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RESEARCH ARTICLE

Cacao agroforestry systems have higher return on labor compared to full-sun monocultures

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Abstract The global demand for cacao has recently increased. To meet this demand, the cultivated area has been expanded in tropical forest areas and production has intensified by replacing traditional agroforestry systems with monocultures. This has led to a loss of biodiversity in cacao-growing areas. More sustainable production systems such as agroforestry and organic managed systems are expected to yield less cacao, but by-crops and premium prices, respectively, might economically compensate for the lower yields. Here, we compared the productivity and the return on labor, that is the return per working day, of four different cacao production systems: agroforestry and monocultures under organic and conventional management. Cacao and by-crop yields, costs, revenues, and labor were registered during the first 5 years after establishment. Results show that cacao yields were, on average, 41% higher in monocultures, but the revenues derived from agroforestry by-crops economically overcompensated for this difference. Indeed, the return on labor across the years was roughly twice as high in the agroforestry systems compared to the monocultures. We found similar cacao yields and return on labor in conventional and organically managed agroforestry systems. However, in the monocultures, cacao yields were 48% lower under organic compared with conventional farming, but the return on labor was similar, mainly due to the higher costs associated to the conventional management. Overall, our findings show that cacao agroforestry systems have higher return on labor.

Keywords Bolivia · Economic analysis · Labor demand · Long-term experiment · Organic farming · *Theobroma cacao* L.

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1 Introduction

The cacao tree (*Theobroma cacao* L.) is native to the lower strata of Amazonian forest regions. Currently, mainly smallholders cultivate cacao in the tropical lowlands of Latin America, West Africa, and South East Asia (Donald 2004; Franzen and Borgerhoff Mulder 2007). The global demand for cacao has been increasing (Vaast and Somarriba 2014), and this trend has led to a change in cacao production systems; traditional cultivation under shade has been replaced with full-sun monocultures with higher input levels (Franzen and Borgerhoff Mulder 2007). Monocultures generally have higher cacao yields compared to shaded systems (Gockowski et al. 2013; Ramirez et al. 2001; Ratnadass et al. 2012) and may improve farmers' incomes in the short-term (Franzen and Borgerhoff Mulder 2007; Siebert 2002). Moreover, expansion of the cultivated area has also occurred to the detriment of forest regions (Vieira et al. 2008). Both the adoption of intensified agricultural practices and the reduction of forest area have been recognized as the main drivers of the loss of biodiversity and ecosystem services (Foley et al. 2005; Klein et al. 2002; Milestad and Darnhofer 2008; Morris 2010).

Agroforestry, i.e., the intentional management of shade trees with agricultural crops, has been proposed to avoid such impacts and to preserve tropical natural resources because they can conserve tropical forest biodiversity by resembling natural forests (Perfecto et al. 2005). However, they can range from very simple systems, with two or very few species, to highly diverse ones. Currently, agroforestry systems represent 38% of the world land-use (Rapidel et al. 2015). Nevertheless, to guarantee a further extension, such systems need to be profitable for the farmers. Organic farming practices have also been reported to be effective at preserving biodiversity (Gabriel et al. 2010). Lower yields compared with conventional farming are commonly reported (Seufert et al. 2012), but are usually compensated by the premium prices of the organic products (Crowder and Reganold 2015). However, cacao production under organic farming is still very low, i.e., approximately 2.3% of the global production area (Willer and Lernoud 2015). Several studies have already demonstrated that agroforestry systems can improve farmers' livelihoods due to self-consumption of by-crops, such as bananas, oranges, and peach palm, among others (Cerda et al. 2014). However, when assessing cacao production systems, most studies focus on cacao yields without quantitatively assessing the economic returns of by-crops (Cerda et al. 2014). Lack of access to the market and the low density at which by-crops are commonly grown are two of the main drawbacks to selling them. Therefore, despite their potential to increase farmer's revenues, they have been mainly considered as self-consumption products. Moreover, information is still scarce regarding the productivity and profitability of organic agriculture in both the full-sun monocultures and agroforestry.

There is an additional knowledge gap in terms of addressing the profitability of young plantations, i.e., during the first years after their establishment. Cacao plantations reach full production in approximately 10 years, and most studies focus on fully productive plantations (Cerda et al. 2014). The first years of plantation are indeed the most sensitive because cacao sales returns are not high. Therefore, in this study, we compared the productivity and the return on labor of four different cacao production systems, i.e., agroforestry systems and full-sun monocultures under organic and conventional management, during the first 5 years of a newly established experimental plantation in Alto Beni, Bolivia (Fig. 1). This is the first study on cacao evaluating the profitability of organic management and economically assessing the potentiality of by-crops for farmer's revenues in a long-term trial. We hypothesized that (i) cacao yields will be higher in full-sun monocultures and conventionally managed systems, but that (ii) by-crops in agroforestry systems and premium prices in organic systems will economically compensate for the lower cacao yields; however, (iii) a lower return on labor is expected in agroforestry and organic systems due to higher work demand.

2 Materials and methods

2.1 Site and trial description

The experimental trial was located in Sara Ana (390 m a.s.l.), Alto Beni, in the department of La Paz, Bolivia. The climate is tropical humid with dry winters; the average annual precipitation and temperature are approximately 1′540 mm and 26.6 °C, respectively. The soils are Luvisols and Lixisols. The natural vegetation is composed of nearly evergreen humid forests.

Land preparation, i.e., slashing the secondary forest, mulching and/or burning, started in 2007, and maize was grown thereafter. The establishment of the plantation started in mid-2008 and finished at the beginning of 2009. In this study, four different cacao production systems were assessed—full-sun monoculture and agroforestry systems under organic and conventional management. The organic managed systems followed the EU regulations (Council Regulation No 889/2008). Agroforestry systems, and to lesser extend monocultures, under organic management (or without external inputs), are the main cacao production systems in Alto Beni. Agroforestry and monocultures under conventional

Fig. 1 Experimental plots showing cacao trees in full-sun monoculture and agroforestry systems

management represent the largest share of cacao production worldwide (Schneider et al. 2016). Each production system was replicated four times in a completely randomized block design. The size of the gross plots was 48 m × 48 m, with a net plot of 24 m × 24 m. The cacao tree spacing was 4 m × 4 m (625 trees ha^{-1}), resulting in 36 trees in the net plot.

In the agroforestry systems, the main shade trees were *Inga* spp. and *Erythrina* spp., complemented by timber, fruit, and palm trees. The total density of the shade trees was 304 trees ha^{-1}. In both the full-sun monocultures and agroforestry systems, plantain was also planted at a density of 625 trees ha^{-1}. They were removed at the end of 2011 in the full-sun monocultures and replaced by banana trees in the agroforestry systems, according to local farmers' practices. A perennial legume cover crop (*Neonotonia wightii* (Arn.) Lackey) was sown in the organically managed systems (Schneider et al. 2016).

From 2010 to 2014, all data were collected from the net plots and all figures were converted to hectares. The local currency, boliviano, was converted to US$ to ease the comparison at an exchange rate of US$ 0.145.

2.2 Sampling procedures

2.2.1 Yields and revenues

The annual yield of cacao was calculated as the sum of all of the single harvests, usually two per month, mainly from March to December. The total fresh bean yield was then converted to the dry bean yield by applying the commonly used standard dry bean factor of 0.33. The plantain and banana yields were recorded as the number and the weight of bunches.

Revenues derived from cacao were calculated for each year, using the total dry yield per plot and annual average sales prices of each category of beans: first-quality conventional beans (average price across years ± SE: 3.04 ± 0.39 $ Kg^{-1}), second-quality conventional beans (1.73 ± 0.13 $ Kg^{-1}), and organic beans (3.48 ± 0.33 $ Kg^{-1}). In the case of plantain, the harvested bunches were sold directly and the bananas were sold in "chipas", which is approximately 1000 bananas. The average weight of bunches necessary for a chipa was estimated to calculate the revenues from the harvested bunches. Both the organic plantains and bananas were sold as conventional because of the lack of an organic market. For each year, the annual average sales price was considered. The average price over the years was 1.62 ± 0.93 and 9.40 $ $chipa^{-1}$ for plantain and banana, respectively.

The potential future revenues of the timber trees in the agroforestry systems were not considered because it was too early to estimate their potential growth at this stage and because we aimed to show the actual figures regarding the costs and benefits in a young cacao plantation.

2.2.2 Costs

Pruning, weeding, and pest control The costs of tools and materials used for pruning the cacao and shade trees (such as pruning scissors and ladders) were estimated considering a lifespan of 3 years.

Weeding in the conventionally managed systems was performed by manual weeding using both machetes and brush cutters, as well as with herbicide applications between four and five times per year. For the brush cutters, we estimated a cost of 3.63 $ h^{-1}, which includes the price of petrol and machinery amortization. The costs per plot were calculated by multiplying the time invested in each activity by the above-mentioned hourly cost. For the herbicides, we calculated the cost per liter of solution considering the annual market price of the product, the transport costs necessary for purchasing it in the nearest market (Palos Blancos, 38 km, once a year), and also the tools and materials necessary for application according to their lifespan, e.g., manual backpack sprayers, gloves, and protections. In the organically managed systems, weeding was performed mainly with machetes, and brush cutters were used only in the last few years. Their cost was estimated as mentioned previously.

Pesticides (Lorsban PlusR, Dow AgroSciences, Chlorpyrifos, 50 g l^{-1}, Cypermethrin 5 g l^{-1}) were only applied once in the conventionally managed plots to control the cacao leaf-cutting ant (*Atta* sp). The cost was estimated using the same approach used for the herbicides. A very low impact of pests and diseases has been detected so far; thus, no other pesticides or means of biological control have been applied in the cacao or plantain/banana trees.

Fertilizer applications Cacao trees were fertilized starting in 2010. Chemical fertilizer (Blaukorn BASF, Germany, 12–8–16-3 N-P_2O_5-K_2O-MgO) was applied in the conventionally managed plots, whereas compost was applied in the organic ones. Agroforestry systems received half of the dose used in full-sun monocultures, i.e., on average, full-sun monoculture conventional: 112 kg ha^{-1}, agroforestry conventional: 56 Kg ha^{-1}, full-sun monoculture organic: 8 t ha^{-1}, and agroforestry organic: 4 t ha^{-1}. The chemical fertilizer dose was split and applied twice a year, in March and December. For each year, the total cost was estimated considering the market price of the fertilizer and the transport cost for its purchase (once a year). The compost was applied once a year and was prepared using biomass from the surroundings of the trial site in addition to purchased woodchips and/or rice shells. Their price and transportation costs were considered. Neither the plantain nor banana trees were fertilized.

Certification costs The organic land was certified by IMO Organic Standard, Institute of Marketecology. Certification required a standard cost of 1403 $ $year^{-1}$. Based on this, a price per plot was calculated considering a total of 40 ha of certified land in the whole plantation.

2.2.3 Working time

From January 2010 to December 2014, the working time devoted to each single agronomic activity in the net plot, mainly the harvest of cacao and plantain/banana, management of the trees, fertilizer applications, and weeding, was registered by recording the initial and final time of each activity as well as the number of people working.

Additionally, the working time of the activities performed outside the plots was also registered. For the fertilizer preparation, the time spent purchasing the chemical fertilizers was considered. For the compost preparation, the time needed to gather the biomass, prepare the composting piles, and manage and monitor the composting process was recorded. Similarly, the time for purchasing the herbicides and pesticides was also considered, as well as the working time to prepare the solution for each application. The time for the post-harvest processes was also considered. For the cacao, we estimated the time required to open and remove the beans per pod, to turn the beans during the fermentation and drying process, and to select the beans according to first and second quality. For both banana and plantain, we considered the transportation time from the field to the research station where they were sold; in the case of banana, we also registered the time for preparing a chipa.

2.2.4 Return on labor

For each year and plot, the gross margins were calculated considering the total annual revenues of the cacao and plantain/banana as well as the total annual costs, excluding labor costs. Labor costs were excluded from the cost calculation to focus on the actual cash needed. Cacao producers, most of whom are smallholders, do not usually pay for labor, since it is mainly family labor. Then, the return on labor, i.e., the benefit per 8 h labor, was calculated by dividing the annual gross margin by the total annual working days. The cost of infrastructures, buildings, and land was not considered.

2.3 Statistical analysis

We tested the effects of the different cacao production systems on the yields, revenues, costs, gross margins, working time, and return on labor through linear mixed-effect models. The production system, year, interaction between production system and year, and block were included as fixed factors; and the plot nested to block as a random factor. Orthogonal contrasts were fixed a priori to compare the levels of the factor production system. Agroforestry systems were compared with full-sun monocultures; within agroforestry systems, conventional management was compared with organic management, and the same was done for the full-sun monocultures. The year was included as an ordered factor. Data were log-transformed when necessary to meet the normality and homoscedasticity requirements. All analyses were performed in R 3.1.10 (R Development Core Team 2015), with the "lme4" package for mixed models (Bates et al. 2015) and "lmerTest" to evaluate the significance of effects (Kuznetsova et al. 2015).

3 Results and discussion

3.1 Cacao and plantain/banana yields

The cacao trees started to produce in 2011, 3 years after they were planted. As expected, the yields of the cacao trees increased over the years (Sum of squares = 591, 820; df = 3; P value = 2.2 e^{-16}; Fig. 2a), with the exception of 2014, which was a year of very low productivity in the whole region due to unfavorable weather conditions. The share of the second-quality cacao was almost negligible in all production systems (on average 3% of the total yield). Productivity slowly reached the average yield in South America, ranging between 400 and 700 kg ha^{-1} (Vaast and Somarriba 2014), and was similar to other young cacao plantations (Ramirez et al. 2001).

Overall, we found higher cacao yields in the full-sun monocultures compared with the agroforestry systems (Estimate ± SE = −52.3 ± 5.3, P value < 0.001). On average, the monocultures were 41% more productive than the agroforestry systems, which is in line with previous studies in Central America and West Africa (Gockowski et al. 2013; Ramirez et al. 2001). This is mainly attributed to the higher light incidence and vigor of the trees under full-sun monocultures compared with agroforestry systems (Koko et al. 2013). However, in our study, the difference between the full-sun monocultures and agroforestry systems was mainly due to the higher yields obtained under conventional compared with organic management in the full-sun monocultures, i.e., 48% lower in the organic system (Estimate ± SE = −80.7 ± 7.5, P value < 0.001; Fig. 2a). This could be explained by the higher amount of readily available nutrients applied with the chemical fertilizer compared with the compost. Higher yields under conventional management are usually reported for a wide range of crops, particularly in developing countries (Seufert et al. 2012). However, similar cacao yields were found between organic and conventional management in the agroforestry systems (Estimate ± SE = 11.5 ± 7.5, P value = 0.16. According to Koko et al. (2013), fertilizer inputs may have no relevant effect on the cacao productivity in agroforestry systems, where light is a stronger limiting factor. In this trial, pests and diseases did not affect differential yields in the organic and conventional systems.

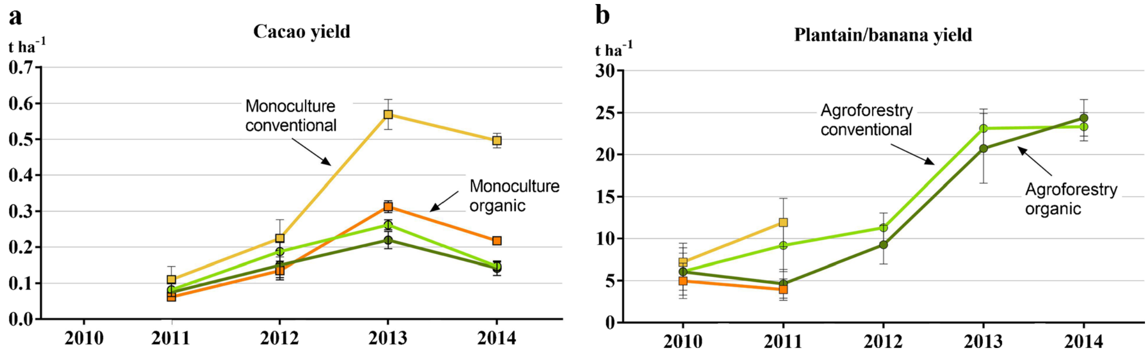

Fig. 2 Mean ± standard error of the **a** cacao and **b** plantain (until 2011) and banana (from 2012) yields in the four production systems, i.e., *agroforestry conventional*, *agroforestry organic*, *full-sun monoculture conventional*, and *full-sun monoculture organic*, from 2010 to 2014. Overall, the cacao yields were higher in the full-sun monocultures compared with the agroforestry systems. Conventional monocultures were more productive than the organic ones, but no differences between conventional and organic agroforestry systems were found. The plantain/banana yields were higher in the agroforestry systems, while no differences between organic and conventional management were detected in both full-sun monocultures and agroforestry systems, respectively.

Concerning the plantain/banana yields, we also found an increase in production over the years (Sum of squares = 576, 268, 017, df = 4, P value < 0.001; Fig. 2b). As expected, the agroforestry systems achieved higher yields across the years (Estimate ± SE = 5505.3 ± 684.7, P value < 0.001). The plantain trees were removed from all the production systems by the end of 2011, and they were replaced by banana trees only in the agroforestry systems. Similar plantain/banana yields were found under organic and conventional management in both the full-sun monocultures (Estimate ± SE = 1019.6 ± 968.2, P value = 0.32) and the agroforestry systems (Estimate ± SE = 795.0 ± 968.2, P value = 0.4).

3.2 Revenues and costs

We found higher total revenues and lower total costs in the agroforestry systems compared with the full-sun monocultures (Fig. 3a; Table 1). This led to twice as high gross margin in the agroforestry systems, i.e., average across years ± SE: agroforestry systems = 820.2 ± 88.71 \$ ha^{-1}; monocultures = 398.7 ± 81.36 \$ ha^{-1} (Table 1).

In this study, we show that even though both the yields and the revenues of cacao were higher in the full-sun monocultures, the revenues obtained from the sales of plantain/banana overcompensated for the lower cacao revenues. This result highlights the potential contribution of by-crops, such as

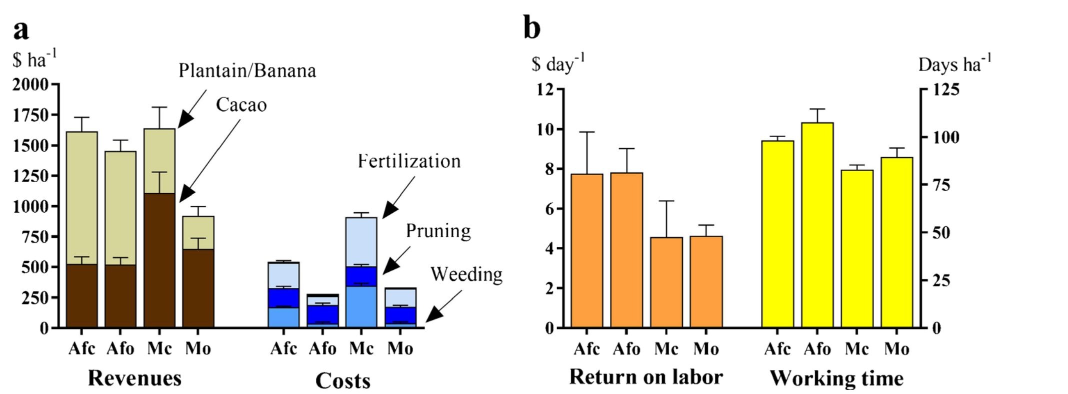

Fig. 3 Annual mean ± standard error from 2010 to 2014 of **a** revenues and costs, and **b** return on labor and working time in the four production systems, i.e., *agroforestry conventional* (Afc), *agroforestry organic* (Afo), full-sun monoculture conventional (Mc), and *full-sun monoculture organic* (Mo). In figure **a**, the costs for certification in the organically managed plots and the costs for planting banana trees in the agroforestry plots are included in the figure, but the segments of the *bars* are too small to be clearly visible. Overall, agroforestry systems had higher revenues than monocultures, mainly because of the sales of banana. In monocultures, revenues were higher under conventional farming, while no significant differences were detected between conventional and organic agroforestry systems. Total costs were higher in the monocultures compared with the agroforestry systems, as well as under conventional compared with organic management, in both the monocultures and agroforestry systems. The return on labor, i.e., the return per working day, was higher in the agroforestry systems compared with the monocultures, while no differences were detected between organic and conventional management in both the full-sun monocultures and agroforestry systems, respectively. The total working time was higher in the agroforestry systems compared with monocultures, as well as in organic compared to conventional agroforestry systems. No differences between both managements under monoculture were detected

Table 1 Results of the linear mixed-effects models assessing the effect of block, production system, year, and interaction between year and production system on the revenues, total costs, gross margin, and on the return on labor

	Revenues								Total costs[a]		Gross margin		Return on labor	
	Total revenues		Cacao		Plantain		Banana							
Fixed effects	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF
Block	1,268,154.8**	3	425,874.8**	3	1,546,681.8**	3	63,875.2	3	0.001	3	1,087,123.7*	3	149.8*	3
System	1,998,123.4**	3	3,336,615.2 **	3	777,140.5*	3	3380.6	1	0.389***	3	1,484,400.9**	3	141.9*	3
Year	16,246,120.3***	4	7,411,311.5***	3	3,359,234.2***	1	1,880,343.4***	2	0.0242***	4	1,049,896.6***	4	1449.3***	4
Year × System	3,155,472.8***	12	2,715,320.5***	9	1,141,843.8**	3	31,025.6	2	0.057***	12	3,958,425.8***	12	563.2***	12
Estimate ± SE	Estimate ± SE		Estimate ± SE		Estimate ± SE				Estimate ± SE		Estimate ± SE		Estimate ± SE	
System Af vs Mono	116.66 ± 39.29*		-178.63 ± 17.35***		-41.89 ± 52.83				0.023 ± 0.002***		225.50 ± 43.27***		1.83 ± 0.44**	
System Afc vs Afo	93.88 ± 55.79		3.66 ± 24.53		114.65 ± 74.72				0.055 ± 0.003***		−32.26 ± 61.40		0.44 ± 0.63	
System Mc vs Mo	287.64 ± 55.34***		228.65 ± 24.53***		261.78 ± 74.72**				0.075 ± 0.003***		4.29 ± 60.97		-0.03 ± 0.61	

Above: ANOVA table showing the effect of the fixed terms block, production system, year, and the interaction between year and production system as well as their significance levels on the tested parameters. Below: coefficients of the orthogonal contrasts for the factor production system comparing *agroforestry systems* (Af) with *full-sun monocultures* (Mono), as well as the farming management within each cropping system, i.e., the *agroforestry conventional* (Afc) with the *agroforestry organic system* (Afo), and the full-sun *monoculture conventional* (Mc) with the full-sun *monoculture organic* systems (Mo)

DF degrees of freedom, *SE* standard error

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$. Orthogonal contrasts were not run for banana because it was only present in the agroforestry systems

[a] log-transformed

plantain and banana, to farmers' incomes, at least at the early stage of cacao plantations, before cacao trees reach full production. For instance, in this trial, from 2010 to 2014, the ratio of banana/plantain revenues to cacao revenues was on average approximately 2 in the agroforestry systems and approximately 0.45 in the full-sun monocultures. In the study area, plantain and banana are common crops and are typically intercropped with cacao trees, but only during the first years of the cacao plantation. A well-developed market for them is generally accessible for the farmers. However, this might not be the case for other by-crops or for other regions. Lack of access to the market (deficient road transportation, by-crops not adapted to local necessities, etc.,) and/or not being able to constantly supply the market due to growing by-crops at low densities, might difficult the sales of by-crops. A thoughtful planning of the agroforestry systems is then capital to profit from the potential returns of by-crops.

In the full-sun monoculture systems, the revenues obtained under conventional management were higher than those under organic management (Table 1). The premium obtained on the organic cacao fetched 13% more compared to the conventionally produced cacao, which was lower than the often reported premium gain of 29–32%. (Crowder and Reganold 2015). Thus, contrary to previous studies, the premium prices did not compensate for the lower yields obtained (Crowder and Reganold 2015). However, it is worth mentioning that the organic–conventional yield gap was larger than those reported by other studies (Seufert et al. 2012; Crowder and Reganold 2015).

On the other hand, in the agroforestry systems, we did not find differences in the revenues obtained under organic and conventional management. Although the yields of both cacao and plantain/banana were similar under both management systems, the premium prices for organic cacao were not high enough to obtain significantly higher revenues. It is worth mentioning again that the plantains/bananas under organic management were not sold as organic products because of the lack of access to the organic market.

As previously mentioned, the total costs were lower in the agroforestry systems compared with the full-sun monocultures (Fig. 3a). This was mainly due to the lower cost of the fertilizer applications because only half of the doses applied in monocultures were applied in the agroforestry systems. In addition, the costs of weeding, both with herbicides and brush cutters, were also lower. This was related to the lower presence of weeds in the agroforestry systems, probably due to lower light penetration and higher soil cover with biomass of the shade trees, which may have hampered the growth of weeds (Pumariño et al. 2015).

When comparing organic and conventionally managed systems, the costs were higher under conventional management (Table 1, Fig. 3a), mainly because of the higher cost of synthetic fertilizers compared with compost. Weeding costs also played a role because they were lower in the organically managed systems due to the absence of herbicide applications and the presence of the legume cover crop controlling the weeds.

Thus, in our trial, lower costs were associated with agroforestry systems and organic management. These results may have a strong implication for smallholder farmers, who usually hold limited savings and lack of access to credit.

3.3 Return on labor

The return per working day invested in all of the agronomic activities across the years was almost two times higher in the agroforestry systems compared with the full-sun monocultures (Table 1; Fig. 3b). Thus, our results show that agroforestry systems not only support farmers' livelihood because of the higher diversification of crops for self-consumption, as has been widely reported (Cerda et al. 2014), but also they have higher return on labor than the full-sun monocultures.

The return on labor obtained can be considered to be a promising result because it exceeds the amount of 1.90 US$ day^{-1} set by the World Bank as the international poverty line (The World Bank 2016), but is still a bit lower than the minimum salary in Bolivia of approximately 8.7 $ day^{-1}. However, we stress that our values cannot be directly applied to the reality of farmers; even though the agronomic practices applied in the trial aimed to mimic farmers' practices, our data were obtained from an experimental trial under optimal management conditions, which may differ considerably from the farmers' management. However, in terms of a systems comparison, there was a clear trend of a higher return on labor in the agroforestry systems compared to the full-sun monocultures.

The return on labor was higher in the agroforestry systems than in the full-sun monocultures, even though the working time was also higher (Table 2; Fig. 3b). This is explained by the fact that the working time was an average of 16% higher in the agroforestry systems; on the other hand, the gross margin was, on average, 51% higher compared with the full-sun monocultures. The higher working time spent in the agroforestry systems was due to harvest of the banana and the management of shade trees, which were highly labor-intensive activities, mainly the pruning of shade trees. All of the other activities, i.e., harvesting and pruning the cacao trees, weeding, fertilizer applications, and the fermentation and drying process, were similarly or less work-demanding than in the monocultures (Table 2). Overall, the working time registered was within the range found in other studies (Juhrbandt et al. 2010).

Comparing organic and conventional management, we did not find differences in the return on labor in both the agroforestry and full-sun monocultures (Table 2; Fig. 3b). This is explained by the lack of differences in the gross margin

Table 2 Results of the linear mixed-effects models assessing the effect of block, production system, year, and the interaction between year and production system on the working time (work-day ha^{-1}) spent for the different management activities

	Total working time		Weeding		Cacao harvest		Plantain/banana harvest		Shade trees management		Pruning		Fertilizer application[a]		Fermentation	
Fixed effects	Sum of squares	*DF*	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF	Sum of squares	DF
Block	2342.0**	3	52.6	3	75.3**	3	21.2	3	280.1*	3	786.3***	3	0.3*	3	1.6**	3
System	3777.8***	3	81.5	3	1003.5***	3	237.0***	3	10,054.7***	3	993.3***	3	38.7***	3	13.3***	3
Year	16,954.0***	4	4692.1***	4	1912.9***	3	444.6***	4	4657.5***	4	9717.1***	4	6.7***	4	20.7***	3
Year × System	3708.6***	12	1102.8***	12	748.7***	9	1421.2***	12	4563.3***	12	687.8***	12	3.2***	12	8.5***	9
	Estimate ± SE		Estimate ± SE		Estimate ± SE		Estimate ± SE		Estimate ± SE		Estimate ± SE		Estimate ± SE		Estimate ± SE	
System Af vs Mono	8.41 ± 1.16 ***		−0.79 ± 0.77		−2.94 ± 0.26***		5.04 ± 0.57***		11.30 ± 0.57***		−3.40 ± 0.45***		−0.17 ± 0.01***		-0.32 ± 0.03***	
System Afc vs Afo	−4.80 ± 1.65 *		−2.17 ± 1.10·		0.48 ± 0.37		−0.06 ± 0.81		−0.08 ± 0.82		0.16 ± 0.64		−0.63 ± 0.02***		0.06 ± 0.04	
System Mc vs Mo	−3.39 ± 1.65		0.20 ± 1.10		3.96 ± 0.38***		0.53 ± 0.81		0.36 ± 0.80		1.28 ± 0.64*		−0.75 ± 0.02***		0.50 ± 0.04***	

Above: ANOVA table showing the effect and the significance levels of the fixed terms block, production system, year, and the interaction between year and system on the working time of the management activities. Below: coefficients of the orthogonal contrasts for the factor system comparing agroforestry (Af) with full-sun monocultures (Mono), as well as the farming management within each cropping system, i.e., the agroforestry conventional (Afc) with the agroforestry organic system (Afo), and the full-sun monoculture conventional (Mc) with the full-sun monoculture organic systems (Mo)

DF degrees of freedom, *SE* standard error

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; $P < 0.1$

[a] log-transformed

between both managements (Table 1) and none or very few differences in the working time. As a matter of fact, no differences in the total working time between organic and conventional management were detected in the monocultures, although some activities were more time-consuming under conventional management and others under organic management (Table 2). In the case of the agroforestry systems, conventional farming was less labor-demanding, but only because of the lower time spent fertilizing with synthetic fertilizer compared with the compost under organic farming. This result contrasts those of previous studies claiming that organic farming is more laborious than conventional farming (Jansen 2000) and underlines the feasibility of organic cacao production with regard to labor demands.

4 Conclusions

Our results show that in addition to maintaining or enhancing biodiversity and farmers' livelihood as previously reported, agroforestry systems and organic management may also be as profitable or even more profitable than full-sun monocultures and conventional management in young cacao plantations.

The revenues obtained by banana sales in the agroforestry systems overcompensated for the higher cacao revenues in the full-sun monocultures. This result highlights the potential major role of by-crops not only in self-consumption but also in revenue. A thoughtful planning of the agroforestry systems including market-oriented by-crops adapted to local needs, combined with by-crops for self-consumption is then capital. In addition, efforts should be made to further develop accessible markets for by-crops.

However, the fast expected cacao yield increase in the monocultures might reduce the positive role that by-crops have on the return on labor in the first years of the plantation. But, this might be counterbalanced by the revenues from sales of the timber trees. Further monitoring of the four systems until reaching full production is, therefore, indispensable for having a comprehensive understanding of the productivity and profitability of each production system.

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