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COCOA AND TOTAL SYSTEM YIELDS OF ORGANIC AND CONVENTIONAL AGROFORESTRY VS. MONOCULTURE SYSTEMS IN A LONG-TERM FIELD TRIAL IN BOLIVIA

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SUMMARY

Cocoa (*Theobroma cacao* L.) is produced in systems of varying complexity ranging from monoculture with temporary shade to highly diverse agroforests. Producers have to weigh high cocoa yields in the short to medium term in monocultures against higher total system yields in the short term and sustainable production systems in the long term in conjunction with ecosystem services in agroforestry systems (AFs). More long-term data on the comparative agronomic, economic and ecological performance of differently managed cocoa production systems is required to make sound recommendations to farmers. This paper describes the only long-term field trial worldwide comparing different cocoa production systems under conventional and organic management. The factors (i) crop diversity (monoculture vs. agroforestry), (ii) management practice (conventional vs. organic) and (iii) cultivar are being tested in a full-factorial, randomized complete block design with four replications. First, results showed significantly faster development of trunk circumferences in monocultures (+21%) compared to AFs. Cocoa yields were 47% lower in the organic compared to the conventional monoculture. In the AFs, however, the organic–conventional yield gap was less pronounced (−16%) and statistically insignificant. The cumulative yields of all products harvested were significantly higher in the AFs (+161%) compared to the monocultures. The productivity of cocoa by-crops in AFs may contribute to local food security and risk distribution in smallholder contexts.

INTRODUCTION

Being a native tree species of the lower strata in alluvial forests of the Amazon, cocoa was traditionally grown beneath shade tree canopies of primary or secondary forest (Rice and Greenberg, 2000; Wood and Lass, 2001). However, there has been a shift from shaded AFs towards monoculture (MONO)-like full-sun systems (Ruf, 2011). Using agro-chemicals, MONO systems quite rapidly (i.e. within 8–10 years) attain higher yield levels than AFs (Beer *et al.*, 1998). However, they often decline in productivity and profitability after about 15–20 years (Ahenkorah *et al.*, 1987; Rice

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and Greenberg, 2000) due to higher physiological stress (Beer *et al.*, 1998), epidemic breakouts of pests and diseases (Ahenkorah *et al.*, 1987; Clough *et al.*, 2009; Tscharntke *et al.*, 2011) and soil fertility depletion (Dawoe *et al.*, 2014; Rice and Greenberg, 2000). Therefore, there is an urgent need for more sustainable cocoa production systems (Degrande *et al.*, 2006; Steffan-Dewenter *et al.*, 2007).

AFs hold a high ecological and social potential (Clough *et al.*, 2009; Jacobi *et al.*, 2014; Tscharntke *et al.*, 2011), as the multiple products grown along with cocoa contribute to farmers' livelihoods (Cerda *et al.*, 2014; Somarriba *et al.*, 2014) and ensure long-term stable cocoa yields (Obiri Darko *et al.*, 2007; Rice and Greenberg, 2000) and a wide array of ecosystem services (Clough *et al.*, 2009; Garrity, 2004; Jacobi *et al.*, 2014; Rice and Greenberg, 2000; Somarriba *et al.*, 2014). Diversification and enhanced biodiversity are well in line with the principles of certified organic (ORG) farming (Mäder *et al.*, 2002). This is a promising approach towards a more sustainable future of cocoa as: (i) it provides incentives for the maintenance of a permanent shade tree canopy (Vaast and Somarriba, 2014) and (ii) with the worldwide demand for certified ORG chocolate products increasing, consumers are becoming more aware of the impact their choice of goods in the supermarkets has on both, the livelihoods of cocoa producers and the environment (Fromm and von Weissenfluh, 2010). However, today certified ORG cocoa still represents a niche market, accounting for only 2.5% of total cocoa production worldwide (Willer and Lernoud, 2016).

Controversy prevails about the way forward. Some claim that ORG certification is crucial to increase sustainability (Fromm and von Weissenfluh, 2010; Jacobi *et al.*, 2014), while others do not see this necessity as long as production systems that conserve biodiversity are combined with good agricultural practices (ICCO, 2007). Various certification schemes such as Fair Trade, Rainforest Alliance and UTZ Certified have been developed for 'sustainable' cocoa production under shade (Vaast and Somarriba, 2014).

The studies published to date have mostly focussed on existing cocoa production systems in farmers' fields (Beer *et al.*, 1998; Dawoe *et al.*, 2014; Jacobi *et al.*, 2013; Jacobi *et al.*, 2014; Ruf, 2011). The limited number of on-station trials compared different shade levels such as heavy shade, partial shade and no shade (full-sun) (Ahenkorah *et al.*, 1987; Somarriba and Beer, 2011). As there is virtually no long-term data on the comparative performance of different cocoa production systems under conventional (CONV) and ORG management, the debate on suitable production systems is often ideological rather than fact-based. Hence, there is an urgent need for systematic evidence from long-term cocoa production systems research, which is the main justification for the initiation of the trial we present in detail in this paper.

Results from various production systems comparison trials that analysed ORG and CONV management practices have shown that even though their average long-term yields are 10–30% lower (de Ponti *et al.*, 2012; Ponisio *et al.*, 2015; Seufert *et al.*, 2012), ORG farming systems exhibit several ecological and economic advantages, particularly a sustainable improvement of soil fertility (Mäder *et al.*, 2002). However, most of these data were obtained from trials in the temperate zones (Gattinger *et al.*, 2012; Mäder *et al.*, 2002). The results by Haggar *et al.* (2011) on coffee represent one of the few exceptions to this general trend. The scarcity of scientific data from tropical and subtropical zones calls for more long-term production systems comparison trials in these regions (Seufert *et al.*, 2012). To contribute to closing this knowledge gap, the Research Institute of Organic Agriculture (FiBL) has set up a large programme with long-term trials in Kenya, India and Bolivia. The main objective of these trials is to collect scientifically robust agronomic, ecological and economic data on major ORG and CONV agricultural production systems in the tropics (http://www.systems-comparison.fibl.org/) (Forster *et al.*, 2013).

In the project region Alto Beni, smallholders produce cocoa in ORG and CONV agroforestry and MONO-like systems using zero to low external input levels (Jacobi *et al.*, 2014). The coexistence of ORG and CONV production systems of various complexity adds to the region's suitability, for example, to study the impact of the international trend towards more intensive land use systems (Schroth and Harvey, 2007).

The specific hypotheses addressed in this paper are:

(1) There are significant effects of the factors tested (crop diversity, management practice) on both the vegetative development and the productivity of the cocoa trees.
(2) In AFs, the yields of by-crops lead to higher total system yields (sum of all marketable goods) compared to MONO systems.

MATERIALS AND METHODS

Site description

The project area is located in the valley of Alto Beni, a settlement region in the department La Paz, in the north-eastern foothills of the Bolivian Andes (15°27'36.60″S, 67°28'20.65″W, see Supplementary Figure S2, available online at http://dx.doi.org/10.1017/S0014479716000417). The climate is tropical winter-dry, with an average annual rainfall of 1440 mm. Temperatures are highest from December to March and lowest in July (see Figure S1). Soils of the region typically belong to the chromic Cambisols, Luvisols and Fluvisols (Elbers, 2002). ORG AFs are among the common cocoa production systems in the region.

Land preparation, terrain homogeneity assessment and allocation of experimental units

Before project activities were initiated in late 2007, the land had been under fallow for about 20 years (secondary forest characterised by *Guadua* spp.). In the year before planting the trial (November 2007 to June 2008), we assessed the terrain's homogeneity with an unfertilized maize (*Zea mays* L.) test crop with undersown jack-bean (*Canavalia ensiformis* (L.) DC). In addition, we performed soil analyses. According to FAO classification (IUSS Working Group WRB, 2006), the soils belong to the reference soil groups Lixisols and Luvisols (see Supplementary Table S1–S5).

For allocation of plots and blocks, a hierarchical cluster analysis was performed, using the hclust function (method = 'average') from the package stats of the statistical software R (Everitt, 1980; Kaufmann and Rousseeuw, 2005; R Core Team, 2014).

Data used in the cluster analysis included the Euclidean distances between the plots, soil pH, organic C, available P and clay content of the soil, as well as the x and y coordinates of the plot centres. The growth of the test crops was assessed qualitatively by visual rating, and homogeneity between trial plots tested by a basic ANOVA model.

Experimental design

The five different cocoa production systems under comparison include two MONOs and two AFs, both under CONV and ORG management, as well as a 'successional' agroforestry system with zero external input (SAFS) under ORG management. The trial is arranged as a full-factorial, randomized complete block design with four replications (pairwise comparison of AF CONV/ORG and MONO CONV/ORG). The factors tested are: (i) *Crop diversity* (MONO vs. AF), (ii) *Management practice* (CONV vs. certified organic) and (iii) *Cultivar* (12 different cocoa cultivars/hybrids). The combination of the factors *Crop diversity* and *Management practice* make up the *System* effect. SAFS is not included in the full-factorial design, as there is no CONV counterpart to it (comparison of the five *Systems*). In addition, a fallow system without crops (BAR) was installed which can be used as a control/reference system for studies on soil fertility, biodiversity and natural species succession. For technical reasons, half of the trial area (Blocks 1 and 2) was cleared by burning after slashing the forest, and plant materials in the other half were mulched (Blocks 3 and 4). To account for this, we included the factor *Land preparation* in the statistical analysis of the data.

Plots were sized 48 m × 48 m (= gross plot) in order to have enough trees per cultivar to test this factor. The resulting 2304 m^2 correspond to the minimum size of 2500 m^2 per plot recommended by Somarriba *et al.* (2001) for multi-strata AFs research. The outermost 12 m of each plot serve as a border, and all data are obtained in the inner sampling plot sized 24 m × 24 m (= net plot) in order to avoid border effects.

Cocoa planting pattern and germplasm used

Cocoa saplings were obtained from the commercial nurseries of El Ceibo and Ecotop Consult. Planting was carried out in December 2008 without application of fertilizers. The spacing is 4 m × 4 m which results in a planting density of 625 trees ha^{-1} or 36/144 trees per net/gross plot. This spacing is common practice in the research area (Quenta *et al.*, 2005) and in Latin America in general (Cerda *et al.*, 2014; Somarriba *et al.*, 2014).

A total of 12 different cocoa cultivars/hybrids were planted in each plot: ICS 1, ICS 6 and ICS 95 are Imperial College Selections; TSH 565 is a Trinidad Selection Hybrid; IIa-22, IIa-58, III-06 and III-13 are local cultivars derived from an elite tree selection programme in Areas II and III of Alto Beni; ICS 1 × IMC 67, ICS 6 × IMC 67, ICS 95 × IMC 67 and TSH 565 × IMC 67 are ICS and TSH hybrids with Iquitos Mixed Calabacillo 67 (Lockwood, 1979; Trujillo, 2007; Turnbull, 2014; Wood and Lass, 2001). Based on El Ceibo's long-term practical experience, we used seedling root stocks of the hybrid IMC 67 × ICS 6 (ICS 6 pollinated by IMC 67) for grafting.

Replanting of dead cocoa trees and trees which showed abnormal growth was done regularly during the rainy season (November–April) each year. The planting date and precise position of each tree in the plot was recorded. In all systems, temporal shade for cocoa saplings was provided by palm leaves at the very beginning, and by plantain (*Musa* × *paradisiaca* L.) planted between the cocoa rows at the same density (4 m × 4 m). As falling plantain trees increasingly caused damage to the cocoa trees, and according to local farmers' practice, they were removed from all plots at the end of December 2011. In the AFs and SAFS, plantain was replaced by banana (*Musa* × *paradisiaca* L.) while in the MONO systems, no replacing took place so as to achieve the targeted full-sun system with maximum cocoa productivity.

Description of crop diversity, management practices and systems

The six systems under comparison (five cocoa production systems and one fallow system) vary in the two factors *Crop diversity* (MONO, AF, SAFS and fallow (BAR)) and *Management practice* (CONV, ORG). Details of the systems are shown in Table 1 and Table S6.

Crop diversity

In the AF systems, fruit, timber and fertilizer trees were planted at a density of 42 trees per plot (excluding plantain/banana trees), corresponding to 227 trees ha^{-1} (see Table S7) which is comparable to the densities reported by Jagoret *et al.* (2012), but considerably higher compared to the standard of the Rainforest Alliance and other studies (Asare and Asare, 2008; SAN, 2005; Somarriba *et al.*, 2014). The high density will allow for thinning out trees. AF tree species were selected according to local practices recommended by PIAF-El Ceibo. For a detailed list of the species planted, disaggregated for lifespan and use, see Table S7. In SAFS, additional non-cocoa crops (by-crops) and trees (fruit, medicinal, spices, timber) were planted or sown (see Figure S3 and Table S8). The number of planted species in MONO CONV, MONO ORG, AF CONV, AF ORG and SAFS was 1, 2, 14, 15 and 37, respectively (see Table S7 and S8). Replanting of shade trees which had died or shown abnormal growth was done each year during the rainy season (November–April).

Management practices

As one of the objectives was to represent local farmers' practice as much as possible, we tackled this issue by ensuring the presence of both, practitioners and members of local partners in the steering committee of our trial. AF ORG as well as SAFS (and to a lesser extent also MONO ORG) represent the predominant local ORG practice and are well in line with local farmer families' needs. In addition, farmers associated with El Ceibo receive training in ORG cocoa AFs (Jacobi *et al.*, 2014). MONO CONV and AF CONV represent the largest share of cocoa production worldwide (Ruf, 2011). Practices applied in ORG systems were based on the standards defined by the International Federation of Organic Agriculture Movements (IFOAM, 2012) and on common practices applied in the region (July *et al.*, 2010; Quenta *et al.*, 2005),

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Table 1. Description of the different cocoa production systems compared in tropical Bolivia (2009–2013).

Crop diversity[*]	Monoculture[†] (1)		Agroforestry[‡] (2)		Successional agroforestry (3)	Fallow (4)
Management practice	Conventional	Organic	Conventional	Organic	Organic	n. a.[§]
System	MONO CONV	MONO ORG	AF CONV	AF ORG	SAFS	BAR
Shade tree canopy						
Targeted average overhead canopy of shade trees	0%	0%	50%	50%	Dynamic	n. a.
Shade tree canopy management and frequency	n. a.	n. a.	Shade tree pruning (once a year)	Shade tree pruning (once a year)	Selective weeding[¶] and shade tree pruning (two to three times a year)	n. a.
Fertilizer input (see Table S6)						
Type, average annual input 2010–2013[**] (N_{total}-P_2O_5-K_2O-MgO) and timing	Mineral fertilizer, 18-12-24-4 kg ha^{-1}, 50% split-application at onset of rainy season (December), 50% at pod formation (March). Occasional foliar sprays	Compost (8.0 t ha^{-1}), 24-17-20-18 kg ha^{-1}, 100% applied at onset of rainy season (December)	Mineral fertilizer, 9-6-12-2 kg ha^{-1}, 50% of MONO CONV dose, 50% split-application at onset of rainy season (December), 50% at pod formation (March). Occasional foliar sprays	Compost (4.0 t ha^{-1}), 12-8-20-9 kg ha^{-1}, 50% of MONO ORG dose, 100% applied at onset of rainy season (December)	None	None
Plant protection (see Table S6)						
Weed control	Herbicide	Cover crop (perennial soybean (*Neonotonia wightii* (Wight & Arn.) J.A. Lackey))	Herbicide	Cover crop (perennial soybean (*Neonotonia wightii* (Wight & Arn.) J.A. Lackey))	Selective hand weeding with machete	None

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Table 1. Continued.

Crop diversity*	Monoculture† (1)		Agroforestry‡ (2)		Successional agroforestry (3)	Fallow (4)
Management practice	Conventional	Organic	Conventional	Organic	Organic	n. a.§
System	MONO CONV	MONO ORG	AF CONV	AF ORG	SAFS	BAR
	Occasional manual weeding using brush cutter and machete (whole plot)	Mulching of cover crop (underneath tree crown) and removal of weeds upon occurrence using brush cutter and machete	Occasional manual weeding using brush cutter and machete (whole plot)	Mulching of cover crop (underneath tree crown) and removal of weeds upon occurrence using brush cutter and machete		
Pest control	Synthetic pesticides, manual removal of cocoa stem borer (CSB) larvae	Manual (trampling heaps of *Atta* spp., removing larvae of CSB)	Synthetic pesticides, manual removal of cocoa stem borer (CSB) larvae	Manual (trampling heaps of *Atta* spp., removing larvae of CSB)	None	None
Disease control	Removal of diseased vegetative material, flower cushions and pods using pruning shears (two to three times a year, pods every harvest)	Removal of diseased vegetative material, flower cushions and pods using pruning shears (two to three times a year, pods every harvest)	Removal of diseased vegetative material, flower cushions and pods using pruning shears (two to three times a year, pods every harvest)	Removal of diseased vegetative material, flower cushions and pods using pruning shears (two to three times a year, pods every harvest)	Removal of diseased vegetative material, flower cushions and pods using pruning shears (two to three times a year, pods every harvest)	None

*Crop diversity increases from 1 (Monoculture) to 4 (Fallow); †in the text, MONO CONV and MONO ORG are referred to consistently as 'the two monoculture(s) (systems)' or 'the MONOs', ‡in the text, AF CONV and AF ORG are referred to consistently as 'the two agroforestry systems' or 'the AFs', §n. a. = not applicable, ¶removing mature grasses, herbaceous species and vines, regulation of plant densities and pruning of trees to optimize light interception, enable optimal system development and avoid spatial competition with cocoa; **levels based on fertilizer recommendations for cocoa in Latin America (INPOFOS, 2007) and confirmed by literature from other cocoa growing regions (Snoeck and Jadin, 1992; Snoeck *et al.*, 2010); N_{total}: total nitrogen; N_{total} includes only fertilizer derived N, nutrient inputs by green manures were not considered; tree pruning (formative and maintenance pruning) and water management (rain-fed, no additional irrigation water) are carried out similarly in all systems.

while in CONV systems, they were adapted from common practices applied in Latin America. In general, our practices can be classified as low (AF) to medium (MONO) input (according to INPOFOS (2007), and e.g. compared to the nutrient inputs applied by Haggar *et al.* (2011)). Except for the plots under CONV management, the whole area of the trial was certified ORG according to the regulation of the European Union.

The targeted average overhead canopy of shade trees is 0% and 50% in the MONO and AF systems, respectively (except temporal shade from plantains during establishment phase in all systems). The level of 50% was adapted from current recommendations of PIAF-El Ceibo to local farmers, which are based on long-term experiences in the region. Several manuals, criteria and indicators for cocoa production advocate a shade level of up to 50% (e.g. The Rainforest Alliance (SAN, 2005) and Beer *et al.* (2004)). Starting from 2012, the shade tree canopy of the AFs was pruned once a year in September. The different types of cocoa tree pruning as well as the management of the plantain and banana trees were identical in all the systems.

The potential of added nutrients by fertilizers can only be fully exploited when sufficient light is available for vigorous cocoa tree growth (Wood and Lass, 2001). Since the targeted average overhead canopy of shade trees in the AF systems was 50%, the nutrient input levels in the AF systems were also reduced by 50% compared to the MONO systems. Details about fertilizer management practices are given in Table 1 and Table S6.

In CONV systems, weeds were mostly controlled by regular herbicide applications (see Table S6) using a knapsack sprayer. In addition, a few manual and mechanical weeding operations were done around the cocoa stem during the establishment phase of the plots using machetes and brush cutters. In ORG systems, perennial soybean (*Neonotonia wightii* (Wight & Arn.) J.A. Lackey) was used as a cover crop in order to suppress weeds, fix nitrogen and cover the soil to prevent it from drying out. The cover crop was mulched manually at regular intervals underneath the cocoa tree crown, and weeds that grew through the cover crop were cut back using machetes.

Control of pests and diseases was mainly done mechanically. The three main diseases – Black Pod (*Phythophthora palmivora*), Witches Broom (*Moniliophthora perniciosa*) and Frosty Pod Rot (*Moniliophthora roreri*) – were controlled sufficiently in all systems by manual interventions. In two to three interventions per year between February and August, diseased pods, flower cushions and vegetative material were removed using pruning shears. In addition, diseased pods were cut out in all the systems at every harvest operation, and covered with plant litter to prevent sporulation. The cocoa mirid (*Monalonion dissimulatum* Dist.) was not specifically controlled, as pest incidences were low. To control leaf-cutting ants (*Atta cephalotes* subsp. d.), nests were destroyed by trampling in ORG systems, while Lorsban Plus® (Dow AgroSciences, Chlorpyrifos, 50 g l^{-1} and Cypermethrin 5 g l^{-1}) was injected into the heaps in CONV systems. Occasional applications of synthetic and ORG insecticides to cocoa trees were carried out when visual appreciation indicated growing pressure by leaf-cutting ants (see Table S6). Attack by the cocoa stem borer (*Steirastoma breve*) was controlled regularly by removing the larvae manually.

Successional agroforestry system

We describe SAFS separately here, because it represents a special system in the trial. A detailed description of the principles of SAFS can be found in Andres *et al.* (2016). In addition to the species mentioned in Table S7 and S8, some trees of the natural regeneration were maintained. In general, shade management in SAFS was more dynamic compared to the two AF systems. Usually, the shade tree canopy was pruned two to three times per year. During an exceptionally heavy pruning of the shade tree canopy in October 2012, all shade trees were cut back below the height of the cocoa stratum and a new species succession was initiated by sowing pioneer species once again to enhance the dynamics in the system and to improve its' stratification

SAFS received no external fertilizer input, solely relying on system-internal nutrient cycling by adding ligneous ORG matter from pruning of shade trees to the soil. Selective weeding operations involved the removal of mature grasses, herbaceous species and vines using machetes while all other herbs, trees and palms were left to grow. At the same time, plant densities were regulated in order to optimize light interception for optimal development of the whole system. Simultaneously, tree species which had fulfilled their function or which were in spatial competition with cocoa were pruned or removed from the system. No pest control products were applied as SAFS aims at sufficient self-regulation by maintaining a large diversity of species and a crop-friendly micro-climate. As there is no CONV counterpart to SAFS, the system is not included in the full-factorial design but is well-suited for the comparison between all five systems.

Data collection, validation and calculations

Vegetative development of cocoa trees. The vegetative development of each single cocoa tree in the net plot was monitored by assessing tree height and stem diameter at 10 cm above ground. Stem diameters were measured twice a year from 2009 to 2011, and once a year in 2012 and 2013. Since the cross section of a cocoa stem corresponds to an ellipse, two stem diameters were measured from May 2010 onwards in order to enable the calculation of trunk circumferences (Eq. 2).

Eq. 2: Formula for calculation of trunk circumference (ellipse):

$$\mathit{Treecirc} \cong \pi(a+b)\left(1+\frac{3\lambda^2}{10+\sqrt{4-3\lambda^2}}\right),$$

where $a = ½ *$ longer stem diameter (semi-major axis), $b = ½ *$ shorter stem diameter (semi-minor axis) and $\lambda = (a-b)/(a+b)$.

Productivity of cocoa trees (2011–2013). Cocoa pods of each single tree in the net plot were harvested once a month by manual pickings from March to December 2011–2013, except for the period of peak production (June–August) where a fortnightly harvest interval was used. Total number of fruits per tree as well as cumulative fresh bean weight of all harvested pods per plot was recorded (all cultivars mixed together). Based on long-term experiences made by El Ceibo, fresh bean weight was converted into cocoa dry bean yield by multiplication with a factor of 0.35. C*urrent stock yield* represented the actual surface area yield while *full stock yield* was calculated as the standardized yield by dividing current stock yield by the number of trees which were three years or older. Results were extrapolated to kg dry beans per ha^{-1}. The specific 'yield' was calculated as the number of fruits cm^{-1} of trunk circumference, taking into consideration the same trees that were also used for analysis of trunk circumferences.

Total system yields (2009–2013). We assessed total system yields by calculating the cumulative yields of all the marketable products harvested during the establishment phase (2009–2013, expressed in kg dry matter ha^{-1}). These products included plantain (harvested in all systems from 2009 to 2011) and banana (harvested in AF CONV, AF ORG and SAFS from 2012 to 2013), as well as a range of by crops harvested in SAFS from 2009 through 2013 (see Table S9). All the data obtained represented actual surface area yields (current stock yield).

Statistical analysis. The experimental design allows for statistical analyses on different levels: (i) the pairwise comparison of AF CONV/ORG and MONO CONV/ORG (excluding SAFS, full-factorial 2 × 2 crossed design) allows for more thorough assessments of the factors *Crop diversity* and *Management practice* by doubling the number of observations per factor; (ii) the inclusion of all the five systems (randomized complete block design) enables investigations of the *System* effect. As data are either assessed on plot level (pooled across all cultivars) or single tree/cultivar level, the design enables looking at effects of the factors *Crop diversity* and *Management practice* or the overall *System* effect, as well as the effect of the factor *Cultivar* and interactions of *Cultivar* with either *Crop diversity*, *Management practice* or *System*.

In the present study, we focussed on the effects of *Crop diversity*, *Management practice* and *System* at the time of the latest available dataset. We analysed our data with linear mixed effect models using the lmer function from the lme4 package (Bates *et al.*, 2013) of the statistical software R, Version 3.1.2 (R Core Team, 2014). For the full-factorial analysis of vegetative development (data on single cocoa tree/cultivar level), we used a model with *Crop diversity*, *Management practice*, *Land Preparation* and the *Crop diversity* × *Management practice* interaction as fixed effects, and *Block* ($n = 4$), *Plot* ($n = 20$), *Cultivar* ($n = 12$), the two interactions *Crop diversity* × *Cultivar* ($n = 24$) and *Management practice* × *Cultivar* ($n = 24$) as random factors. In order to ensure a sound comparison, all trees which had to be replanted (and were thus younger than the trees initially planted in 2009) were classified as outliers and removed from the dataset. For the full-factorial analysis of cocoa dry bean yields (data on plot level), we used a model with *Crop diversity*, *Management practice*, *Land Preparation* and the *Crop diversity* × *Management practice* interaction as fixed effects, and *Block* ($n = 4$) as random factor. For *System* analyses, the fixed effects *Crop diversity*, *Management practice* and *Crop diversity* × *Management practice* were replaced by *System* (*System* and *Land Preparation* as fixed effects) while maintaining the same random factors as in the full-factorial analysis.

To compare the means of the different systems, we used a multilevel modelling approach (Gelman *et al.*, 2012). We defined *System* or *Crop diversity* and *Management practice* as random factors, and used the shrinked group mean estimate to do post-hoc comparisons. We first simulated a random sample ($n = 5000$) of the joint posterior distribution of the model parameters using the sim() function of the arm package (Gelman and Hill, 2006). Then, we calculated the differences between the group means which gives a random sample from the posterior distribution of the between-group differences. From these posterior distributions, we calculated the probabilities of the hypothesis that the difference is bigger than zero $p(\text{Diff} > 0)$ and we defined a difference to be significant if $p(\text{Diff} > 0) < 0.025$ or > 0.975 (equal to $p < 0.05$ in common linear models).

In order to check for effects of the factor *Land Preparation*, we performed the post-hoc comparisons with the model including *Land Preparation* as a fixed factor and checked whether the outcome differed from the outcome of the model without *Land Preparation*. As none of the dependent variables was significantly influenced by *Land Preparation* (see Tables 2 and 3), we did not discuss this factor in the following sections. p-values for the F-tests shown in Tables 2 and 3 were obtained by analysing the model including *Land Preparation* using the lme function from the nlme package (Pinheiro *et al.*, 2013). No violation of model assumptions was encountered by graphical checks of residual analysis (normal Q-Q and Tukey-Anscombe plots).

RESULTS

Vegetative development of cocoa trees

Over the first five years, 8% of the trees had to be replanted on average. The number of trees replanted in the different systems was not significantly different, varying between 5.6 ± 2.0% in AF ORG and 9.0 ± 3.7% in SAFS. The mortality rates we show here are comparable to the results of other studies (Bastide *et al.*, 2008; Lachenaud *et al.*, 1994) which reported average values of 8.2 and 10.6% mortality of trees of the same age, respectively.

Until month 34, the dynamics of tree height development in the different systems was similar. The mean tree heights ranged from 2.1 m in MONO ORG to 2.5 m in AF CONV, and none of the systems differed significantly from each other (Table 2). This is mainly due to the fact that the cocoa tree pruning regime was the same in all the systems. The values we report here are in the same range as the results reported by Adeyemi (1999) for trees of the same age.

Until 29 months after planting, the increment in trunk circumferences was similar, reaching around 18 cm in all systems, except for SAFS which was 31% lower. After that, the two MONOs and AFs started diverging, and especially between 39 and 54 months after planting the MONOs showed considerably faster cocoa tree growth when compared to the AFs. At 54 months after planting, trunk circumferences ranged from 33.3 cm in MONO CONV to 22.7 cm in SAFS (Figure 1). The MONOs did not differ significantly from each other, but showed significantly higher

Table 2. Height and trunk circumferences [cm] of cocoa trees 34 months and 54 months after planting in five different cocoa production systems.

Factor/system	Tree height (cm)				Trunk circumferences (cm)			
Post-hoc comparison of Crop diversity and Management practice analysis		Mean		sem		Mean		sem
AF		240^{a}		8		27.0^{b}		0.4
MONO		220^{a}		10		32.8^{a}		0.5
CONV		237^{A}		12		30.3^{A}		0.5
ORG		222^{A}		8		29.3^{A}		0.5
ANOVA of Crop diversity and Management practice analysis								
Source of variation	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value
Crop diversity (D)	1	9	0.115	0.743	1	9	62.569	0.001
Management practice (M)	1	9	0.023	0.883	1	9	3.351	0.100
D × M	1	9	3.505	0.832	1	9	0.000	0.991
Land preparation	1	2	0.048	0.202	1	2	2.863	0.233
Post-hoc comparison of System analysis		Mean		sem		Mean		sem
AF CONV		251^{a}		3		27.7^{b}		0.7
AF ORG		231^{a}		13		26.4^{b}		0.7
MONO CONV		227^{a}		20		33.3^{a}		0.6
MONO ORG		213^{a}		7		32.4^{a}		0.6
SAFS		219^{a}		25		22.7^{c}		0.5
ANOVA of System analysis								
Source of variation	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value
System	4	12	0.151	0.959	4	12	38.755	< 0.001
Land preparation	1	2	4.891	0.158	1	2	2.657	0.244

sem: Standard error of the mean; MONO CONV: Monoculture under conventional management, MONO ORG: Monoculture under organic management, AF CONV: Agroforestry system under conventional management, AF ORG: Agroforestry system under organic management, SAFS: Successional agroforestry system under organic management (dynamic multi-strata, zero external input system); different superscript letters indicate significant difference between mean values (multilevel modelling approach according to Gelman *et al.* (2012), p(Diff>0) < 0.05); *p* value and degrees of freedom (numDf: nominator Df, denDf: denominator Df) of fixed effects in linear mixed effect models, random factors in the model: Block ($n = 4$), Plot ($n = 20$), Cultivar ($n = 12$), System × Cultivar ($n = 57$).

values (+21%) than the AFs which, in turn, were not significantly different. SAFS showed significantly lower stem circumferences (−26%) than all the other systems (Table 2).

Productivity of cocoa trees (2011–2013)

Mean cocoa dry bean yields in 2013 (5th year after planting) ranged from 587 kg ha^{-1} in MONO CONV to 105 kg ha^{-1} in SAFS (Figure 2, data refer to marketable beans only). MONO CONV showed significantly higher yields than all the other systems (+153%), followed by MONO ORG which, in turn, achieved significantly higher yields than the two AFs (+33%). The two AFs showed no significant difference between each other, yet they attained significantly higher yields compared to SAFS

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Table 3. Cumulative dry matter yields (kg ha^{-1}) of marketable products harvested in five different cocoa production systems from 2009 to 2013.

Factor	Cocoa beans full stock yields* (2011–2013)				Cocoa beans current stock yields† (2011–2013)				Plantain bunches (2009–2011)				Banana bunches (2012–2013)				Diversified grains‡ (2009–2013)		Diversified fruits and tubers§ (2009–2013)		Total (current stock yields 2009–2013)			
Post-hoc comparison of Crop diversity and Management practice analysis		Mean		sem		Mean		sem		Mean		sem		Mean		sem	Mean	sem	Mean	sem		Mean		sem
AF		598^{b}		48		498^{b}		45		3568^{a}		902		8036^{a}		841	–	–	–	–		$12\,101^{a}$		1720
MONO		1012^{a}		155		756^{a}		110		3874^{a}		921		0^{b}		0	–	–	–	–		4630^{b}		1002
CONV		1009^{A}		157		767^{A}		109		4469^{A}		930		4478^{A}		1738	–	–	–	–		9714^{A}		1914
ORG		601^{B}		45		487^{B}		38		2972^{A}		802		3558^{A}		1496	–	–	–	–		7017^{A}		1940
ANOVA of Crop diversity and Management practice analysis																								
Source of variation	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value	–	–	–	–	numDf	denDf	*F* value	*p* value
Crop diversity (D)	1	9	26.209	0.001	1	9	20.778	0.001	1	9	0.151	0.706	1	9	91.440	< 0.001	–	–	–	–	1	9	24.430	0.001
Management practice (M)	1	9	27.516	0.001	1	9	24.376	0.001	1	9	3.618	0.090	1	9	1.200	0.302	–	–	–	-	1	9	2.591	0.142
D × M	1	9	11.373	0.008	1	9	11.347	0.008	1	9	0.320	0.585	1	9	1.200	0.302	–	–	–	–	1	9	0.076	0.789
Land preparation	1	2	5.467	0.144	1	2	4.000	0.184	1	2	17.835	0.052	1	2	0.610	0.517	–	–	–	–	1	2	7.870	0.107

Table 3. Continued.

Factor	Cocoa beans full stock yields* (2011–2013)				Cocoa beans current stock yields† (2011–2013)				Plantain bunches (2009–2011)				Banana bunches (2012–2013)				Diversified grains‡ (2009–2013)		Diversified fruits and tubers§ (2009–2013)		Total (current stock yields 2009–2013)			
Post-hoc comparison of System analysis		Mean		sem		Mean		sem		Mean		sem		Mean		sem	Mean	sem	Mean	sem		Mean		
AF CONV		658^{b}		53		542^{b}		53		4093^{a}		1410		8957^{a}		853	–	–	–	–		13 592^{a}		2183
AF ORG		538^{b}		74		453^{b}		73		3042^{b}		1275		7115^{a}		1'416	–	–	–	–		10 610^{ab}		2749
MONO CONV		1360^{a}		173		991^{a}		139		4845^{a}		1398		–		–	–	–	–	–		5837^{c}		1521
MONO ORG		665^{b}		35		521^{b}		26		2903^{b}		1172		–		–	–	–	–	–		3424^{c}		1183
SAFS		239^{c}		30		195^{c}		34		1230^{b}		795		99^{b}		99	1'750	104	5'118	562		8392^{b}		796
ANOVA of System analysis																								
Source of variation	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value	numDf	denDf	*F* value	*p* value	–	–	–	–	numDf	denDf	*F* value	*p* value
System	4	12	34.969	< 0.001	4	12	30.905	< 0.001	4	12	3.551	0.039	4	12	35.115	< 0.001	–	–	–	–	4	12	8.617	0.002
Land preparation	1	2	5.079	0.153	1	2	3.978	0.184	1	2	14.645	0.062	1	2	0.713	0.487	–	–	–	–	1	2	7.663	0.101

*Cocoa dry bean yields after fermentation and drying (water content: 8%), full stock yield = current stock yield standardized with number of trees > 3 years; sem: standard error of the mean; †current stock yield = actual surface yield; ‡diversified grains included maize, rice, pigeon pea and achiote (see Table S9); §diversified fruits and tubers included cassava, hibiscus, pineapple, tannia, ginger and turmeric (see Table S9); MONO CONV: Monoculture under conventional management, MONO ORG: Monoculture under organic management, AF CONV: Agroforestry system under conventional management, AF ORG: Agroforestry system under organic management, SAFS: Successional agroforestry system under organic management (dynamic multi-strata, zero external input system); different superscript letters indicate significant difference between mean values (multilevel modelling approach according to Gelman *et al.* (2012), $p(\text{Diff} > 0) < 0.05$ p value and degrees of freedom (numDf: nominator Df, denDf: denominator Df) of fixed effects in linear mixed effect models, random factors in the model: Block ($n = 4$).

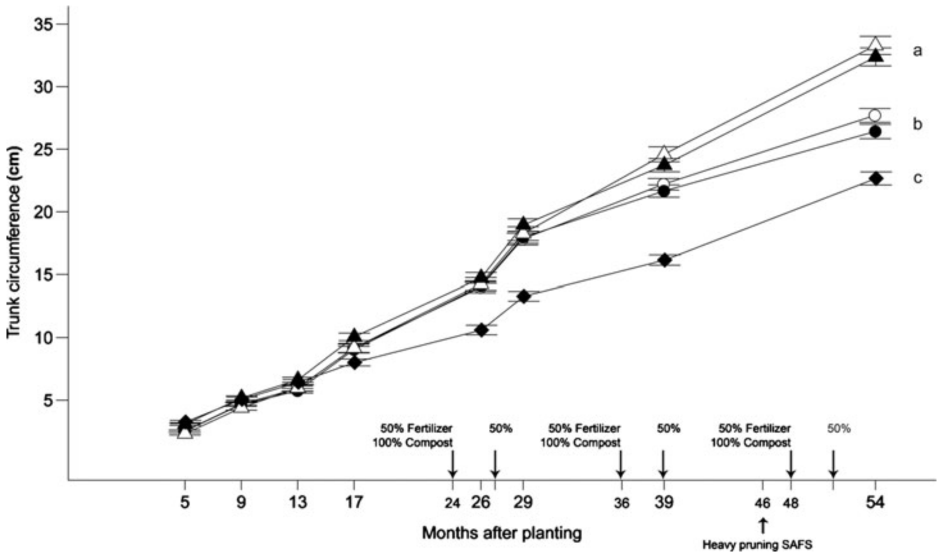

Figure 1. Development of trunk circumferences (mean ± standard error) 2009–2013 in five cocoa production systems. Production systems: (Δ) full-sun monoculture under conventional management (MONO CONV), (▲) full-sun monoculture under organic management (MONO ORG), (○) agroforestry system under conventional management (AF CONV), (●) agroforestry system under organic management (AF ORG), (♦) successional agroforestry system under organic management (SAFS, dynamic multi-strata, zero external input system).

(+136%). The percentage of diseased fruits in the total amount of harvested fruits was low, ranging from 0 to 6%, and did not significantly differ between the systems (data not shown).

Total system yields (2009–2013) and ecological benefits

In the AFs, substantial amounts of banana were harvested in 2012 and 2013 (8036 kg ha^{-1}). In SAFS, considerable amounts of diversified fruits and tubers were harvested between 2009 and 2013 (5118 kg ha^{-1}, Table 3). SAFS was the only system in which these crops were cultivated. The MONOs achieved both the highest cocoa dry bean yields, and MONO CONV additionally exhibited the highest plantain yields (4845 kg ha^{-1}, harvested from 2009 to 2011) compared to all the other systems (+72%). Despite this, the cumulative yields of all marketable products in MONO CONV and MONO ORG could not reach the level of the three AFs (Table 3).

Total system yields ranged from 13 618 kg dry matter ha^{-1} in AF CONV to 3464 kg dry matter ha^{-1} in MONO ORG (Table 3). The AF CONV showed significantly higher values than SAFS and the MONOs (+131%), followed by AF ORG and SAFS which were significantly higher than the MONOs (+105%) but did not differ significantly from each other. The MONOs ranged lowest (−57% compared to the other three systems) and were not significantly different from each other.

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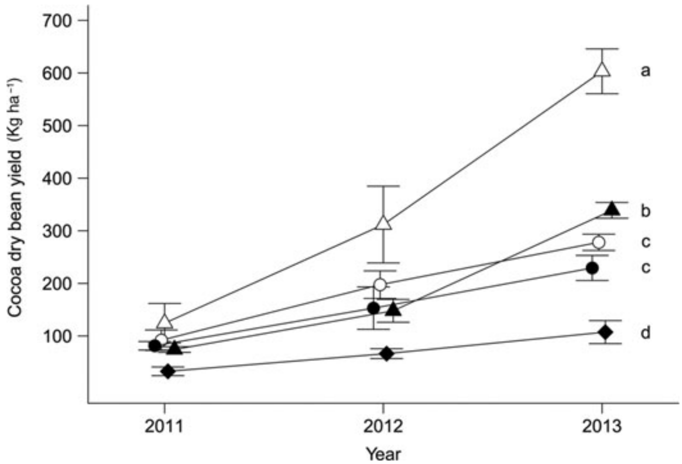

Figure 2. Development of cocoa dry bean yields 2011–2013 [kg ha^{-1}] (current stock yield). Production systems: (Δ) full-sun monoculture under conventional management (MONO CONV), (▲) full-sun monoculture under organic management (MONO ORG), (○) agroforestry system under conventional management (AF CONV), (●) agroforestry system under organic management (AF ORG), (♦) successional agroforestry system under organic management (SAFS, dynamic multi-strata, zero external input system.

DISCUSSION

Vegetative development of cocoa trees

These trunk circumference data are in the same range as the ones reported by Glendinning (1960), and Maharaj and Ramnath (2013), but the increment in stem diameter is higher (approximatively +30%) compared to trees of the same age in the study of Anim-Kwapong and Oppong (2009), which may be due to the good growing conditions with high initial soil fertility in our trial.

Zuidema *et al.* (2005) showed that light interception is a key factor determining vegetative development of cocoa trees, which was most probably also the main reason for the significant influence of the factor *Crop diversity* we observed in our study (Table 2): The canopy openness measured 1.3 m above ground in the AFs at 38 months after planting was only 20% as compared to 63% in the MONOs (Niether *et al.*, 2013). This important degree of shading was caused by both the shade trees which had at this time point grown above the cocoa stratum, as well as by auto-shading of cocoa trees. These suggestions are supported by the findings of Anim-Kwapong and Oppong (2009). The higher level of nutrient inputs applied in the MONOs (Table 1) may have been partially compensated for by nutrient cycling through litter fall in the AFs. These nutrient inputs were not considered for this study, and will be assessed in the future. Nevertheless, we can state that no obvious symptoms of nutrient deficiencies could be observed from visual observations of cocoa trees.

All ORG systems exhibited only marginally lower trunk circumference values at 54 months after planting compared to their CONV counterparts (−4% in AF, −5% in MONO). The results of the statistical analysis did not show a significant influence of the factor *Management practice* (Table 2). Apparently, the management practices

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applied in the ORG systems were able to ensure an equally vigorous cocoa tree growth.

In the case of SAFS, the much higher species density and resulting competition for nutrients, light and water likely explains the significantly slower vegetative development of cocoa trees compared to the other systems from about 15 months after planting onwards. Consequently, a heavy pruning of the shade tree canopy was performed in October 2012 in order to enhance the dynamics in the system and to improve its' stratification. This resulted in less shading (33% canopy openness at 51 months after planting, compared to 25% at 38 months after planting, see Niether *et al.* (2013)) and considerably increased cocoa tree growth (Figure 1).

Productivity of cocoa trees (2011–2013)

These results confirm the findings of other studies (Franzen and Mulder, 2007; Nunoo *et al.*, 2013), showing that cocoa trees yield best during the first decade of production in full-sun systems. The yield levels obtained in our trial are comparable to the data reported by Padi *et al.* (2012) and Adeyemi (1999) for trees of the same age. However, compared to most other studies, which usually report the average yield levels one or two decades after planting (Martin and Lockwood, 1979; Somarriba and Beer, 2011), our values are rather low since we are only in the third year of harvest. Reported average annual yields for Alto Beni are below 400 kg ha^{-1} (dry beans) (Somarriba and Trujillo, 2005). We expect the yield in our trial to reach higher levels than reported averages for Alto Beni, as the plantation is younger, and the trial management is done using higher input levels compared to common plantations and practices in the region. The data on specific 'yield' (number of fruits cm^{-1} of trunk circumference) followed the same trend as described for the cocoa dry bean yields on plot level and are therefore not shown.

The factor *Crop diversity* had a strong effect on cocoa dry bean yields (p value of *Crop diversity* in factorial analysis = 0.001, Table 3) with the two MONO systems yielding higher than the AFs (+86%). Similarly as with trunk circumferences, the lower light interception in the AFs due to the overhead canopy of shade trees most probably explains the difference between the MONOs and the AFs best (Zuidema *et al.*, 2005). The yield gap between MONOs and AFs has led people to prejudge AFs as not being suitable to produce sufficient cocoa in a reasonable period. To address this, ecological intensification of AFs in order to enhance early cocoa productivity is desperately needed. If higher early cocoa productivity in AF systems is desired, lower shading than the 50% applied in our study might be favourable. However, the higher level of nutrient inputs applied in the MONOs as compared to the AFs may also partly explain our results. A recent study by Jacobi *et al.* (2013), which was conducted in 10–15 years old cocoa plantations in Alto Beni, found a different order of cocoa yields in the different production systems as compared to the results from our trial: The study reported highest annual yields of 510 kg ha^{-1} for SAFS, followed by 423 kg ha^{-1} in AF and 350 kg ha^{-1} in MONO.

The factor *Management practice* also had a significant influence on cocoa dry bean yields ($p = 0.001$, Table 3), with ORG systems consistently showing lower yields compared to their CONV counterparts (−36%). In the case of the AFs, however, cocoa dry bean yields were not significantly different between AF CONV and AF ORG, which is in line with the results reported by Haggar *et al.* (2011) for coffee under *Erythrina poeppigiana* shade trees, a leguminous tree we also integrated into our trial (see Table S7). Normally, a linear correlation is expected between trunk circumferences and early cocoa productivity in the first few years after planting, as shown by Glendinning (1960). However, even though the trunk circumferences were similar in MONO CONV and MONO ORG, significantly higher cocoa dry bean yields were achieved in MONO CONV compared to MONO ORG (Figures 1 and 2). This finding is in line with the results of Haggar *et al.* (2011) for coffee in three out of 6 years in Costa Rica.

Despite MONO systems not being advised by the norms for organic production (IFOAM, 2012), they are a reality in ORG cocoa production. The reasons for the observed yield gap between MONO CONV and MONO ORG may relate to one or several of three factors: (i) competition for nutrients, (ii) competition for water and (iii) incidence of pests and diseases. Our data indicate that the competition with the vigorous cover crop probably lowered the availability of phosphorus in the soil in MONO ORG in 2013, as suggested by Hall *et al.* (2010): The results of soil analyses performed in 2011 showed 13% lower levels of available P in MONO ORG compared to MONO CONV (data not shown). Even though the cover crop was mulched regularly underneath the cocoa tree crowns, these interventions may not have been carried out frequently enough. In addition, the weed-free area may have been too small (i.e. not as big as the tree crowns) during certain time periods, indicating again the need to develop sound recommendations for good agricultural practices (in this case, regarding the integration and management of cover crops during the first 3 to 5 years of plantation establishment) in cocoa production systems as suggested by a recent study (Dawoe *et al.*, 2014). This competition may have been lower in MONO CONV due to the eradication of all weeds using herbicides. Our results indicate reduced efficiency of ORG fertilizer applications for full-sun cocoa production systems. Moreover, the faster availability of nutrients achieved through applications of synthetic fertilizer as compared to compost amendments in ORG systems may partly explain our results.

A current PhD study carried out in our trial is investigating the dynamics and use efficiencies of water in the different systems. The extent to which the observed yield gap is explained by water competition between cocoa trees and the vigorous cover crop will thus be addressed. With regard to incidence of pests and diseases, we monitored on average 12% more Witches Broom (*M. perniciosa*) in MONO ORG compared to MONO CONV in the year 2013 (data not shown), which could be an important cause of the yield gap between MONO CONV and MONO ORG.

The 70% lower cocoa dry bean yields in SAFS compared to all the other systems in 2013 may be due to the fact that shade trees naturally regenerated from old root stocks were dominating SAFS too much from 2011 to 2012. Furthermore, the system was managed in order to maximize yields from the different by-crops during the establishment phase (see Table 3), and the fact that no inputs of system-external nutrient were applied in SAFS may also partly explain our results. The mentioned heavy pruning of the shade tree canopy performed in October 2012 not only aimed at obtaining substantially higher cocoa yields than previously, but also at improving the synchronization of by-crops with cocoa. Dawoe *et al.* (2014) proposed that mechanisms for the cultivation of annual crops during the establishment phase of cocoa production systems need to be developed, highlighting once more the lack of recommendations for good agricultural practices.

Total system yields (2009–2013) and ecological benefits

Several studies have shown that intercropping different crops increases total system yields as compared to MONO systems in tropical crop production systems and could thus make significant contributions to local food security and risk distribution in smallholder contexts (Bellow *et al.*, 2008; Jaggi *et al.*, 2004). Furthermore, it was reported that multispecies systems hold a large potential to contribute to the development of sustainable AFs. However, research on such systems to optimize total system yields and understand tree–crop interactions is scarce (Bellow *et al.*, 2008). They are difficult to understand and assess in their complexity and appropriate methodologies have to be developed to enable adequate, quantitative assessments (Nair, 2001). The fundamental questions with respect to total system yields are economic system performance and different provisioning of ecosystem goods and services. Quelca *et al.* (2005) reported that more than 80% of farmers who produce cocoa in SAFS systems in Alto Beni target increased food self-sufficiency through production of by-crops in their SAFS.

Besides production and economic viability, AFs offer ecological benefits such as self-regulation of pests and diseases, conservation of biodiversity and soil fertility, as well as climate change mitigation and adaptation. Paradoxically, intensification of cocoa production systems (i.e. the removal of shade) has reduced their ecological resilience while environmental change and climate extremes require higher resilience than ever (Lin *et al.*, 2008; Steffan-Dewenter *et al.*, 2007; Tscharntke *et al.*, 2011). With regard to agro-biodiversity, the AFs and SAFS contain higher numbers of species than the MONOs. Diversification is an important feature for the adaptability of agro-ecological systems to climate change (Henry *et al.*, 2009), besides other environmental benefits (Soto-Pinto *et al.*, 2010). ORG certification may be a means to incentivize AFs, as they are recommended for certification standards (IFOAM, 2012). The ongoing research we are conducting at the trial site is addressing soil fertility, biodiversity, carbon sequestration for climate change adaptation and mitigation, as well as dynamics of pests and diseases and mid- to long-term economic systems' performance.

CONCLUSION

This paper responds to the urgent need for long-term scientific production systems comparison trials in the tropics (Gattinger *et al.*, 2012; Seufert *et al.*, 2012) by describing the, to our knowledge, only long-term field trial worldwide comparing MONO and agroforestry cocoa production systems under CONV and ORG management, and presenting first results from the establishment phase.

Early cocoa productivity in MONO systems was clearly above the values found for AFs (+86%), which is likely explained by the higher light availability for cocoa trees in the MONOs. On the other hand, all three AFs showed significantly higher total system yields compared to the two MONOs (+135%), which underlines the reported potential of AFs to contribute to local food security and risk distribution in smallholder contexts.

The observed yield gaps between ORG and CONV production systems (−47% in MONOs, −16% in AFs) pinpoint the urgent need to develop specific recommendations for good agricultural practices in ORG cocoa production systems for the agro-ecological and socio-economic context of Alto Beni. Our experiences suggest that ORG cocoa production is feasible in AFs. However, in full-sun MONO systems, such production seems to be distinctly more challenging. In order to optimize management practices and to explain the underlying causal factors determining the observed yield gaps, in-depth studies on: (i) nutrient and water competition between cocoa and both the cover crop and associated non-cocoa crops, (ii) efficiencies of ORG and CONV fertilizers and (iii) incidence of pests and diseases are currently being carried out.

Our findings underline the high importance of elucidating the economic viability of the different systems during the period covered in this study, particularly in the context of projected price increases for cocoa on the global market. Further research in the trial is focussing on the trade-offs between productivity and environmental sustainability, which may eventually allow a thorough assessment of the different cocoa production systems in both ecological and economic terms.

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SUPPLEMENTARY MATERIALS

For supplementary material for this article, please visit http://dx.doi.org/10.1017/S0014479716000417.

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