led to approx. 284 trees and palms ha^{-1}, 909 individuals ha^{-1} including plantain/banana, a relatively high shade tree density as compared to other studies and practices (Schneider et al. 2017).

In AFS-SUC, initial shade consisted of a high diversity of trees seeded together with crops and other species of short life cycle, both seeded (rice, corn, hibiscus, achiote, pigeon pea) or by vegetative propagation (cassava, pineapple) in November 2008. In April 2009, the design was complemented with planted shade trees from seedlings, among them fruit trees at 8 m × 8 m (Supplementary material 3). Additionally, natural regeneration from rootstocks and the existing seedbank was growing vigorously due to the delayed seeding of crops 1 year after the initial land preparation, contrary to recommendations for AFS-SUC, as a corn crop was first used to assess field homogeneity (Schneider et al. 2017). Shade tree density varied considerably over the years as trees were gradually thinned over time, but at the same time, natural regeneration also led to new individuals. In 2011, around 3600 young trees ha^{-1} were counted, excluding plantains; in 2020, shade tree density was approx. 800 trees ha^{-1} (956 including banana); and at the end of 2022, shade tree density was reduced to approx. 600 trees ha^{-1} (756 including banana).

In AFS-CON, AFS-ORG, and AFS-SUC, starting from 2010 the shade tree canopy was pruned once to twice a year in order to increase light access and accelerate cycling of nutrients (Supplementary material 2), leading to a dynamic shade, which for the period of 2018–2022 varied from 19 to 37% for AFS-CON/AFS-ORG (mean 29%) and from 30 to 61% for AFS-SUC (mean 48%) after and before pruning, respectively.

Before removal of the plantains at the end of 2011, banana of the variety Cavendish was planted in AFS-CON and AFS-ORG (October 2010, 4 m × 4 m). This is a common practice among farmers in the region. In AFS-SUC, 4 different banana varieties (Guayaquil (Gros Michel), Manzano rojo, Manzano amarillo, and Motacusillo (Ticona Aliaga and Condori Chipana 2018)) were planted at the same time (8 m × 8 m). However, they did not develop well, and planting needed to be complemented in October 2012. Additionally, Cavendish banana was added to AFS-SUC at 4 m × 8 m at this time; the plants were taken out again at the end of 2015/beginning of 2016.

In AFS-SUC, after a heavy intervention pruning back the canopy and thinning of the shade trees in October 2012, higher light access was used to grow a second time some crops of short life cycle (tannia, pigeon pea, corn), as well as introducing ginger and curcuma to the systems and seeding some additional shade trees. Ginger and curcuma were harvested in most years only in small areas, depending on market opportunities. Part of the harvested tubers was directly re-sown afterwards for the following year.

In 2013, coffee was introduced to AFS-SUC, in a double row at 2 m × 4 m, to occupy the strata below cacao. Coffee was also introduced to AFS-CON and AFS-ORG at the same density in 2016.

2.2.3 Yield data collection and extrapolation

All products harvested in the net plot were registered and weighed, or the number of fruit/bunches counted. All yields were converted into fresh or dry weight, depending on the form in which they were marketed, hereafter called "marketable yields." Fresh weight of cacao beans has been converted to dry bean yield (~8% humidity) with a factor of 0.33. Coffee has been converted to dry parchment (~10–12% humidity) with a factor of 0.2. Pigeon pea, rice, and achiote were recorded and marketed as dry grains. Corn was marketed once as dry grains and once as cobs. All other crop yields are reported as fresh yields. Banana and plantain weight have been corrected with a factor of 0.85 to exclude the weight of the bunch stalk. Four different banana varieties are reported grouped as banana in AFS-SUC.

Yields per hectare have been calculated based on the assumption that the planting design continues in a regular manner outside of the net plot. Yields per ha^{-1} include unproductive (dead, replanted, or in development) individuals.

2.3 Statistical analysis

Data were analyzed across all the studied years from the initial agricultural production (2009) until 2022, but for cacao also separately in 2 phases. The young phase (2011–2016) included the first productive years of cacao trees; the increase in cacao production was fast, and the cacao canopy was not fully developed. In the mature phase (2017–2022), the canopy of the cacao trees was fully developed (i.e., the canopy of one tree was touching another tree), and the rate of increase of cacao slowed down (but the peak of production may not have been reached yet). Statistical analyses were done in R Statistical Software (R version 4.3.1; R Core Team 2023). Yield data was analyzed with linear mixed models (R package lmerTest; Kuznetsova et al. 2017) using restricted maximum likelihood (REML) and testing for the effects of year, system, and their interaction, with block as a random factor. Block was used to include the potential spatial variability of the trial, which covers a vast area of >5 ha. Each

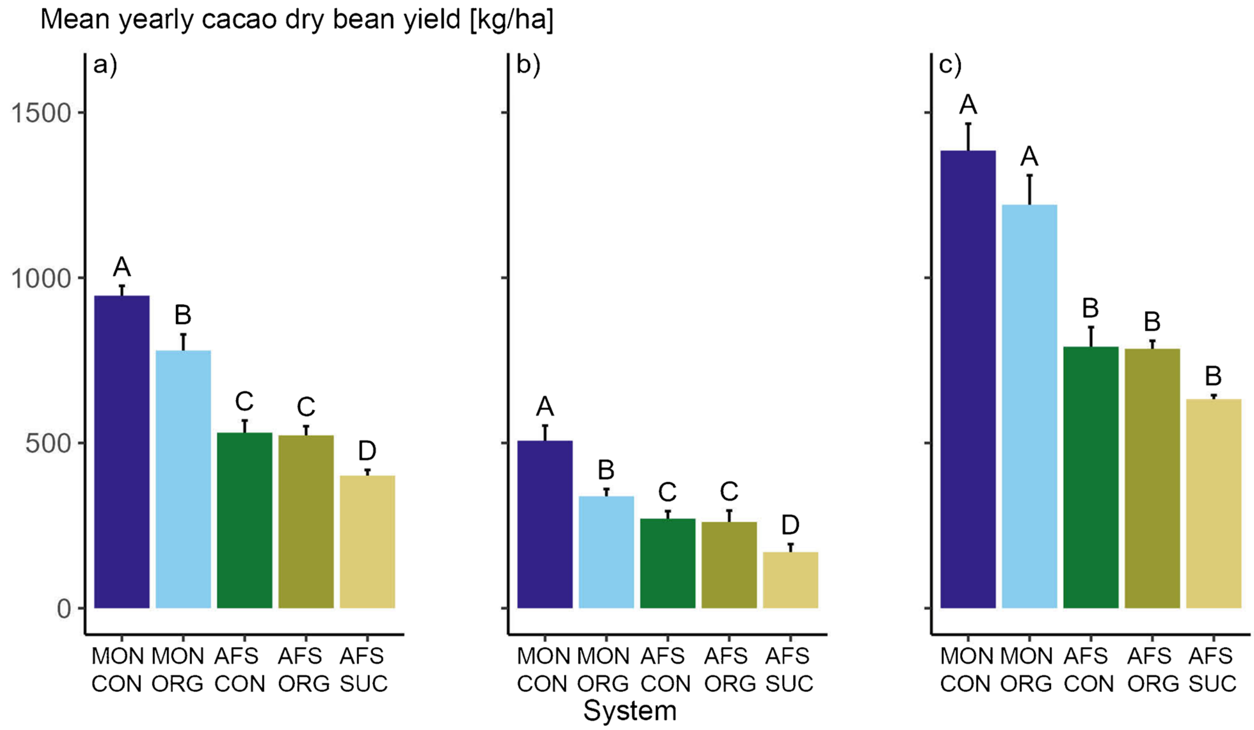

Fig. 2 Mean yearly cacao dry bean yield (kg ha^{-1}) for each cropping system: **a** over the cacao productive years in the whole study period (2011–2022), **b** in the youth phase (2011–2016), and **c** in the mature phase (2017–2022). MON-CON stands for conventional monoculture, MON-ORG for organic monoculture, AFS-CON for conventional agroforestry, AFS-ORG for organic agroforestry, and AFS-SUC for successional agroforestry. Different letters indicate significant differences between the systems during the respective phase. Error bars represent standard error.

plot was associated with a block. Year was included in the model to account for annual variability and avoid pseudoreplication. Assumptions for normal distribution and homoscedasticity of the residuals were checked, and when needed, data were transformed. As a post hoc test, we used difflsmeans (R package lmerTest). Statistical significance was set at $p < 0.05$.

3 Results

3.1 Cacao yields

Cacao yields were affected by the production system ($p < 0.001$, $F = 51.27$), the year ($p < 0.001$, $F = 358.13$), and their interaction ($p < 0.001$, $F = 3.79$). Mean cacao dry bean yields over the whole studied period were highest in MON-CON, followed by MON-ORG, and by the agroforestry systems (Figure 2a, Supplementary material 4). No differences were found between AFS-ORG and AFS-CON; AFS-SUC had the lowest cacao yield. On average, MON-CON had 1.2 times higher cacao yields than MON-ORG, 1.8 times higher yields than both AF, and 2.4 times higher than AFS-SUC.

Cacao yields increased most rapidly in MON-CON (Fig. 3), but after 2016, MON-ORG reached similar yields in 5 out of 7 years (Supplementary material 4). Yields fluctuated strongly in some years, especially in 2014 and 2016, when much lower yields compared to the adjacent years were observed. From 2017 on, yields appeared more stable in all systems. In 2021 and 2022, we observed a tendency of yield increase in the monoculture systems, corresponding to increasing production of the grafted trees (see Section 2). MON-CON yields were higher than all agroforestry systems already after the second year, but this was not always the case for the MON-ORG. MON-ORG, AFS-ORG, and AFS-CON developed very similarly throughout the studied years.

The differences in cacao dry bean production between systems depended on the phase of the plantation (Table 1). The average annual dry bean yield in the young phase (2011–2016) was higher in MON-CON (507 kg ha^{-1}) compared to MON-ORG (399 kg ha^{-1}); it was lower in both agroforestry systems (overall mean of AFS-ORG, AFS-CON: 266 kg ha^{-1}) than in the monocultures, and AFS-SUC

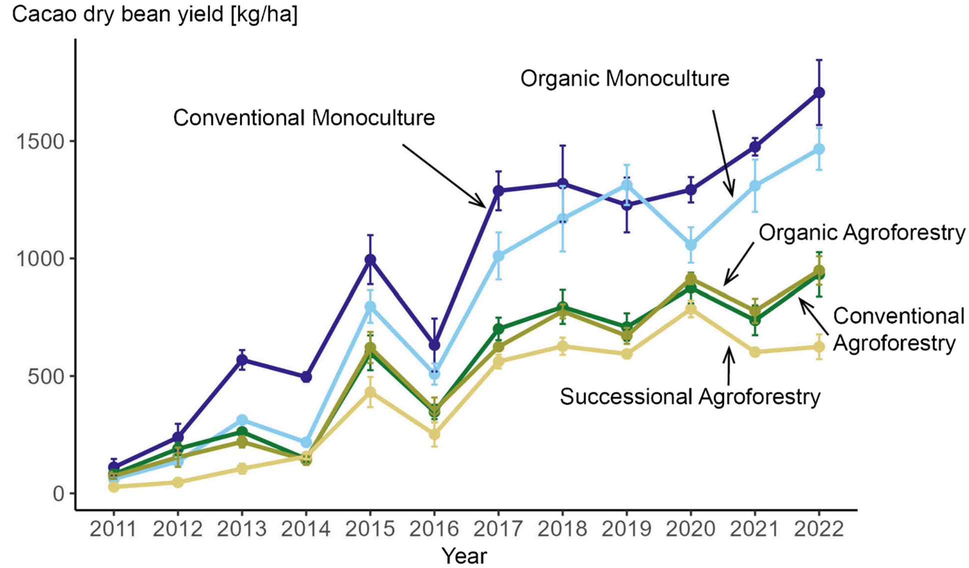

Fig. 3 Temporal evolution of the cacao yield (kg ha^{-1}) for each production system.

had the lowest yields (170 kg ha^{-1}) (Fig. 2b, Supplementary material 4). However, in the mature phase (2017–2022), yields did not significantly differ between both monocultures (overall mean of both monocultures: 1303 kg ha^{-1}) and neither between the three agroforestry systems (736 kg ha^{-1}) (Fig. 2c, Supplementary material 4).

3.2 Total marketable system yields

Total marketable system yields were affected by the cropping system ($p < 0.001$, $F = 139.94$). Total system yields cumulated over the 15 years were highest in both AFS-CON and AFS-ORG, followed by AFS-SUC, MON-CON, and MON-ORG (Fig. 4). Total system yields in AFS-CON and AFS-ORG were on average 6.9 times higher than in the monocultures and 2.1 times higher than AFS-SUC. Total system yields in AFS-SUC were 3.3 times higher than in the monocultures.

Cacao yield represented 4.3%, 4.7%, and 7.0% of the total yields in the AFS-CON, AFS-ORG, and AFS-SUC, respectively. The total number of harvested crops was 7 and 9 for AFS-ORG and AFS-CON, respectively (in AFS-CON, a small harvest of rambutan and acai was achieved in 1 year). The major contribution in both AFS-CON and AFS-ORG was from banana, making up 87% and 88% of total yields over the whole study period, respectively. This was followed by plantain, cacao, and coffee. All other crops contributed <1% to cumulative yields. In AFS-SUC, a total of 22 crops were harvested over the 15 years, with 4 crops contributing >10% and another 9 crops contributing >1% to the total harvest. Banana (30%) together with peach palm (16%) were the crops contributing the most to total yields, followed by ginger and curcuma (12% together). The 8 crops with a short life cycle (annual, biannual), planted and harvested only between 2009 and 2014, mainly pineapple and cassava, contributed 27% to total yields over the 15 years. Fruit trees, apart from peach palm, contributed very little to total cumulative production (<0.4% in AFS-ORG/AFS-CON, 0.8% in AFS-SUC).

3.3 Agroforestry crop diversity and dynamics

In early years (2009–2011), the total production in the AFS-SUC was higher than in the AFS-CON/AFS-ORG due to the presence of the crops with a short life cycle (Fig. 5, data for AFS-CON not shown). This also led to high fluctuations in AFS-SUC, which depended on the number and types of crops. For instance, in 2010, plantain was the only crop harvested. After 2012, annual crops like corn and tannia were implemented again in AFS-SUC, after heavy management of the natural regeneration. From 2015 on, a more stable composition of crops was harvested in AFS-SUC, with main contributions from banana, peach palm, and curcuma apart from cacao. On the contrary, the composition of crops was very stable in the AFS-ORG and AFS-CON from the beginning (cacao, plantain/banana), and changed only in the last years with the introduction of coffee.

Cacao, banana, and coffee developed similarly between AFS-CON and AFS-ORG, with no significant differences, except for plantain, which in its third year (2011) produced higher yields in AFS-CON (and also in the MON-CON compared to the MON-ORG) (Supplementary material 5). Banana yield showed a relatively high variability between years and plots, but reached an average yearly yield of approx. 11 t ha^{-1} (Table 1). Banana yields in the AFS-SUC were much lower (mean yearly yield of 2050 kg ha^{-1}) compared to AFS-ORG and AFS-CON, but the

Table 1 Mean marketable yield ± standard error, initial planting density and planting date, number of productive years, and first year of production for all associated crops in the 5 cropping systems, including information on the regularity of production and possible drawbacks. MON-CON stands for conventional monoculture, MON-ORG for organic monoculture, AFS-CON for conventional agroforestry, AFS-ORG for organic agroforestry, and AFS-SUC for successional agroforestry. Mean and standard error of marketable yield was calculated based on yields across years by system; years with no production were excluded. Crops marked with [a] are reported as dry grain: coffee as dry parchment, achiote as dry grains, corn as a combination of dry grains and cobs, pigeon pea as dry grains, rice as dry grains before peeling.

Crop	Scientific name	System	Marketable yield (kg ha^{-1})	Date planting	Initial density (m × m)	Productive years	Earliest production	Comments
Main associated crops								
Plantain	*Musa × paradisiaca*	MON-CON	4343 ± 1569	04/2008	4 × 4	3	2009	Regular production, removed after 3 years
		MON-ORG	2488 ± 312	04/2008	4 × 4	3	2009	Regular production, removed after 3 years
		AFS-CON	3587 ± 1480	04/2008	4 × 4	3	2009	Regular production, removed after 3 years
		AFS-ORG	2680 ± 630	04/2008	4 × 4	3	2009	Regular production, removed after 3 years
		AFS-SUC	1183 ± 216	04/2008	4 × 4	3	2009	Regular production, removed after 3 years
Banana	*Musa × paradisiaca*	AFS-CON	11,803 ± 653	10/2010	4 × 4	11	2012	Regular production
		AFS-ORG	10,758 ± 716	10/2010	4 × 4	11	2012	Regular production
		AFS-SUC	2050 ± 510	10/2010	8 × 8	10	2012	Replanted in 10/2012 due to very low production Additionally, complemented with Cavendish 4 × 8 until 2016. After 2014 regular production
Coffee[a]	*Coffea arabica*	AFS-CON	431 ± 103	03/2016	(4 × 2)×2	4	2019	Regular production
		AFS-ORG	454 ± 120	03/2016	(4 × 2)×2	4	2019	Regular production
		AFS-SUC	154 ± 47	01/2013	(4 × 2)×2	7	2016	Regular production
Fruit trees and palms								
Avocado	*Persea americana*	AFS-CON	36 ± 17	04/2009	32 × 32	3	2016	Trees died after three productive years
		AFS-ORG	36 ± 14	04/2009	32 × 32	2	2019	Only 2 out of 4 trees survived
		AFS-SUC	69 ± 18	04/2009	8 × 32	5	2018	Regular production, started later than in CA

Table 1 (Continued)

Crop	Scientific name	System	Marketable yield (kg ha^{-1})	Date planting	Initial density (m × m)	Productive years	Earliest production	Comments
Copoazú	*Theobroma grandiflorum*	AFS-CON	65 ± 12	04/2009	32 × 32	6	2017	Regular production
		AFS-ORG	39 ± 11	04/2009	32 × 32	7	2017	Regular production
Rambutan	*Nephelium lappaceum*	AFS-CON	27 ± NA	04/2009	32 × 32	1	2021	Male and female trees, OA no production
		AFS-SUC	70 ± NA	04/2009	8 × 32	1	2021	Male and female trees
Peach palm	*Bactris gasipaes*	AFS-SUC	1370 ± 174	04/2009	12 × 24	8	2015	Regular production
Açaí	*Euterpe precatoria*	AFS-CON	9 ± NA	04/2009	Irregular	1	2021	Fruit bunches too small, wrong variety
		AFS-SUC	5 ± NA	04/2009	Irregular	1	2021	Fruit bunches too small, wrong variety
Achachairu	*Garcinia gardneriana*	AFS-CON	7 ± NA	04/2009	32 × 32	1	2022	Probably before not harvested due to small fruits (not interesting for marketing nor self-consumption)
		AFS-ORG	27 ± NA	04/2009	32 × 32	1	2022	Probably before not harvested due to small fruits (not interesting for marketing nor self-consumption)
		AFS-SUC	22 ± NA	04/2009	8 × 32	1	2022	Probably before not harvested due to small fruits (not interesting for marketing nor self-consumption)
Arazá	*Eugenia stipitata*	AFS-SUC	20 ± 4	11/2008	Irregular	2	2015	Not regularly harvested, no market, only in 2 plots
Starfruit	*Averrhoa carambola*	AFS-SUC	37 ± 25	11/2008	Irregular	2	2021	Not regularly harvested, no market, only 1 tree per plot
Additional crops in the successional agroforestry system								

Table 1 (Continued)

Crop	Scientific name	System	Marketable yield (kg ha^{-1})	Date planting	Initial density (m × m)	Productive years	Earliest production	Comments
Achiote[a]	*Bixa orellana*	AFS-SUC	245 ± 5	11/2008	2 × 0.5	2	2011	Short life cycle crop, mainly for biomass production
Cassava	*Manihot esculenta*	AFS-SUC	8088 ± NA	11/2008	1 × 2	1	2009	Annual crop
Curcuma	*Curcuma longa*	AFS-SUC	796 ± 276	10/2012	Irregular	8	2013	Regular production, harvested only on small surface, due to missing market, reseeded each year from harvested amount
Ginger	*Zingiber officinale*	AFS-SUC	245 ± 36	10/2012	Irregular	8	2013	Regular production, harvested only on small surface, due to missing market, reseeded each year from harvested amount
Hibiscus	*Hibiscus sabdariffa*	AFS-SUC	317 ± NA	11/2008	2 × 1	1	2009	Annual crop
Corn[a]	*Zea mays*	AFS-SUC	338 ± 58	11/2008	irregular	2	2009	Annual crop, reseeded in 2012 with harvest in 2013
Pigeon pea[a]	*Cajanus cajan*	AFS-SUC	529 ± NA	11/2008	1 × 0.5	1	2009	Short life cycle crop, mainly for biomass production
Pineapple	*Ananas comosus*	AFS-SUC	4039 ± 3105	12/2008	2 × 0.3	2	2011	Short life cycle crop, not on complete net plot surface
Rice[a]	*Oryza sativa*	AFS-SUC	299 ± NA	11/2008	0.4 × 0.4	1	2009	Annual crop, only in 2 of 4 plots
Tannia	*Xanthosoma sagittifolium*	AFS-SUC	152 ± NA	10/2012	Irregular	1	2013	Annual crop

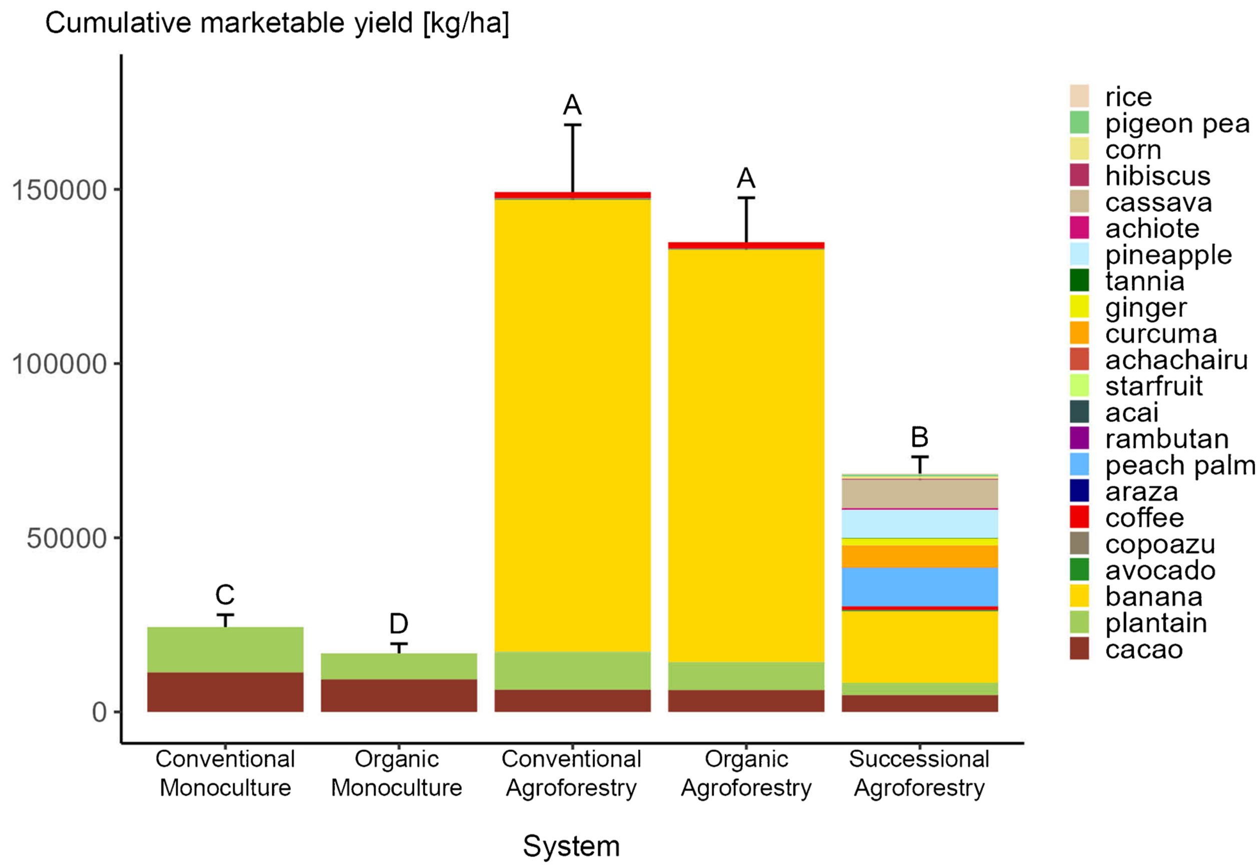

Fig. 4 Total cumulative marketable system yield (kg ha^{-1} ± standard error) across the 5 systems studied from 2009 to 2022. The graph represents the crop yields as they were sold, i.e., either dry or fresh weight. Cacao yields were converted to dry bean yield (~8% humidity) with a factor of 0.33. Coffee has been converted to dry parchment (~10–12% humidity) with a factor of 0.2. Pigeon pea, rice, and achiote were marketed as dry grains. Corn was marketed once as dry grains and once as cobs. All other crops have been sold as fresh yields. Banana and plantain weight have been corrected with a factor of 0.85 for the peduncle which is removed before selling. Different banana varieties in the successional agroforestry system are reported as banana. Different letters indicate significant differences between systems.

varieties were different and planting density was lower in AFS-SUC. Coffee in AFS-CON and AFS-ORG started production in 2019, reaching a mean yearly yield of 443 kg of dry parchment coffee ha^{-1} (Table 1, Supplementary material 6). Coffee yields in AFS-SUC (154 kg ha^{-1} of dry parchment) were significantly lower than those in both AFS-CON and AFS-ORG, although they were planted at the same density.

Peach palm, which was only planted in the AFS-SUC, was the most regularly producing associated crop after banana (Supplementary material 7) with a mean annual yield of 1370 kg ha^{-1} (Table 1). Ginger and curcuma were introduced to occupy the herbaceous strata in AFS-SUC in 2013, with mean yields of 245 kg ha^{-1} (ginger) and 796 kg ha^{-1} (curcuma) (Table 1 Supplementary material 7). However, the tubers were mostly harvested on small subplots and not on the whole planted surface, due to missing market opportunities.

Despite the presence of fruit trees in both AFS-ORG and AFS-CON, tree mortality and high fluctuations in the production of the few fruit trees included in the plots led to negligible production (Table 1, Supplementary material 7): avocado showed a low survival rate, rambutan entered production only in 2021, and the production of achachairu, starfruit, and acai was too irregular to be always harvested. An interesting crop was copoazú, with more regular fruit production in both AFS-CON and AFS-ORG. Of the fruit trees in AFS-SUC, the only regular production came from avocado, which after starting production in 2018 steadily increased. Other fruit trees produced only in specific years or were not systematically harvested due to small amounts.

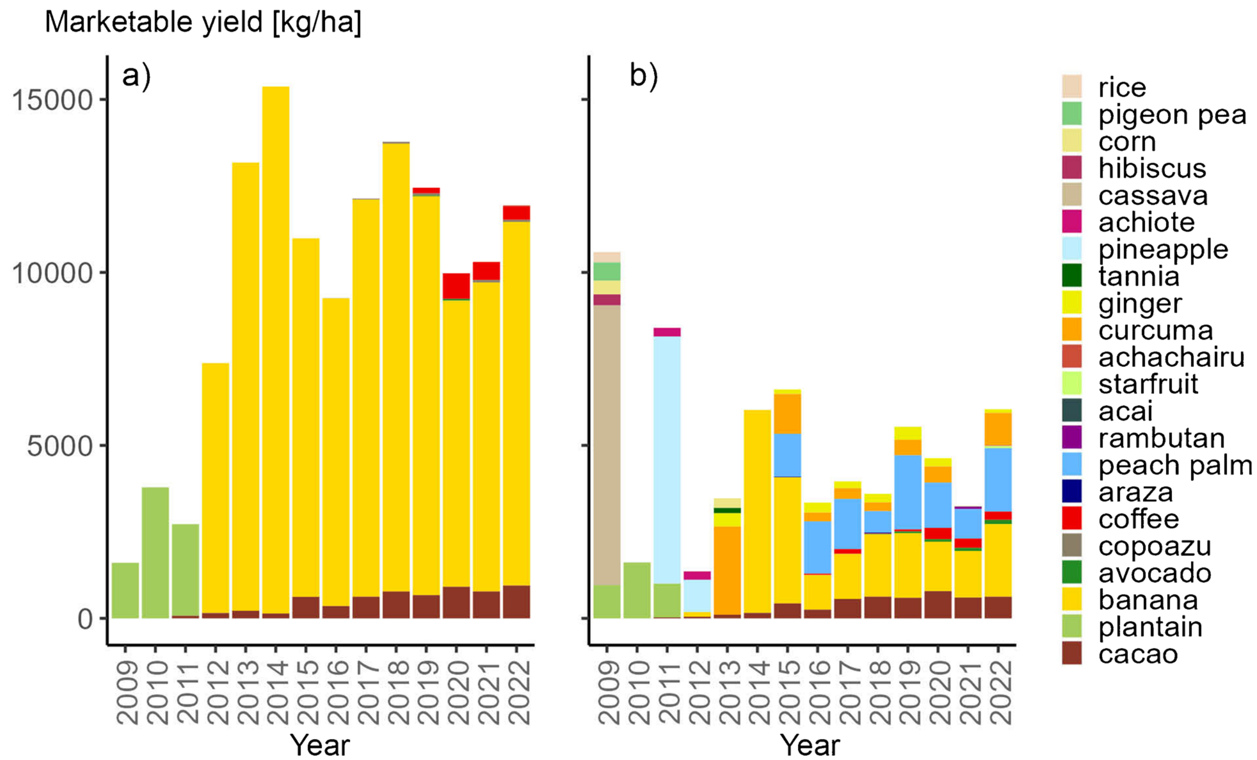

Fig. 5 Temporal development of total marketable system yields (kg ha^{-1}) in the **a** organic agroforestry system and in the **b** successional agroforestry system.

4 Discussion

4.1 Cacao yields

Our study is unique for providing data from a longitudinal study with an extensive research period (15 years since the establishment of the systems), as it is recommended to better understand systems development and agroecological transitions (Ollinaho & Kröger 2021).

Cacao yields observed in this study were similar to or higher than averages reported in Latin American producing countries (Bolivia (average between 2017 and 2022: 560 kg ha^{-1}), Ecuador (548 kg ha^{-1}), Peru (873 kg ha^{-1})), as well as in the world's leading cacao producing countries (Ghana (535 kg ha^{-1}) and Ivory Coast (514 kg ha^{-1})) (FAOSTAT 2024). Higher yields in this trial may still be expected, as peak yields for cacao have been reported to be reached between 15 and 25 years of the plantation (Somarriba et al. 2021, see also Fig. 3). In addition, the re-grafting of 1/3 of cacao trees in all systems in 2018 may increase yields even more in the following years. Nevertheless, some studies have reported relatively higher cacao yields: up to 2000 kg ha^{-1} (for clone CATIE-R6 in Costa Rica (Phillips-Mora et al. 2013) or for CCN-51 in Ecuador (Jaimez et al. 2021). It should be considered that cacao yields in this study do not represent the full production potential, as they include non-producing (replanted) trees and correspond to a mix of 12 varieties with differing production potential (Armengot et al. 2023). Moreover, the comparably low planting density of the cacao trees in all production systems in our study (625 trees ha^{-1}) (Niether et al. 2020; Mattalia et al. 2022) also affected the production per hectare, especially the yields in the young phase (mean overall yield 310 kg ha^{-1}). However, this low cacao density is common in the study region and enables a substantial production of other crops in between (see Section 4.2).

4.1.1 Comparable cacao yields in organic and conventional systems

For the monocultures, organic and conventional management led to comparable cacao yields in the mature phase, reaching an average yield of 1300 kg ha^{-1}, which is higher than worldwide cacao production in monocultures (Mattalia et al. 2022). Additionally, during the whole study period, cacao yields in AFS-ORG and AFS-CON showed no differences (mean over 15 years of 527 kg ha^{-1}). Thus, our results show that organically managed cacao production systems can reach similar yields compared to conventional management. This contradicts the usual yield gap between organic and conventional farming (Ponisio et al. 2015), but it is in line with other studies reporting no differences between organic and conventional yields (Asigbaase et al. 2021; Schader et al. 2021; Kofi Doe et al. 2023).

Reasons for these comparable yields in this trial might be explained by the management applied. For instance, pest and disease management was done through cultural management in both organic and conventional systems (regular and timely cacao pruning, biweekly harvesting and removal of infested pods), and the incidence of pests and diseases was relatively low with no differences between systems (Armengot et al. 2020). However, the different management could explain the differences between organic and conventional monocultures in the young phase: Organic yields were about 33% lower than conventional ones for the monocultures, and trees developed slower, as found in Schneider et al. (2017). This resulted in an average of 18% less cacao in MON-ORG as compared to MON-CON for the whole studied period. This may be attributed to differences in nutrient contents between compost and mineral fertilizer applied, to the slower mineralization of the compost, and to the competition with the perennial soybean cover crop in MON-ORG, which at the beginning was allowed to grow under the cacao canopy (Schneider et al. 2017). In the mature phase, once the trees were fully developed, organic fertilization with continuous compost application was able to reach a similar production level as fertilization with mineral fertilizer.

On the other hand, in agroforestry systems, we observed no differences between organic and conventional management over the whole study period, and yields in AFS-ORG even remained similar to the AFS-CON after stopping the compost application in 2016. This indicates that light availability played a stronger role limiting yields than nutrient availability in these diverse systems. Moreover, in the mature phase, the AFS-SUC reached similar cacao yields to both AFS-CON and AFS-ORG, without external inputs from the start. Thus, associated trees, especially intensively pruned "biomass species," may offer an alternative to organic fertilization with external inputs like compost, which is often not available or very time-consuming to produce for smallholders. The positive effect of shade tree litterfall and pruning residues on soil fertility has been pointed out as a low-tech solution for soil fertility elsewhere (Schneidewind et al. 2019; Amponsah-Doku et al. 2022; Mensah et al. 2023). However, depletion of soil nutrients might occur in the long term and should be monitored along with deficiency symptoms in crops, especially if initial soil fertility conditions are less favorable than in the present study.

4.1.2 Competitive cacao yields in diversified agroforestry systems

In agroforestry systems, yields (average of the 3 systems: 736 kg ha^{-1} for mature phase) were higher or similar to the values found in the literature for agroforestry systems (Niether et al. 2020; Mattalia et al. 2022). However, they only reached between 56 and 60% of the cacao yields recorded in the monocultures, a percentage that was constant over the whole study period. Previous studies have reported smaller differences between cacao yields in agroforestry systems and monocultures (Niether et al. 2020; Mattalia et al. 2022; Blaser et al. 2018). The yield gap between monocultures and agroforestry systems was found to be very small—or even negligible—when the agroforestry systems studied were simple and had low levels of shade (Mattalia et al. 2022; Blaser et al. 2018). Shade density and diversity, as well as shade canopy management, are key factors determining cacao yields (Somarriba et al. 2024). The higher yield gap observed in this study can therefore be explained by the very diverse and dense agroforestry systems studied as well as with the comparably higher yields in the studied monocultures. The density of associated species in the studied systems was >900 stems ha^{-1} (including both shade trees and bananas) in the mature phase. These agroforestry systems can, therefore, be considered as highly dense and complex systems. Thus, cacao yields can be ranked as relatively high compared to yields from simpler agroforestry systems in the literature. For instance, cacao yields ranged from 380 to 2367 kg ha^{-1}, with an average of 765 kg ha^{-1}, in a long-term trial in Honduras comparing different combinations of single timber species with cacao with a density around 100 stems ha^{-1} (Ramírez-Argueta et al. 2022).

Light has been reported as a main limiting factor for cacao yields in agroforestry systems (Jagoret et al. 2017; Blaser et al. 2018; Mortimer et al. 2018; Jaimes-Suárez et al. 2022). We observed this effect also in our trial. First, yields were highest in the monocultures and lowest in AFS-SUC. Second, cacao and associated crop yields in AFS-ORG remained similar to AFS-CON, even after stopping compost application in AFS-ORG in 2016, indicating that light was probably more limiting than nutrients. Third, cacao yields in AFS-SUC were lower during the young phase compared with the ones in AFS-ORG/AFS-CON, but reached similar yields in the mature phase after reducing shade tree density and increasing the intensity of canopy management, even without external inputs. In early years, missing experiences and management recommendations for these highly diverse systems were the reason for untimely management, leading to increased competition (Schneider et al. 2017). In this regard, the regular canopy pruning applied in all three agroforestry systems was probably the main factor for reaching the comparably high cacao yields in such dense and diverse systems. Furthermore, this probably also affected the yields of associated crops positively.

4.2 Yields of associated crops

4.2.1 Total system yields in agroforestry systems were higher than in monocultures

Agroforestry systems, in addition to timber trees, leguminous trees, and biomass trees, included a wide range of crops in addition to cacao. Cacao yields represented less than 10% of the total marketable yields harvested in these systems. Thus, agroforestry systems not only achieved competitive cacao yields compared to worldwide average cacao production, but, in addition, they provided up to 7 times more food than the monocultures. These crops may be sold on local or national markets, complementing the income from cacao sales or self-consumed. The contribution to family benefits from associated crops (including self-consumption) and timber may balance or exceed those from cacao, depending on the market context (Cerda et al. 2014; Notaro et al. 2020; Armengot et al. 2016). A previous study in the same trial (excluding AFS-SUC) reported that associated crops and cacao contributed similarly to the total gross margin (Riar et al. 2024). Our results confirm that agroforestry systems have the potential to contribute to the food security and sovereignty of farming families and communities, with the reported benefits for nutrition, income, economic resilience, and health (Vaast and Somarriba 2014; Ten Hoopen et al. 2019). However, it needs to be further investigated how agroforestry design choices together with context-specific market prices of cacao and associated crops influence the income and nutrition of smallholder families.

The agroforestry systems in the trial were designed with two different approaches. For AFS-CON and AFS-ORG, although being very diverse systems, a market-oriented design was applied, i.e., a smaller number of crops at higher density aimed at selling these products on local markets. This was similar to designs described in the literature combining cacao with single or multiple associated crops (Notaro et al. 2020; Gama-Rodrigues et al. 2021). Still, in both systems, some of the principles of dynamic agroforestry practiced in the AFS-SUC were also applied, such as the combination of crops with different strata as well as the use of biomass trees for regular pruning and nutrient cycling.

On the other hand, the strategy in AFS-SUC was prioritizing crop and species diversification in all phases, aiming at diversity of crops both for self-consumption and for selling while maintaining a high tree and biomass species density for nutrient cycling through intensive management. The extremely high initial density of associated species and crops was then reduced over time. This led to clear differences in the crops produced and their yields as compared to AFS-CON/AFS-ORG, especially in the young phase. Short life cycle crops represented roughly 1/3 of the total system yield in AFS-SUC, indicating a high potential to increase surface productivity at the farm level in the early years with this strategy. The practice of using the empty space between young cacao trees for food crops for self-consumption or local markets is known from farmers in other regions (Jagoret et al. 2012). In the region of Alto Beni, practicing farmers plant crops for self-consumption (tannia, corn, rice) and for biomass production in early years (achiote, pigeon pea) as well as for selling on the local market (rice, corn, pineapple, cassava).

4.2.2 Various associated crops could be successfully combined with cacao in mature systems

Banana, coffee, peach palm, avocado, and copoazú as well as ginger and curcuma contributed regularly to system yields in mature agroforestry systems depending on the design. In the case of banana and coffee in AFS-CON and AFS-ORG, yields were only slightly lower when compared to yields in the region (FAOSTAT 2024), indicating that competitive production could be reached in these systems with a clear focus on these two cash crops in addition to cacao. Banana and coffee yields in AFS-SUC were much lower, partly due to lower planting density and different varieties (in the case of banana) but certainly also due to more competition for resources through the higher density of both crops and associated trees and palms.

On the other hand, the potential of ginger as well as curcuma in AFS-SUC was not fully explored, as it was only partly harvested in the trial due to missing market opportunities. Copoazú, rambutan, and avocado are fruit trees with interesting markets in the region of the trial; however, due to low planting densities, tree mortality, and low producing trees, yields were rather low in this study. These crops might still represent interesting crops for including at a higher density in market-oriented agroforestry systems. In older dynamic agroforestry systems with a high density of fruit trees, these can make up considerable amounts of income also in farmers' fields (Rüegg et al. 2024).

Our results demonstrate that, even under a high shade tree density, a regular diversified production in cacao agroforestry is also possible at the mature phase of the system, which can be designed and managed according to market opportunities or for self-consumption purposes.

4.2.3 Similar yields of associated crops in organic and conventional systems

The yields obtained for the associated crops in both AFS-ORG and AFS-CON followed the same trend as for cacao, i.e., similar yields in both organic and conventional systems were achieved. It is important to mention that companion trees and crops were not directly fertilized with external inputs. However, plantain might have benefited indirectly from the mineral fertilization of the cacao trees, since in 2011 higher yields were obtained in MON-CON and AFS-CON compared to the organic systems (Supplementary material 5). As discussed for cacao, in these highly diversified agroforestry systems, light was probably more limiting to yields than nutrients. Further, the similar and competitive banana and coffee yields in AFS-ORG and AFS-CON indicate that the nutrient cycling from opened pods, litter, and pruning residues of cacao and shade trees was sufficient to maintain a competitive production of cacao as well as some associated crops during the study period.

4.2.4 Designing and managing agroforestry systems: learnings for practitioners and agroforestry programs

Both types of agroforestry designs (i.e., successional agroforestry versus conventional/organic agroforestry systems) studied showed benefits and challenges. According to our results, we propose that a combination of a market-oriented approach as applied in AFS-CON/AFS-ORG (focusing on a few crops) with principles of dynamic agroforestry as applied in AFS-SUC may represent a good guiding principle for productive and diversified agroforestry systems. We identified various learnings with practical implications from the two different design approaches.

First, the strategy to implement a high diversity and density of fruit trees in AFS-SUC resulted in a more reliable production (i.e., for avocado and peach palm) and offered the possibility to select the most promising tree species and individuals over time and depending on market opportunities. This strategy may help to avoid losses from tree mortality, increase yields and quality of fruit, and adapt to market demands. This is especially important also for timber trees, although they were not prioritized in the studied systems.

Second, while a high diversity of crops may balance losses of some crops and contribute to nutrition and self-consumption, an increased complexity is challenged by the effort of its management, needing a lot of knowledge and regular presence in the field. Additionally, reaching sufficient quantities from single crops for their commercialization may be difficult. The focus on two main associated crops in AFS-CON and AFS-ORG (banana and coffee) led to higher and more regular yields compared to the same crops in AFS-SUC.

Third, the inclusion of short life cycle crops as practiced in AFS-SUC may increase productivity in early years before cacao production starts, with possible positive impacts for nutrition and a quicker return on investment. However, results presented here reveal challenges regarding the timing of management, which have impacted cacao and associated crops' yields negatively. This shows that knowledge and capacities are central needs for managing these systems successfully.

Lastly, our results show that diversification can be an ongoing process and that it is possible to include certain additional crops in established agroforestry systems, like corn and tannia after strong canopy management in early years, or coffee, ginger, and curcuma, using the lower strata below well-established cacao trees. The selection of crops and associated species should be site- and context-specific, according to the goals set for the system and also to different market opportunities (Notaro et al. 2020; Gama-Rodrigues et al. 2021). We, therefore, argue for an adaptive approach to agroforestry design and management, weighing original and new goals, to be able to take up new learnings regularly and adjust to the evolving socio-economic context.

Other studies have shown the positive environmental services for biodiversity, microclimate, nutrient cycling, and soil fertility as well as lower environmental impacts for the studied systems (Naoki et al. 2017; Niether et al. 2018; Schneidewind et al. 2019; Saavedra et al. 2020; Marconi and Armengot 2020; Pérez-Neira et al. 2023). Ecological intensification of agroforestry systems, i.e., a higher complexity of crops, increased inputs and/or workforce, has been pointed out as an option to reduce trade-offs and reconcile production with ecology (Clough et al. 2011; Saj et al. 2017). Our results show that for balancing the trade-offs between those services and productivity, an intensive management in the form of regular pruning of shade trees and managing competition between different crops is needed. The economic viability of this activity, which also needs knowhow and equipment, has received poor attention up to now (but see Esche et al. 2023). In the early years in the same trial (excluding AFS-SUC), 16% more labor was needed in the agroforestry systems compared to the monocultures, mainly to manage the shade trees and associated crops (Armengot et al. 2016). However, return on labor was found to be higher in agroforestry systems. This is in line with other studies reporting that agroecological practices, especially diversification measures, often require more labor, but may also offer more return on labor (Mouratiadou et al. (2024). Continuous support, in the form of trainings and services, is, therefore, crucial for the adoption of such highly diverse agroforestry systems and may be provided, for instance, by organic farmers organizations along with certification or by other institutional actors (Jacobi et al. 2015; Andres et al. 2016; Männle 2024). In the study region, two organizations are currently offering professional shade tree pruning services for farmers with mature and overshaded agroforestry systems (Esche et al. 2023), but they are partially subsidized by cooperation projects.

4.3 Limits of the study and future prospects

This study had the aim of comparing yields across production systems, providing details on designs and managements. Given the long-term data series and the complexity of the systems analyzed, it was necessary to focus on yields as a critical metric for understanding the dynamics and trade-offs between different approaches, such as diversification of production versus market-oriented strategies. Yields are the most used agronomic indicator for comparing production systems, and they also provide a foundation for assessing other key indicators related to the sustainability and viability of these systems.

This approach has certain limitations that point to potential future lines of research. In this sense, one priority is the economic evaluation of the different production systems. A particular emphasis should be given to the labor. Data generated in this trial overcomes the common drawbacks when analyzing data from farmers' fields (e.g., varying varieties and ages, differing socio-economic context, differences in farmers' skills and experience, scarce management information). However, some agricultural practices applied in the trial are not yet common among producers in the study area and/or could be difficult to adopt, such as compost application and regular pruning of shade trees. This is mainly related to the labor required to carry out these tasks, as well as the knowledge and equipment needed, as discussed earlier. Poor management is one of the identified factors for the general low productivity of cacao farms (Wessel and Quist-Wessel 2015; Blaser et al. 2018). The economic benefit that farmers can expect from their cacao plantations influences their decision to invest time in farm management or not. Cacao price is volatile and low, and producers often engage in other jobs beyond farming to sustain their income (Kongor et al. 2024), which makes the adoption of agroecological practices even more difficult due to higher labor demand (Mouratiadou et al. (2024). In this regard, and considering the discussions within the cacao sector on the living income (annual net income required for a household to maintain an adequate standard of living in its respective location), it is crucial to determine the minimum price of cacao necessary to ensure the economic sustainability of each system. Furthermore, incorporating the monetization of ecosystem services could support the development of compensation frameworks (Brander et al. 2024) to bridge differences between various production models.

Beyond the economic perspective, other approaches are needed for comparing production systems according to the framework of the Sustainable Development Goals and the FAO's food security objectives (FAO, 2006). For instance, the potential contribution of the studied agroforestry systems to nutrition should be further assessed. Additionally, yields must be related to the environmental impact of the inputs used through eco-efficiency indicators (i.e., carbon footprint or energy demand per kg of food) in order to enable more comprehensive discussions on sustainability. A previous study (excluding AFS-SUC) found higher nutritional values and energy efficiency in agroforestry systems compared to monocultures (Pérez-Neira, 2023).

Finally, the yield dataset, in conjunction with comprehensive records of agronomic management and meteorological data, offers a valuable resource for identifying the key drivers of cacao production and its interannual variability, as well as for simulating scenarios aimed at optimizing management strategies.

5 Conclusions

The results from the presented long-term trial are unique for comparing different cacao cropping systems over 15 years in a longitudinal study, including complex and successional agroforestry systems with a diversified crop production.

Our results demonstrate that elevated competitive cacao yields can be achieved in highly complex agroforestry systems with little or no external inputs. In addition, these systems provide staple food crops and fruit as well as high-value crops, potentially contributing to income and/or nutrition of smallholders. Furthermore, we also found that organic management can achieve similar cacao yields as conventional management.

Previous studies have shown the positive role of agroforestry systems and organic farming in the provision of ecosystem services. Our findings demonstrate that systems that balance environmental and productive functions are possible. The challenges and lessons learnt discussed in this study provide valuable insights for the design of site- and context-specific diversified agroforestry systems, and they can contribute to the development of supportive measures aimed at facilitating the transition toward more sustainable cacao production models.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest JM has been employed by ECOTOP SRL and ECOTOP Suisse GmbH. The remaining authors have no conflicts of interest to declare that are relevant to the content of this article.

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