Shade trees: a determinant to the relative success of organic versus conventional coffee production

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Abstract

Greater understanding of the influences on long-term coffee productivity are needed to develop systems that are profitable, while maximizing ecosystem services and lowering negative environmental impacts. We examine a long-term experiment (15 years) established in Costa Rica in 2000 and compare intensive conventional (IC) coffee production under full sun with 19 agroforestry systems combining timber and service tree species with contrasting characteristics, with conventional and organic managements of different intensities. We assessed productivity through coffee yield and coffee morphological characteristics. IC had the highest productivity but had the highest yield bienniality; in the agroforestry systems productivity was similar for moderate conventional (MC) and intensive organic (IO) treatments (yield 5.3 vs 5.0 t/ha/year). Significantly lower yields were observed under shade than full sun, but coffee morphology was similar. Low input organic production (LO) declined to zero under the shade of the non-legume timber tree *Terminalia amazonia* but when legume tree species were chosen (*Erythrina poepiggiana*, *Chloroleucon eurycyclum*) LO coffee yield was not significantly different than for IO. For the first 6 years, coffee yield was higher under the shade of timber trees (*Chloroleucon* and *Terminalia*), while in the subsequent 7 years, *Erythrina* systems were more productive, presumably this is due to lower shade covers. If IC full sun plantations are not affordable or desired in the future, organic production is an interesting alternative with similar productivity to MC management and in LO systems incorporation of legume tree species is shown to be essential.

Keywords: Agroforestry systems; Coffee yield; Coffee morphology; Sustainable production; Shade trees; Biennial bearing

1 Introduction

Conventional coffee management under full sun conditions has been promoted over agroforestry and/or organic practices, due to the belief that it yields higher coffee production (Beer et al. 1998; Haggar et al. 2011). This gain in productivity has been achieved by the high use of external inputs of agrochemicals, shortcutting ecological cycles (Haggar et al. 2011) which contributes to environmental pollution, degradation of soils (DaMatta 2004) and health hazards e.g. nitrate in waste water (Tully et al. 2012). These high inputs, moreover, generate a high annual cost that cannot easily be reduced leading to greater vulnerability of coffee farmers to the volatile international coffee market (Haggar et al. 2011). In general, organically grown coffee was reported to yield lower than conventional on coffee farms in Costa Rica, but a subgroup of farms showed a similar or even higher productivity (Lyngbæk et al. 2001). Our first hypothesis is therefore, that organic management can be highly productive, under appropriate shade trees, and with sufficient levels of nutrient inputs.

Agroforestry systems as an alternative to full sun production are proposed to have numerous benefits including protection of soil and water resources (Beer et al. 1998), reduced erosion and nitrogen leaching (DaMatta 2004; Tully et al. 2012), buffering of climate extremes (Lin 2007), less microclimatic variation (Gomes et al. 2016), higher carbon storage as well as higher local biodiversity (Tscharntke et al. 2011; Ehrenbergerová et al. 2016) and enhanced resource capture, such as light (Taugourdeau et al. 2014). Legume shade tree species have been also shown to compensate for lower external inputs (Nygren et al. 2012) and under sub-optimal growing conditions shaded coffee out-produced full sun and had lower yield bienniality (DaMatta 2004; Vaast et al. 2005). However, competition for growth resources such as light, water and nutrients (e.g. Beer et al. 1998) can be serious drawbacks for coffee plantations. For example light limitation led to less floral initiation and lower yields under optimal growing conditions

(Beer et al. 1998; Campanha et al. 2004). In contrast, Defrenet et al. (2016) showed a high competitiveness of coffee roots in the top soil and no negative effect through tree root competition. This leads to our second hypothesis that coffee productivity will be greater under legume trees compared to non-legume timber trees or full sun under low-input conditions but not at high inputs.

In contrast to yield, vegetative growth can be similar or even higher under shade (Morais et al. 2003; Vaast et al. 2005), which demonstrates different responses of vegetative and reproductive coffee development to shade. The complex interaction between the tree and coffee component and management practices on the ecophysiology of coffee has been attempted to be explained through the number of nodes and lateral growth (Campanha et al. 2004), height and diameter development (Morais et al. 2003; Coltri et al. 2015) and their relationships to coffee yield (Carvalho et al. 2010), however, these studies were carried out over short time periods. Coffee crop-models were designed to estimate yield, as a function of system structure, microclimate and management and require long-term field data for verification (van Oijen et al. 2010; Rodríguez et al. 2011). However, yield is a labour intensive and costly variable to assess, long-term observations are scarce and alternatives are required. Our third hypothesis is that coffee yield and coffee morphology may change along time with the development of the shade trees: hence extensive long-term data on coffee yield, coffee morphological characteristics, their relationships, as well as proxies for yield would be extremely useful and are currently lacking.

In the search for more ecologically and economically sustainable coffee production, the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) and local partners in Costa Rica established a long-term coffee experiment in 2000 using both conventional and organic managements of different intensities in plantations under full sun and under the shade of timber and service tree species with contrasting characteristics (e.g. legume vs non-legume). The aim was to determine what levels of shade and which species characteristics were beneficial for different types and levels of agronomic inputs.

Therefore, in the present study we review current field data from the trial at CATIE and aim to 1) explain the impact of shade and management treatments on coffee yield and coffee plant morphology up to 15 years after planting and to 2) explain the interaction between reproductive and vegetative coffee components using relationships between yield, morphological characteristics, pruning and shade cover. In addition, we aim to develop general recommendations for coffee agroecosystems that sustain yields over time whilst reducing external impacts as far as practically possible.

2 Materials and methods

2.1 Experimental design

The experiment was established in 2000 at CATIE (Tropical Agricultural Research and Higher Education Center), Turrialba, Costa Rica (9°53’44’’ N, 83°40’7’’ W, CATIE, Turrialba, Costa Rica), which is defined as a low altitude (600 m.a.s.l), wet coffee zone without a marked dry season. Average annual rainfall, temperature, relative humidity and solar radiation were 2,915 mm yr^{-1}, 22°C, 90.2 % and 15.9 MJ m^{-2} d^{-1} (2000-2013, metrological station of CATIE, Turrialba, Costa Rica).

Twenty systems with different “shade types” and “managements” consisting of an incomplete randomized block-design with shade type as main effect and subplots represented by management were set up (Table 1). For each system, three replicates were established. Shade type (initially 417 trees per ha^{-1} (6m x 4m spacing)) consisted of timber and service tree species with contrasting characteristics (Table 2). Trees were progressively thinned to maintain a reasonable shade environment for coffee production (Table 3).

Table 1 Agroforestry systems with main plot (shade type) and subplot (management) treatments.

Shade types *	1	2	3	4	5	6	7
	E	T	C	C+T	E+T	C+E	Full Sun
Managements **	IC	IC				IC	IC
	MC	MC	MC	MC	MC	MC	MC
	IO	IO	IO	IO	IO	IO	
	LO	LO				LO	

* *E: Erythrina poepiggiana, C: Chloroleucon eurycyclum, T: Terminalia amazonia;* ** *IC: Intensive conventional, MC: Moderate conventional, IO: Intensive organic, LO: Low organic; (n=3)*

Table 2 Characteristics of shade trees, adapted from Haggar et al. (2011).

Species	Phenology	Canopy	N-fixer	Use
Erythrina poepiggiana (E)	Evergreen	Low compact	Yes	Service
Chloroleucon eurycyclum (C)	Deciduous *	High spreading	Yes	Timber
Terminalia amazonia (T)	Deciduous *	High compact	No	Timber

* *deciduous for about 20-30 days per year*

Table 3 Mean shade tree density after thinning.

Agroforestry system		Tree density per ha^{-1}		
System	Tree species	2008	2011	2013
Monocultures				
E	E	360	285	241
C	C	381	154	65
T	T	317	167	73
Polycultures				
C+E	C	183	100	45
	E	181	134	115
C+T	C	166	77	39
	T	170	77	34
E+T	E	147	143	109
	T	158	81	34

Intensive conventional (IC) *Erythrina* trees were biannually pollarded to a 1.8-2.0 m main trunk. Whilst this is normal practice in Costa Rica, Muschler (2001) found that coffee quality benefited from increased

Erythrina shade levels, therefore, for all the other treatments with *Erythrina*, trees were pollarded to 4 m leaving three branches for partial shade. Temporary shade was planted in form of *Ricinus* in organic treatments, a year after the coffee plants, to improve coffee plant survival and impede weed growth. Lower branches of the timber trees were pruned annually (year 1-7) to improve stem quality. In all pruning scenarios, pruning residuals from coffee trees and shade trees were left on the ground (trunks were removed). Management consisted of fertilization, weed, disease and pest control, detailed in Table 4.

Table 4 Mean input levels of fertilizers, weed, disease/pest control since 2006, adapted from Haggar et al. (2011); Noponen et al. (2012).

Management	Fertilization N:P:K **	Weed control	Disease/Pest control
IC	287:20:150	6* Herbicides	3-4* Fungicides/ Insecticides
MC	150:10:75	5 Herbicides	1-4 Fungicides/ Insecticides as required
IO	248:205:326	4 Manual	Organic substances as required
LO	66:2:44	4 Manual	No

* *Number of treatments applied per year*.

** *Fertilization levels (kg ha^{-1} yr^{-1}) are 7 year means (2003-2009), from the second to forth year LO systems received the same fertilization as IO ones, due to the site limitations that did not allow organic coffee to establish effectively with lower inputs. IO fertilisation: chicken manure 10 t ha^{-1} yr^{-1} and Kmag 100kg ha^{-1} yr^{-1}; LO fertilisation: Coffee pulp 5 t ha^{-} yr^{-1}*

Coffea Arabica L. var. Caturra, was planted at 5000 holes ha^{-1} with dead plants replaced each year. Two plants per planting hole were planted (local practice) but were treated as one plant in every analysis. The distance between rows and holes were 2 m and 1 m. Sub-plots were 500-600 m^2 of which the central 300-225 m^2 was studied (100 coffee plants and 24 shade trees). Coffee plants were manually pruned from 2004 leaving 1-4 resprouts per stump, according to the productive potential of each resprout. Every coffee planting hole thus comprised 1-2 stumps and a total of 1–4 resprouts per stump.

2.2 Coffee yield and pruning intensity

Annual coffee yield (2002-2014) was measured by weighing fresh coffee cherries harvested per plot. Bienniality (BI) of coffee yield, an index for the intensity of the difference between two successive years, was as per Cilas et al. (2011) with modifications.

$$BI = |y_2 - y_1| + |y_3 - y_2| + \ldots |y_n - y_{n-1}| / N$$

Where: y_i coffee yield (y) for year i; N Total number of years

In each treatment plot, the cumulative percentage of totally and partially (some resprouts only) pruned coffee resprouts was recorded annually (2004-2014).

2.3 Coffee morphology

Coffee resprout height (H) (from the soil surface to the top), diameter (D) and the total number of branches (TB) was measured (2002, 2014). In 2014, the number of productive branches (PB) (>60 % living tissue) was also measured. D was measured 5 cm above the intersection with the main stump or 10 cm above the ground if there was no pruning. Resprout variables (without stump and roots) were measured as they are the productive fraction of the coffee plant. Twenty-four coffee plants, equally spaced, were selected in each plot in 2002, while twenty-six coffee plants were measured in 2014. The highest resprouts were measured up to a maximum of 4 resprouts for each planting hole. The highest resprout was defined as the dominant one, the rest of resprouts were regarded as secondary ones. The variables of dominant and the average of secondary resprouts were recorded separately per plot and finally averaged to create one single morphological variable.

2.4 Shade cover

Absolute and average shade cover (%) over seven months per plot was estimated monthly (January 2014 – August 2014, without May) using a densiometer, following Lemmon (1956). Four measurement points equally spaced, were selected along with the East-West diagonal of each plot. Shade cover was recorded in each detecting point from four directions (North, South, West and East).

2.5 Statistical analysis

Data was analysed using mixed linear models (LMM) for a block-design with 3 repetitions, treatments as fixed effect and blocks as random effect. In case of repeated measurements, years and the interaction between treatments and years were incorporated as fixed effects. Heteroscedasticity was modelled through variance functions. The model presenting the lowest AIC was chosen in all analysis. The experimental design consisted of shade types as main plot and subplots represented by managements but with an unbalanced structure due to not all managements being represented under all shade types (Table 1). Therefore, specific pre-planned contrast models were used to test for shade type and management effects (Haggar et al. 2011), (Table 5).

Linear regression analysis was used to explore the relationships between coffee yield, yield bienniality, coffee pruning intensity (%), coffee morphology and shade cover (%). Data was compared at the end of the observations (2014) for regressions including morphological variables and/or shade cover (%). For variables with repeated measurements, values integrated over the whole time span (2002-2014) were used. For all linear regression analysis, mean values per treatment were used. Normality and homogeneity of variance were tested and, if necessary, data was log-transformed. INFOSTAT (Di Rienzo et al. 2011) was used for statistical analysis with a significance level of α =0.05.

Table 5 Principal contrasts used in the analysis of shade type and management effects.

Contrast	Treatments compared
Management	
IC vs. MC	IC(FS, E, T, CE) vs. MC(FS, E, T, CE)
MC vs. IO	MC(E, T, C, CE, CT, ET) vs. IO(E, T, C, CE, CT, ET)
IO vs. LO	IO(E, CE) vs. LO(E, CE)
IC vs. IO	IC(E, T, CE) vs. IO(E, T, CE)
Shade type	
Full sun vs. shaded	FS(IC, MC) vs. E(IC, MC) + T(IC, MC) + CE(IC,MC)
Erythrina vs. full sun*	E(IC, MC) vs. FS(IC, MC)
Service vs. timber	E(MC, IO) vs. T(MC, IO) + C(MC, IO) + TC(MC, IO)
Legume timber vs. non-legume timber	C(MC, IO) vs. T(MC, IO)

* *Erythrina was regarded as a low canopy tree with low shade cover and compared with full sun (FS).*

3 Results

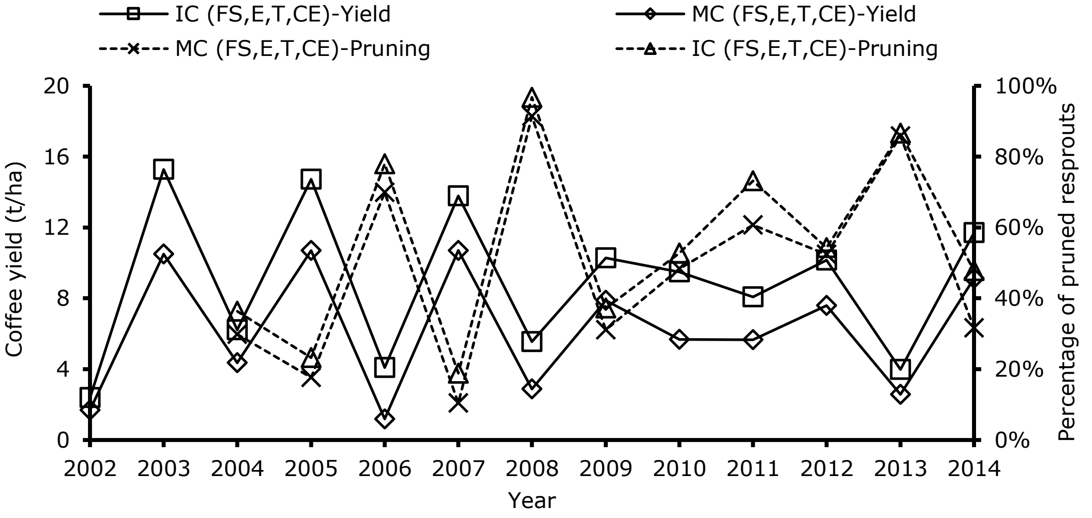
3.1 Coffee yield and pruning intensity

Coffee yield and coffee pruning intensity were significantly different between treatments (p<0.0001) and between years (p<0.0001). Integrated mean coffee yield was significantly higher under IC than under MC or IO managements, with 30 % and 31 % lower yields, respectively (Table 6). No significant difference could be found between MC and IO treatments (mean yield 5.3 and 5.0 t/ha/year) (Table 6). The integrated mean pruning (%) of coffee plants was significantly higher under IC compared to MC while the difference between IC and IO was not significant (Table 6). Mean coffee yield of LO management was not significantly different from IO, under the shade of the legume tree species *Erythrina* (E) and *Chloroleucon* (C) (Table 6). The yield of LO under the timber species *Terminalia* (TLO) began to fail in 2008 and collapsed totally in 2010 (Fig. 1 (c)).

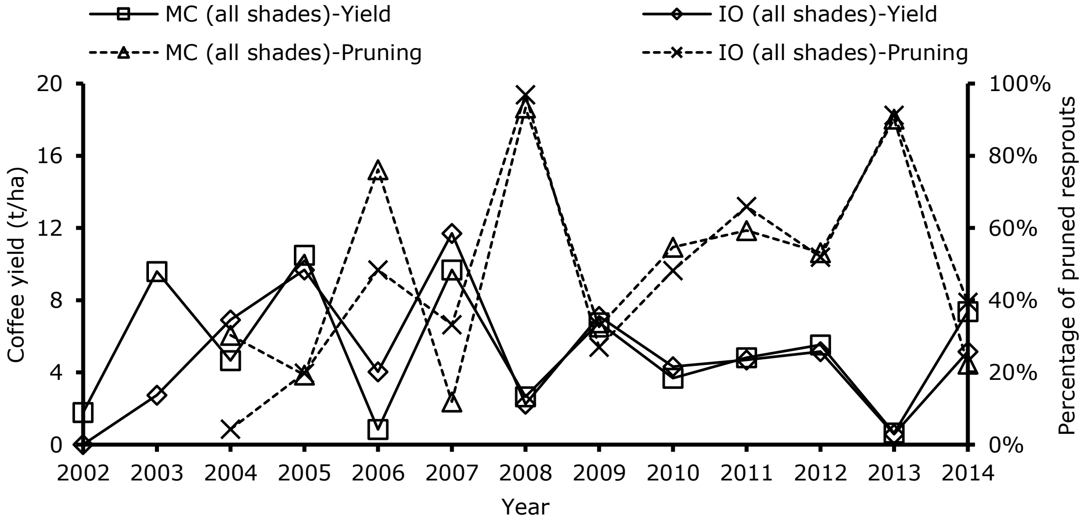
Table 6 Contrast results for the variables integrated coffee yield (t ha^{-1} year^{-1}), bienniality index (BI) of coffee yield, integrated pruning (%) and shade cover (%). Values are presented as mean, standard error of the contrast difference (S.E.$_{D}$) and significance of the difference (p-value). P-values < 0.05 are printed in bold.

Contrast	**Coffee yield**			**BI yield**			**Pruning**			**Shade cover**		
Managements	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value
IC vs MC	8.9 6.2	0.6	< **0.0001**	7.2 6.0	0.5	**0.0240**	55.0 48.1	2.4	**0.0035**	37.2 40.4	2.7	0.2417
MC vs IO	5.3 5.0	0.3	0.3372	5.7 4.6	0.4	**0.0101**	49.4 47.9	1.9	0.4589	45.9 46.1	1.9	0.9074
IO vs LO	5.8 4.8	0.6	0.1048	4.8 3.8	0.7	0.1720	49.1 44.8	3.2	0.1831	32.6 33.7	3.3	0.7422
IC vs IO	8.1 5.6	0.6	**0.0002**	6.8 5.1	0.6	**0.0051**	55.2 49.8	2.8	0.0600	37.2 38.8	2.7	0.5731
Shade types												
Full sun vs shade	10.4 6.6	0.9	< **0.0001**	8.0 6.1	0.6	**0.0022**	53.2 51.0	2.8	0.4796	- -	-	-
Erythrina vs full sun	8.0 10.4	1.0	**0.0203**	6.2 8.0	0.7	**0.0165**	50.1 53.2	3.4	0.3994	- -	-	-
Service vs timber	6.5 4.8	0.5	**0.0012**	5.3 5.3	0.6	0.9992	47.3 49.8	2.7	0.3703	18.4 56.0	2.7	< **0.0001**
Legume timber vs non-legume timber	4.9 5.0	0.6	0.8888	4.8 5.9	0.7	0.1491	51.0 50.8	3.4	0.9953	63.1 51.7	3.3	**0.0014**

Conventional (IC, MC) and organic treatments (IO, LO) reached their close to maximum productivity in 2003 and 2005, respectively (Fig. 1). A biennial bearing pattern could be observed for all managements in some years, but fluctuations were stronger for conventional ones. Bienniality index (BI) was significantly higher under IC than under MC and IO treatments, with BI being also significantly higher under MC than IO (Table 6). While conventional management showed a clear biennial yield pattern in the first 8 years of production, organic coffee yield rose steadily in the first 4 years until entering a biennial phase (Fig. 1). From 2009 to 2012 all treatments entered a more stable phase with medium yields. Yield bienniality led to higher yields in the conventionally managed treatments in years of high yields but in years of low yields similar or even higher yields could be observed in the organically treated ones (Fig. 1 (b) and (d)).



(a)



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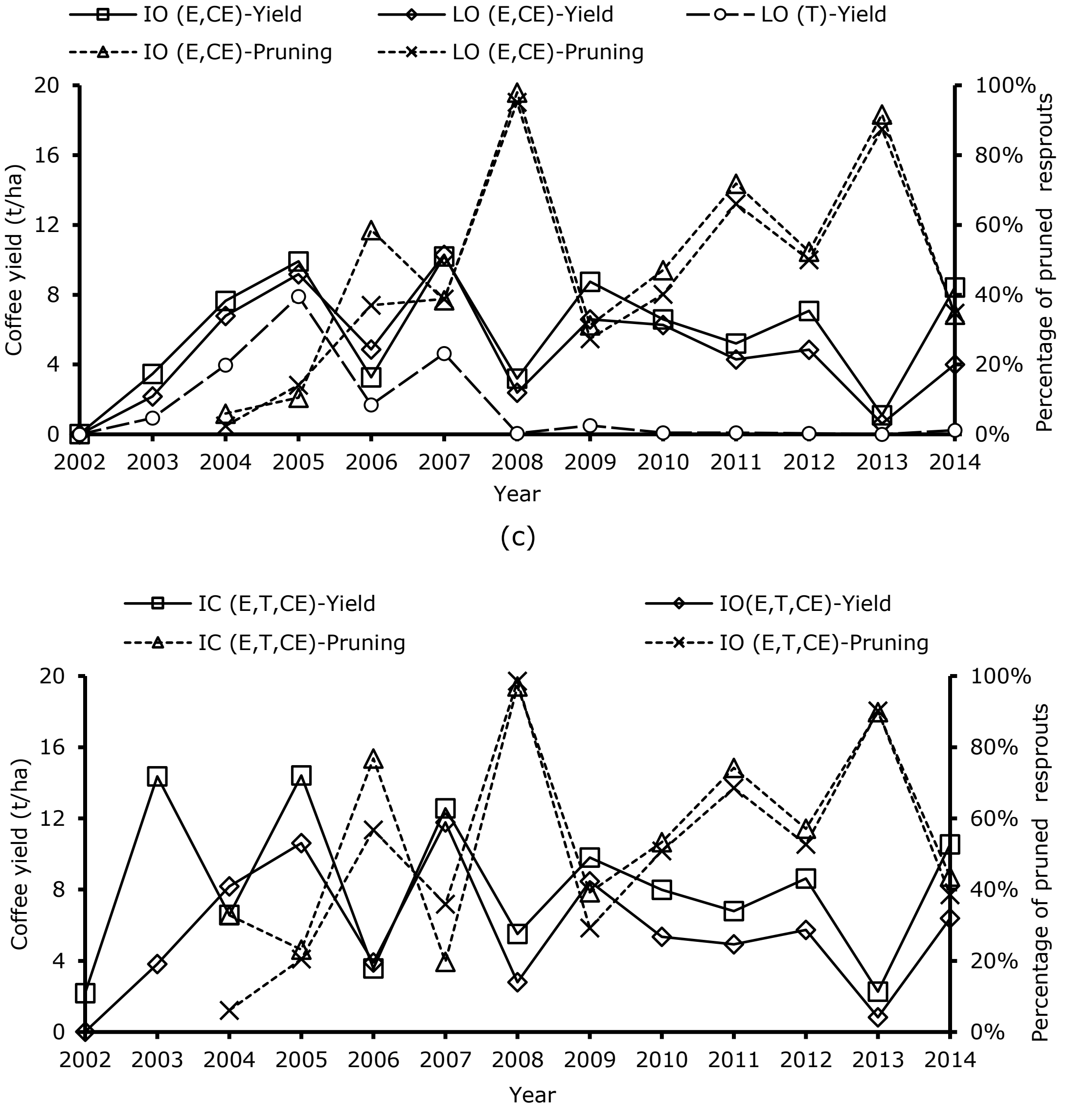


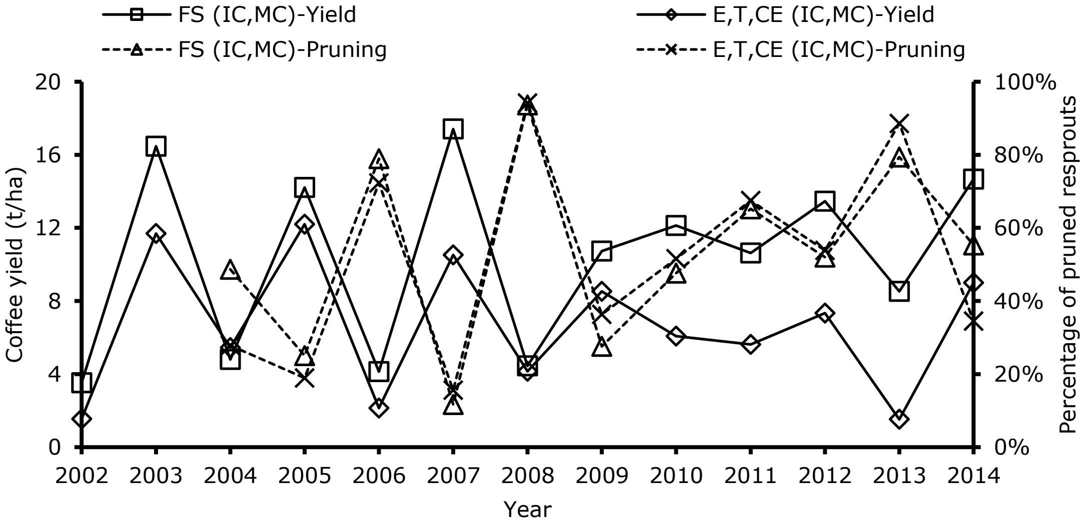
(c)

(d)

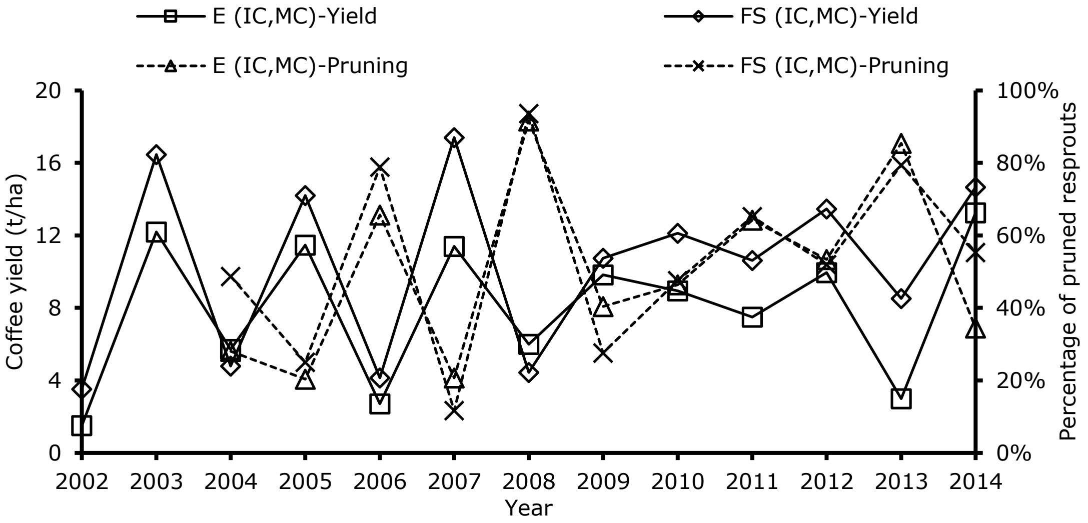
Fig. 1 Mean coffee yield and mean pruning intensity (%) of coffee resprouts per year under different managements and same shade types. A detailed contrast description can be found in Table 5.

When the different shade types were contrasted under the same managements (Table 5), integrated mean coffee yield (over 13 years) was significantly higher under full sun than in the shaded systems, with 37 % lower yields under shade (Table 6). Furthermore, coffee under the shade of the service tree species *Erythrina* had a significantly higher yield than under the timber species *Chloroleucon* and *Terminalia* (26 % lower yield), while still presenting a 23 % significantly lower coffee yield than full sun coffee (Table 6). The integrated mean pruning (%) of coffee plants did not differ significantly between the full sun and shaded systems and there was no significant difference for any other shade tree combination (Table 6).

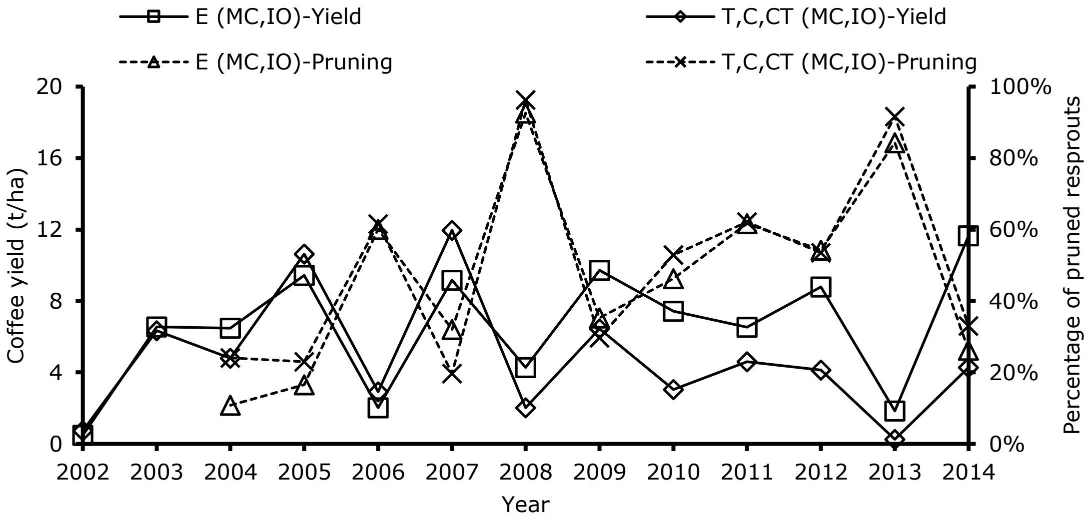
Shade and full sun coffee began producing high yields in the same years (2002 and 2003) i.e. shade type did not affect the onset of production (Fig. 2). Yield fluctuations were larger for full sun coffee when compared to shaded systems (Fig. 2 (a) and (b)). In accordance, BI was significantly higher for full sun than shade, whereas no significant differences could be detected for BI in between the different shade systems (Table 6). Full sun coffee out yielded shade coffee in years of high yields in the biennial phase (2002-2009) and in the stable yield phase (2009-2012), while in years of low yields (biennial phase), performance of shaded coffee was similar (Fig. 2 (a) and (b)). Furthermore, shade systems with the high canopy timber trees (*Chloroleucon* and *Terminalia*) showed a similar or even higher yield than systems with the low canopy service tree species *Erythrina* until 2007 but from 2008 onwards systems with *Erythrina* appeared to outperform these high canopy systems (Fig. 2 (c)).



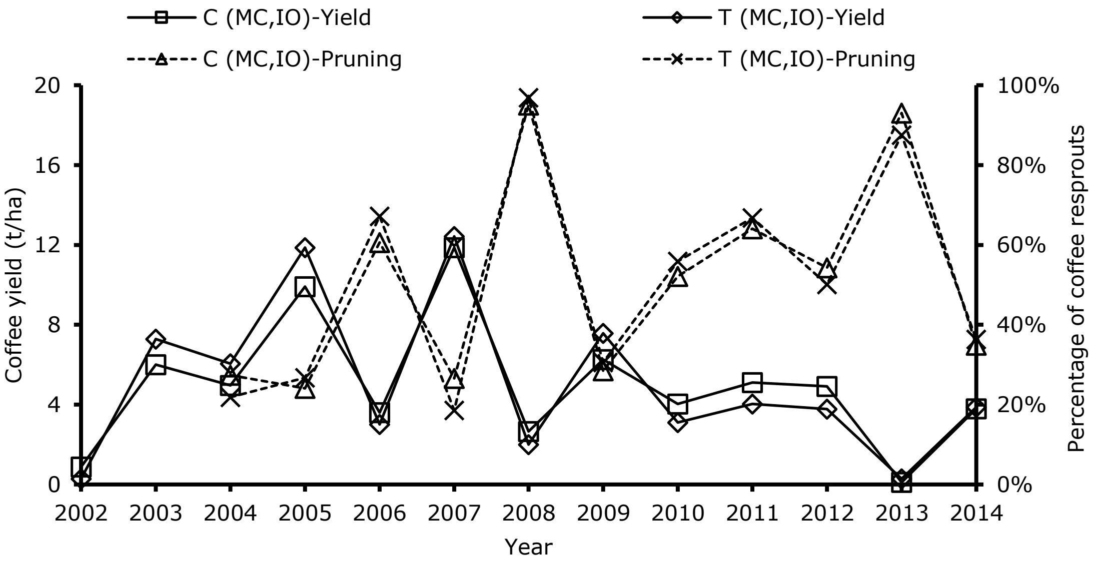
(a)


E (IC,MC)-Yield
FS (IC,MC)-Yield
E (IC,MC)-Pruning
FS (IC,MC)-Pruning
Coffee yield (t/ha)
0
4
8
12
16
20
Percentage of pruned resprouts
0%
20%
40%
60%
80%
100%
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

(b)


E (MC,IO)-Yield
T,C,CT (MC,IO)-Yield
E (MC,IO)-Pruning
T,C,CT (MC,IO)-Pruning
Coffee yield (t/ha)
0
4
8
12
16
20
Percentage of pruned resprouts
0%
20%
40%
60%
80%
100%
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

(c)


C (MC,IO)-Yield
T (MC,IO)-Yield
C (MC,IO)-Pruning
T (MC,IO)-Pruning
Coffee yield (t/ha)
0
4
8
12
16
20
Percentage of coffee resprouts
0%
20%
40%
60%
80%
100%
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

(d)

Fig. 2 Mean coffee yield and mean pruning intensity (%) of coffee resprouts per year under different shade types and same managements. A detailed contrast description can be found in Table 5.

Years of high coffee yields were always followed by high pruning intensities in the subsequent year, especially in the period until 2009 (Fig. 1 and 2). All treatments experienced three drastic falls in coffee yield (2006, 2008, 2013), especially in 2013 (coffee rust outbreak), that were preceded by very high pruning percentages in the same year (in February-March) (Fig. 1 and 2). These falls and the following recovery (2007, 2009, and 2014) were observed in all management and shade systems.

3.2 Coffee morphology

Height (H), diameter (D), total branches (TB) and productive branches (PB) differed significantly ($p<0.0001$) between shade and management treatments. Treatment differences depended on the observed year (2002 or 2014) as shown by the significant interaction of treatment and year for H ($p=0.0028$), D ($p=0.0001$) and TB ($p=0.0002$). The contrast results for coffee morphology (2002 and 2014) are shown in Table 7, TLO was excluded as a failed system as most plants were dead in 2014.

The only morphological variable in 2002 with significantly higher values under IC compared to MC was coffee resprout diameter (D), while in 2014 all 4 variables (H, D, TB, PB) had significantly higher mean values under IC than under MC (Table 7). Moreover, IC treatments led to coffee resprouts with significantly higher mean values for all 4 variables (H, D, TB, PB) compared to IO treatments in 2002 and 2014 (Table 7). While in 2002 H, D and TB had significantly higher mean values under MC than IO, no significant difference remained in 2014 (Table 7). In contrast no significant differences existed between both IO and LO in 2002, while all four variables (H, D, TB, PB) were higher under IO than LO in 2014 (Table 7).

Table 7 Contrast results for coffee morphology: The variables height (cm), diameter (cm), N° total branches and N° productive branches for 2002 and 2014. Values are presented as mean, standard error of the contrast difference (S.E.$_{D}$) and significance of the difference (p-value). P-values < 0.05 are shown in bold.

Contrast	**Height 2002**			**Height 2014**			**Diameter 2002**			**Diameter 2014**			**Total branches 2002**			**Total branches 2014**			**Prod. branches 2014**		
Managements	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value	Mean	S.E.$_{D}$	p-value
IC vs MC	103.7 97.4	4.2	0.1318	184.3 167.7	4.2	**0.0002**	23.5 20.7	1.3	**0.0296**	22.5 20.6	0.8	**0.0156**	40.1 32.7	4.1	**0.0696**	44.7 39.4	1.4	**0.0002**	42.4 37.0	1.1	< **0.0001**
MC vs IO	96.4 75.1	3.4	< **0.0001**	164.5 163.2	3.4	0.7136	20.1 13.7	1.0	< **0.0001**	20.3 19.9	0.6	0.4636	29.9 12.7	2.6	< **0.0001**	38.1 35.8	1.2	0.0550	35.7 32.9	1.3	**0.0307**
IO vs LO	79.8 73.8	5.9	0.3093	176.8 155.5	5.9	**0.0006**	15.2 13.7	1.8	0.3966	21.3 18.0	1.1	**0.0026**	16.4 14.5	3.9	0.6534	39.2 33.1	2.1	**0.0045**	36.9 28.4	2.6	**0.0021**
IC vs IO	102.3 77.7	4.8	< **0.0001**	183.4 165.6	4.8	**0.0004**	22.9 14.7	1.5	< **0.0001**	22.5 20.1	0.9	**0.0081**	37.1 14.8	4.0	< **0.0001**	44.8 36.8	1.6	< **0.0001**	42.3 33.5	1.6	< **0.0001**
Shade types																					
Full sun vs shade	106.7 98.5	4.8	0.0924	180.1 174.7	4.8	0.2626	24.5 21.2	1.5	**0.0285**	21.1 21.7	0.9	0.5028	47.2 32.9	5.4	**0.0098**	42.8 41.8	1.6	0.5291	41.1 39.3	1.2	0.1426
Erythrina vs full sun	103.3 106.7	5.9	0.5582	182.8 180.1	5.9	0.6510	21.2 24.5	1.8	0.0667	22.6 21.1	1.1	0.1589	35.6 47.2	6.3	0.0752	45.9 42.8	1.9	0.1065	43.7 41.1	1.3	**0.0489**
Service vs timber	92.1 84.3	4.8	0.1138	184.3 154.0	4.8	< **0.0001**	18.9 16.3	1.5	0.0874	22.7 19.2	0.9	**0.0002**	26.6 19.4	3.9	0.0724	43.4 34.2	1.6	< **0.0001**	41.2 31.2	1.4	< **0.0001**
Legume timber vs non-legume timber	85.1 82.8	5.9	0.6950	155.9 148.2	5.9	0.2035	16.9 16.3	1.8	0.7562	18.6 18.7	1.1	0.8728	20.2 18.7	4.3	0.7313	33.7 33.9	2.1	0.8976	31.0 29.5	2.7	0.5800

When the different shade types were contrasted under the same management (Table 5), no significant difference could be found for H, D, TB and PB between full sun and shade in 2014 (Table 7). Under the service tree species *Erythrina* coffee resprouts had significantly higher mean values for H, D, TB and PB compared to the timber tree systems in 2014 but not in 2012. No significant difference existed in both years between systems under the shade of legume timber (*Chloroleucon*) and non-legume timber trees (*Terminalia*).

3.3 Shade cover

Shade cover (%) in 2014 differed significantly ($p<0.0001$) between the different agroforestry systems (Fig. 3). When the different managements were contrasted for the same shade types (Table 5) no significant difference was found while significant differences in shade cover existed between the shade tree species (Table 6). The service tree species *Erythrina* had a lower shade cover than the timber tree species (*Chloroleucon* and *Terminalia*) and their combinations (18.4 vs 56.0 %) (Table 6).

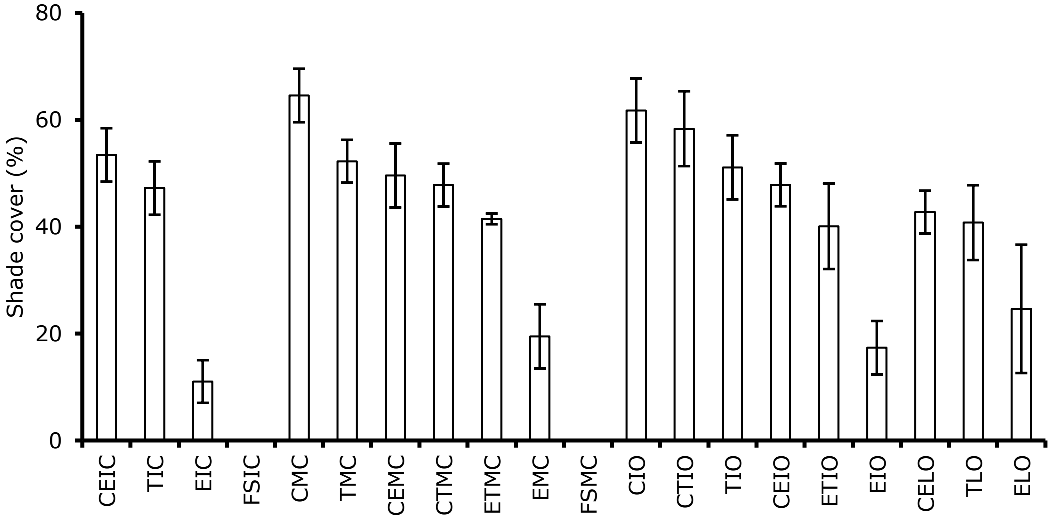


Fig. 3 Shade cover (% mean ± SD) under the different agroforestry systems in 2014.

Moreover, shade cover was significantly higher under *Chloroleucon* than under *Terminalia* (51.7 vs. 63.1 %) (Table 6). In general, shade cover in mixed species systems that incorporated *Erythrina* was always lower than in the corresponding timber tree monocultures (Fig. 3).

3.4 Relationships between coffee yield, morphological characteristics, shade cover and pruning

Mean shade cover (2014) per treatment had a significant linear, negative influence on coffee yield and on the three morphological variables H, TB and PB (Table 8). Of these models, the one between coffee yield and shade cover had by far the best fit (R^2). H, TB, PB and to a lesser extent D showed a highly significant, positive linear relationship and good model fit with the log-transformed mean coffee yield per treatment in 2014 (Table 8). There were no significant relationships between the morphological variables and pruning intensity. Integrated coffee yield per treatment (2004–2014) showed a significant and positive linear relationship with the integrated pruning intensity (Table 8). Finally, both integrated pruning intensity and integrated coffee yield had highly significant positive linear relationships with the BI index (Table 8).

Table 8 Regression models for coffee yield (t/ha), yield bienniality (BI index), coffee morphological variables height (H) and diameter (D) in cm, N° total branches (TB), N° productive branches (PB), shade cover (%) and coffee plant pruning intensity (%). Models were calculated (1) at the end of the observations (2014) and (2) integrated over the time span of measurements. Models are shown as formula, number of observations (n), model fit (R^2) and significance of relationship (p-value). Bold p-values are significant.

Variables	**Model**	**n**	**R^2**	**p-value**
Relationships 2014				
Yield - Shade cover	y = 14.40 – 0.18 x	19	0.72	**<0.0001**
LN (Yield) - H	y = - 4.34 + 0.04 x	19	0.79	**<0.0001**
LN (Yield) - D	y = - 3.32 + 0.25 x	19	0.62	**<0.0001**
LN (Yield) - TB	y = -2.33 + 0.11 x	19	0.87	**<0.0001**

LN (Yield) - PB	y = - 1.69 + 0.10 x	19	0.89	**<0.0001**
H - Shade cover	y = 185.09 - 0.45 x	19	0.39	**0.0041**
D – Shade cover	y = 22.01 - 0.04 x	19	0.21	0.0492
TB – Shade cover	y = 44.85 -0.17 x	19	0.43	**0.0024**
PB – Shade cover	y = 42.49 - 0.18 x	19	0.39	**0.0041**
Integrated Relationships				
Pruning$_{2004\text{-}14}$ – Yield$_{2004\text{-}14}$	y = 0.43 + 0.01 x	19	0.31	**0.0135**
BI$_{2004\text{-}14}$ – Pruning$_{2004\text{-}14}$	y = - 4.65 + 20.10 x	19	0.58	**<0.0001**
BI$_{2002\text{-}14}$ – Yield$_{2002\text{-}14}$	y = 2.26 + 0.54 x	19	0.69	**<0.0001**

4 Discussion

4.1 Effects of management on yield. In what circumstances can organic compete with conventional?

A general perception in coffee agriculture is that organic managements produce lower yields than their conventional counterparts (Blackman and Naranjo 2012). In our experiment, intensive organic (IO) productivity (yield and morphology), despite receiving higher phosphorus (P) and potassium (K) inputs and only slightly lower total nitrogen (N) inputs, always remained below the intensive conventional (IC), however, it showed similarity to moderate conventional (MC) management that received half the amount of IC fertilizer. Thus, our first hypothesis is partially confirmed in that highly productive organic coffee can be achieved, although it is not as productive as high-input conventional.

The accumulative effect of (1) the slower release of plant available N from organic inputs (Seufert et al. 2012) (2) better availability of chemical fertilizers and (3) the positive correlation of coffee yield and N-fertilizer input reported on coffee farms in Costa Rica (Castro-Tanzi et al. 2012) are likely to be the main cause for the better performance of IC compared to MC and organic systems, although conventional managements do not always out-yield organic coffee. In a similar experiment in Nicaragua, Haggar et al. (2011) reported similar yields between IC and organic coffee systems, that received the same total amounts of N per ha whether in inorganic or organic form. The difference between these results may be due to the Nicaraguan site having previously been in coffee production, having higher organic matter, generally better soil conditions and overall lower productivity than the Costa Rican sites due to lower rainfall. Moreover, Lyngbæk et al. (2001) reported that even though organic coffee farms in general had 22% lower coffee yields, a group of organic farms showed similar or even higher yield than their conventional counterparts.

In our experiment, coffee productivity (yield and morphology) under MC was only better than IO in the first 2 years of production (4 years after establishment), caused by the already mentioned longer release period of organic fertilizers and the time needed for soil organic matter recovery after the previous management of the plots as sugar cane plantation (Haggar et al. 2011). Lower initial yields and increasing productivity over time in organic agriculture, 3 years after conversion onwards, are often reported phenomena (Seufert et al. 2012). Accordingly, IO systems had a similar productivity (yield and morphology) as their MC counterparts from year 3 onwards, leading to similar mean coffee yields for both systems in the 13 years of observation.

4.2 Compensation effects of legume trees

In organic systems with low nutrient inputs (LO) coffee yield was not significantly different from IO systems when combined with the legume species *Erythrina* and *Chloroleucon;* while LO systems under the shade of the non-legume species *Terminalia* collapsed totally. Indeed, in low input plantations legume trees, especially if they are pruned like *Erythrina*, may compensate the lower external inputs and harvest exports through N_2 fixation (Nygren et al. 2012) with inputs through N_2 fixation from *Erythrina* ranging from 70 to 90 kg N ha^{-1} yr^{-1} (Tully and Lawrence 2011). In plantations with non-legume tree species however N-availability was most likely too low to maintain coffee productivity over time, which would explain the collapse of the systems under the shade of *Terminalia*. These findings confirm our second hypothesis in that legume shade has positive effects on coffee productivity in low-input systems and that production under non-N-fixing timber trees such as *Terminalia* largely depends on the level of external fertilization. The less developed coffee morphology in LO systems compared with IO ones in 2014 (significantly lower H, D, TB, PB values), however, suggests that these systems can not totally compete with the more intensively fertilized and managed IO systems.

4.3 Comparing full sun and shaded treatments for yield and morphological variables

Mean coffee yield in the 13 years of observation was reduced by 23 - 37 % in agroforestry systems compared to full sun, while in contrary to coffee yield, morphological variables (H, D, TB and PB) were similar in 2014. Under optimal site conditions, lower yields under shade compared to full sun are an often reported phenomena due to the lower light availability and competition for the coffee component (e.g. Vaast et al. 2005; DaMatta 2004). Whereas, under sub-optimal conditions, shade is considered essential for a sustained coffee production due to it ameliorating adverse site conditions (e.g. temperature extremes) (Gomes et al. 2016; Lin 2007) leading to similar or even higher yields under shade (DaMatta 2004; Vaast et al. 2005). Optimal growing conditions for *Coffea arabica* lie in the range of 1200-1800 mm and 18-21 °C for annual rainfall and temperature, respectively (Alègre 1959). Turrialba in Costa Rica (2,915 mm/year and 22°C) can thus be considered as suboptimal due to a surplus in precipitation and slightly higher average temperature. As hypothesized, possible positive effects of shade trees did thus not compensate for yield losses due to lower light availability, even under adverse site conditions, if conventional management practices were used.

The lower light incidence in agroforestry systems depletes nodal and flower bud development (Beer et al. 1998; Campanha et al. 2004) and consequently coffee yield, while vegetative development (e.g. height, number of branches/leaves or biomass) of coffee plants is favoured leading to often similar or even superior vegetative performance under shade (e.g. Morais et al. 2003; Vaast et al. 2005). Other often cited possibilities for lower yields such as competition for water and nutrients (Beer et al. 1998) are unlikely given the abundant rainfall and the high fertilisation levels (IC, MC) used in our comparison.

The examined morphological traits (H, TB and PB) may be used, to some extent, as surrogates for coffee yield within shaded or full sun production systems due to their highly significant relationships with coffee yield of the same year. The trade-off between vegetative and reproductive development, however, makes them inappropriate in comparisons between plantations under full sun and shade. Similarly, Carvalho et al. (2010) reported a positive correlation between yield and several growth traits including coffee plant height, diameter, number of plagiotropic branches and nodes. Measuring one or two morphological variables (best H, TB, PB) should be sufficient due to their similar performance.

4.4 The changing performance of service and timber tree species

Mean 13-year coffee yield was significantly higher under the service tree species *Erythrina* compared to the timber tree species *Chloroleucon* and *Terminalia*. Coffee performance, however, clearly differed for the initial and late development stage of the plantation. We thus confirmed hypothesis three in the sense that long-term observations are crucial for assessing the performance of agroforestry systems. In the first 6 years of production similar or even higher coffee yields were observed under the shade of the timber tree species than under the service tree *Erythrina*. Haggar et al. (2011) who examined this period of the experiment, drew the conclusion that timber trees might be the more favourable option given the revenue of timber sales and found indications of higher competition from *Erythrina* (higher shade cover prior to pruning and higher basal area than timber trees) with the coffee plants. In later years (2008 onwards) this pattern, however, shifted to clearly higher yields and improved coffee morphology under *Erythrina*.

Erythrina was pruned (heavily or partially) every year while the timber trees got their lower branches pruned (first 7 years) and were thinned twice reducing their density to a third of the *Erythrina* trees. Nevertheless, the expanding growth of the timber tree crowns, while shade and competition remained regulated for *Erythrina*, steadily decreased light availability for the coffee crop. This led to far higher (56 vs 18 % in 2014) shade covers and consequently lower yields under the timber tree species than under *Erythrina* in later years. In contrast Haggar et al. (2011) reported shade covers after and prior to pruning of 36 – 77 % for *Erythrina* and 42 - 44 % for timber trees in 2006. Thus, thinning of the timber trees was insufficient or too late to maintain adequate shade levels of approximately 20 - 40 % (Vaast et al. 2005), while more severe pruning of *Erythrina* after 2008 promoted higher coffee productivity. This is not an isolated phenomena as Vaast et al. (2005) reported after a survey of 100 farms in Costa Rica that timber tree density was often too high for providing both, acceptable coffee yields and a diversified production through timber sales. Nonetheless, other factors too, like the higher biomass inputs and nutrient recycling through pruning and litter fall in *Erythrina* compared to timber tree treatments (Haggar et al. 2011), might have facilitated the better performance of these systems on the long-term.

4.5 Implications for coffee producers and ecosystem services

A crucial aspect for farmers, apart from overall yields, is the ability of the chosen system to provide a stable production. Even though providing the highest overall yields, plantations under full sun and IC management presented the highest yield bienniality especially in the first 8 years. Moreover, biennial production was positively correlated with pruning intensity; i.e. it should impact the overall labour cost. This stronger biennial production pattern under full sun conditions compared to shaded coffee has been commonly reported (e.g. DaMatta 2004; Vaast et al. 2006).

The most probable explanation is plant exhaustion. Sun-grown coffee produces high cherry loads at the cost of vegetative development which exhausts the reserves of the plants and results in a subsequent year of low yields used for the recovery of growth and nutrients (DaMatta 2004). The mechanism of exceptional high berry loads and resulting plant exhaustion is supported by the found significant positive relationship of (1) pruning intensity and coffee yield, (2) bienniality (BI) and yield and (3) bienniality (BI) and pruning intensity of coffee plants. The higher pruning intensity under IC and after years of high yields further supports this conclusion, as higher exhaustion and fluctuation reduces the life span of coffee plants (DaMatta 2004). Pruning intensity caused through plant exhaustion could be discarded as driver for the biennial yield pattern as it started markedly before the first pruning in 2004.

The high cost for external inputs in IC full-sun plantations cannot easily be reduced if coffee prices fall, as full-sun grown coffee can die if no fertilizers are applied (Haggar et al. 2011). This leads to higher vulnerability of coffee farmers to the always volatile international coffee market (Haggar et al. 2011; DaMatta 2004). Out of these concerns farmers already began to cut back on intensive external inputs during periods of high costs (Haggar et al. 2011) while findings from experimental farms support the belief that economically viable production can be maintained while applying moderate doses of fertilizers (Castro-Tanzi et al. 2012).

Environmental impacts of coffee production are crucial concerns for policy makers and farmers alike. In our experiment N-fertilization was found to be the main cause for greenhouse gas emissions, with less emissions at lower inputs and organic managements alike (Noponen et al. 2012), while greenhouse gas emissions in all agroforestry systems were found to be fully compensated by the carbon storage in above and below ground tree biomass (Noponen et al. 2013). Accordingly, the newly designed Costa Rican NAMA-café program (Nieters et al. 2015) recommends significant reductions in N-fertilizer inputs and holds the possibility of financial compensation for coffee production in agroforestry systems. Moreover, timber sales can constitute a significant income, for example 11 – 49 % of total revenues from different agroforestry systems in Nicaragua and Honduras (Sousa et al. 2016), and are additionally a saving in times of low prices and crop failures (Beer et al. 1998).

Finally, organic farming compared to conventional may reduce the costs for purchased inputs through substitution of chemical fertilizers (Blackman and Naranjo 2012) and results in better soil properties like higher soil organic matter content (Haggar et al. 2011). Nonetheless, generally lower yields of organic production (Seufert et al. 2012) are a main limitation to its adoption, due to a relatively small price premium of 10 - 20 % and associated certification costs (Blackman and Naranjo 2012). The fact that both organic systems were equally productive as MC ones, if legume tree species were used, therefore translates into a strong argument to support organic coffee production at least if the full chemical package (IC) is not affordable, poses too high a risk or is not desired by coffee producers.

5 Conclusions

Full sun plantations with intensive conventional (IC) management produced the highest overall coffee yields even under sub-optimal site conditions. However, this maximum productivity comes at the cost of a high total yield fluctuation through coffee plant exhaustion. For all producers for which these intensive plantations are not affordable and/or not desired, shaded organic coffee production offers an interesting and viable alternative. It allowed a similar productivity in terms of both yield and coffee morphology as moderate conventional (MC) management, while offering a price premium and the possibility to enter specialty markets. We observed lower coffee yields but similar coffee morphology (H, D, TB and PB) under shade in comparison to full sun. Under the same shade type, however, the measured coffee morphological variables, especially H, TB and PB, are possible surrogates for coffee yield due to their highly significant relationships. Coffee yield was higher under timber tree shade (*Chloroleucon* and *Terminalia*) in the first 6 years of production, while during the subsequent 7 years *Erythrina* shaded coffee was more productive. This highlights the importance of long-term observations. Finally, we could establish two specific recommendations for shaded systems: (1) Considerable yield reductions and less developed coffee morphology in the late development stage of the plantation resulted from the intense shading by the developed timber trees. More intense thinning of matured timber trees is thus crucial to maintain adequate shade levels for coffee production. (2) Coffee productivity in organic systems with low nutrient additions (LO) collapsed totally when non-legume timber trees were used. The incorporation of legume tree species, like *Erythrina* and *Chloroleucon* is thus compulsory to provide a sufficient N-supply in low input systems.

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Abbreviations

BI: Bienniality index; **C**: *Chloroleucon eurycyclum*; **D**: Coffee resprout diameter; **E**: *Erythrina poepiggiana*; **H**: Coffee resprout height; **IC**: Intensive conventional; **IO**: Intensive organic; **LO**: Low organic; **MC**: Moderate conventional; **N**: Nitrogen; **PB**: Productive branch number of coffee resprouts; **TB**: Total branch number of coffee resprouts, **T**: *Terminalia amazonia*

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Tables

Table 1 Agroforestry systems with main plot (shade type) and subplot (management) treatments.

Table 2 Characteristics of shade trees, adapted from Haggar et al. (2011).

Table 3 Mean shade tree density after thinning.

Table 4 Mean input levels of fertilizers, weed, disease/pest control since 2006, adapted from Noponen et al. (2012); Haggar et al. (2011).

Table 5 Principal contrasts used in the analysis of shade type and management effects.

Table 6 Contrast results for the variables integrated coffee yield (t ha^{-1} $year^{-1}$), bienniality index (BI) of coffee yield, integrated pruning (%) and shade cover (%). Values are presented as mean, standard error of the contrast difference ($S.E._D$) and significance of the difference (p-value). P-values < 0.05 are printed in bold.

Table 7 Contrast results for coffee morphology: The variables height (cm), diameter (cm), N° total branches and N° productive branches for 2002 and 2014. Values are presented as mean, standard error of the contrast difference (S.E.D) and significance of the difference (p-value). P-values < 0.05 are shown in bold.

Table 8 Regression models for coffee yield (t/ha), yield bienniality (BI index), coffee morphological variables height (H) and diameter (D) in cm, N° total branches (TB), N° productive branches (PB), shade cover (%) and coffee plant pruning intensity (%). Models were calculated (1) at the end of the observations (2014) and (2) integrated over the time span of measurements. Models are shown as formula, number of observations (n), model fit (R^2) and significance of relationship (p-value). Bold p-values are significant.

Table 1 Agroforestry systems with main plot (shade type) and subplot (management) treatments.

Shade types *	1	2	3	4	5	6	7
	E	T	C	C+T	E+T	C+E	Full Sun
Managements **	IC	IC				IC	IC
	MC	MC	MC	MC	MC	MC	MC
	IO	IO	IO	IO	IO	IO	
	LO	LO				LO	

* *E: Erythrina poepiggiana, C: Chloroleucon eurycyclum, T: Terminalia amazonia;* ** *IC: Intensive conventional, MC: Moderate conventional, IO: Intensive organic, LO: Low organic; (n=3)*

Table 2 Characteristics of shade trees, adapted from Haggar et al. (2011).

Species	Phenology	Canopy	N-fixer	Use
Erythrina poepiggiana (E)	Evergreen	Low compact	Yes	Service
Chloroleucon eurycyclum (C)	Deciduous *	High spreading	Yes	Timber
Terminalia amazonia (T)	Deciduous *	High compact	No	Timber

* *deciduous for about 20-30 days per year*

Table 3 Mean shade tree density after thinning.

Agroforestry system		Tree density per ha^{-1}		
System	Tree species	2008	2011	2013
Monocultures				
E	E	360	285	241
C	C	381	154	65
T	T	317	167	73
Polycultures				
C+E	C	183	100	45
	E	181	134	115
C+T	C	166	77	39
	T	170	77	34
E+T	E	147	143	109
	T	158	81	34

Table 4 Mean input levels of fertilizers, weed, disease/pest control since 2006, adapted from Haggar et al. (2011); Noponen et al. (2012).

Management	Fertilization N:P:K **	Weed control	Disease/Pest control
IC	287:20:150	6* Herbicides	3-4* Fungicides/ Insecticides
MC	150:10:75	5 Herbicides	1-4 Fungicides/ Insecticides as required
IO	248:205:326	4 Manual	Organic substances as required
LO	66:2:44	4 Manual	No

* *Number of treatments applied per year*.

** *Fertilization levels (kg ha*$^{-1}$ *yr*$^{-1}$*) are 7 year means (2003-2009), from the second to forth year LO systems received the same fertilization as IO ones, due to the site limitations that did not allow organic coffee to establish effectively with lower inputs. IO fertilisation: chicken manure 10 t ha*$^{-1}$ *yr*$^{-1}$ *and Kmag 100kg ha*$^{-1}$ *yr*$^{-1}$*; LO fertilisation: Coffee pulp 5 t ha*$^{-}$ *yr*$^{-1}$

Table 5 Principal contrasts used in the analysis of shade type and management effects.

Contrast	Treatments compared
Management	
IC vs. MC	IC(FS, E, T, CE) vs. MC(FS, E, T, CE)
MC vs. IO	MC(E, T, C, CE, CT, ET) vs. IO(E, T, C, CE, CT, ET)
IO vs. LO	IO(E, CE) vs. LO(E, CE)
IC vs. IO	IC(E, T, CE) vs. IO(E, T, CE)
Shade type	
Full sun vs. shaded	FS(IC, MC) vs. E(IC, MC) + T(IC, MC) + CE(IC,MC)
Erythrina vs. full sun*	E(IC, MC) vs. FS(IC, MC)
Service vs. timber	E(MC, IO) vs. T(MC, IO) + C(MC, IO) + TC(MC, IO)
Legume timber vs. non-legume timber	C(MC, IO) vs. T(MC, IO)

* *Erythrina was regarded as a low canopy tree with low shade cover and compared with full sun (FS).*

Table 7 Contrast results for the variables integrated coffee yield (t ha^{-1} $year^{-1}$), bienniality index (BI) of coffee yield, integrated pruning (%) and shade cover (%). Values are presented as mean, standard error of the contrast difference ($S.E._D$) and significance of the difference (p-value). P-values < 0.05 are printed in bold.

Contrast	**Coffee yield**			**BI yield**			**Pruning**			**Shade cover**		
Managements	Mean	$S.E._D$	p-value	Mean	$S.E._D$	p-value	Mean	$S.E._D$	p-value	Mean	$S.E._D$	p-value
IC vs MC	8.9 6.2	0.6	< **0.0001**	7.2 6.0	0.5	**0.0240**	55.0 48.1	2.4	**0.0035**	37.2 40.4	2.7	0.2417
MC vs IO	5.3 5.0	0.3	0.3372	5.7 4.6	0.4	**0.0101**	49.4 47.9	1.9	0.4589	45.9 46.1	1.9	0.9074
IO vs LO	5.8 4.8	0.6	0.1048	4.8 3.8	0.7	0.1720	49.1 44.8	3.2	0.1831	32.6 33.7	3.3	0.7422
IC vs IO	8.1 5.6	0.6	**0.0002**	6.8 5.1	0.6	**0.0051**	55.2 49.8	2.8	0.0600	37.2 38.8	2.7	0.5731
Shade types												
Full sun vs shade	10.4 6.6	0.9	< **0.0001**	8.0 6.1	0.6	**0.0022**	53.2 51.0	2.8	0.4796	- -	-	-
Erythrina vs full sun	8.0 10.4	1.0	**0.0203**	6.2 8.0	0.7	**0.0165**	50.1 53.2	3.4	0.3994	- -	-	-
Service vs timber	6.5 4.8	0.5	**0.0012**	5.3 5.3	0.6	0.9992	47.3 49.8	2.7	0.3703	18.4 56.0	2.7	< **0.0001**
Legume timber vs non-legume timber	4.9 5.0	0.6	0.8888	4.8 5.9	0.7	0.1491	51.0 50.8	3.4	0.9953	63.1 51.7	3.3	**0.0014**

Table 7 Contrast results for coffee morphology: The variables height (cm), diameter (cm), N° total branches and N° productive branches for 2002 and 2014. Values are presented as mean, standard error of the contrast difference (S.E.$_D$) and significance of the difference (p-value). P-values < 0.05 are shown in bold.

Contrast	**Height 2002**			**Height 2014**			**Diameter 2002**			**Diameter 2014**			**Total branches 2002**			**Total branches 2014**			**Prod. branches 2014**		
Managements	Mean	S.E.$_D$	p-value	Mean	S.E.$_D$	p-value	Mean	S.E.$_D$	p-value	Mean	S.E.$_D$	p-value	Mean	S.E.$_D$	p-value	Mean	S.E.$_D$	p-value	Mean	S.E.$_D$	p-value
IC vs MC	103.7 97.4	4.2	0.1318	184.3 167.7	4.2	**0.0002**	23.5 20.7	1.3	**0.0296**	22.5 20.6	0.8	**0.0156**	40.1 32.7	4.1	**0.0696**	44.7 39.4	1.4	**0.0002**	42.4 37.0	1.1	< **0.0001**
MC vs IO	96.4 75.1	3.4	< **0.0001**	164.5 163.2	3.4	0.7136	20.1 13.7	1.0	< **0.0001**	20.3 19.9	0.6	0.4636	29.9 12.7	2.6	< **0.0001**	38.1 35.8	1.2	0.0550	35.7 32.9	1.3	**0.0307**
IO vs LO	79.8 73.8	5.9	0.3093	176.8 155.5	5.9	**0.0006**	15.2 13.7	1.8	0.3966	21.3 18.0	1.1	**0.0026**	16.4 14.5	3.9	0.6534	39.2 33.1	2.1	**0.0045**	36.9 28.4	2.6	**0.0021**
IC vs IO	102.3 77.7	4.8	< **0.0001**	183.4 165.6	4.8	**0.0004**	22.9 14.7	1.5	< **0.0001**	22.5 20.1	0.9	**0.0081**	37.1 14.8	4.0	< **0.0001**	44.8 36.8	1.6	< **0.0001**	42.3 33.5	1.6	< **0.0001**
Shade types																					
Full sun vs shade	106.7 98.5	4.8	0.0924	180.1 174.7	4.8	0.2626	24.5 21.2	1.5	**0.0285**	21.1 21.7	0.9	0.5028	47.2 32.9	5.4	**0.0098**	42.8 41.8	1.6	0.5291	41.1 39.3	1.2	0.1426
Erythrina vs full sun	103.3 106.7	5.9	0.5582	182.8 180.1	5.9	0.6510	21.2 24.5	1.8	0.0667	22.6 21.1	1.1	0.1589	35.6 47.2	6.3	0.0752	45.9 42.8	1.9	0.1065	43.7 41.1	1.3	**0.0489**
Service vs timber	92.1 84.3	4.8	0.1138	184.3 154.0	4.8	< **0.0001**	18.9 16.3	1.5	0.0874	22.7 19.2	0.9	**0.0002**	26.6 19.4	3.9	0.0724	43.4 34.2	1.6	< **0.0001**	41.2 31.2	1.4	< **0.0001**
Legume timber vs non-legume timber	85.1 82.8	5.9	0.6950	155.9 148.2	5.9	0.2035	16.9 16.3	1.8	0.7562	18.6 18.7	1.1	0.8728	20.2 18.7	4.3	0.7313	33.7 33.9	2.1	0.8976	31.0 29.5	2.7	0.5800

Table 8 Regression models for coffee yield (t/ha), yield bienniality (BI index), coffee morphological variables height (H) and diameter (D) in cm, N° total branches (TB), N° productive branches (PB), shade cover (%) and coffee plant pruning intensity (%). Models were calculated (1) at the end of the observations (2014) and (2) integrated over the time span of measurements. Models are shown as formula, number of observations (n), model fit (R^2) and significance of relationship (p-value). Bold p-values are significant.

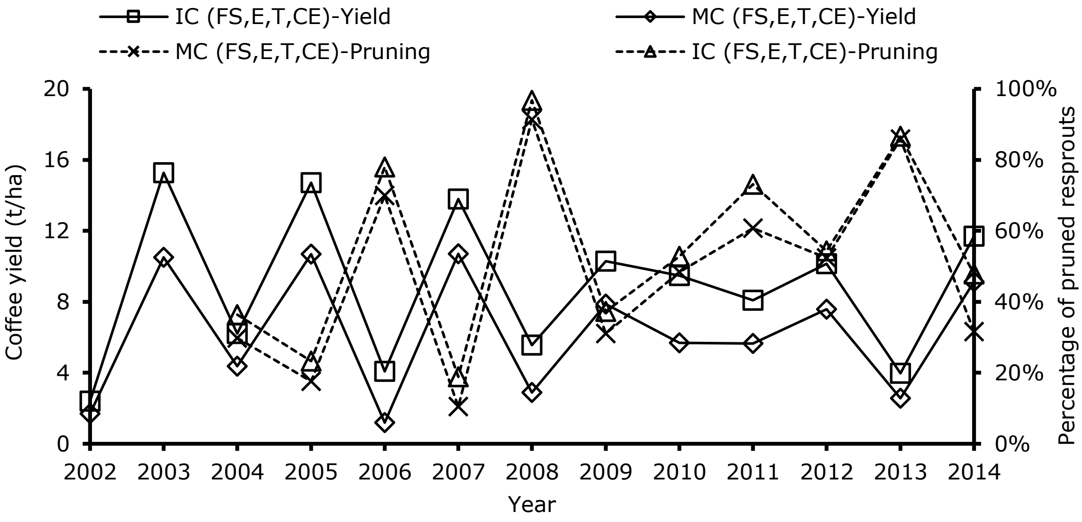
Variables	**Model**	**n**	**R^2**	**p-value**
Relationships 2014				
Yield - Shade cover	y = 14.40 – 0.18 x	19	0.72	**<0.0001**
LN (Yield) - H	y = - 4.34 + 0.04 x	19	0.79	**<0.0001**
LN (Yield) - D	y = - 3.32 + 0.25 x	19	0.62	**<0.0001**
LN (Yield) - TB	y = -2.33 + 0.11 x	19	0.87	**<0.0001**
LN (Yield) - PB	y = - 1.69 + 0.10 x	19	0.89	**<0.0001**
H - Shade cover	y = 185.09 - 0.45 x	19	0.39	**0.0041**
D – Shade cover	y = 22.01 - 0.04 x	19	0.21	0.0492
TB – Shade cover	y = 44.85 -0.17 x	19	0.43	**0.0024**
PB – Shade cover	y = 42.49 - 0.18 x	19	0.39	**0.0041**
Integrated Relationships				
Pruning$_{2004-14}$ – Yield$_{2004-14}$	y = 0.43 + 0.01 x	19	0.31	**0.0135**
BI$_{2004-14}$ – Pruning$_{2004-14}$	y = - 4.65 + 20.10 x	19	0.58	**<0.0001**
BI$_{2002-14}$ – Yield$_{2002-14}$	y = 2.26 + 0.54 x	19	0.69	**<0.0001**

Figures

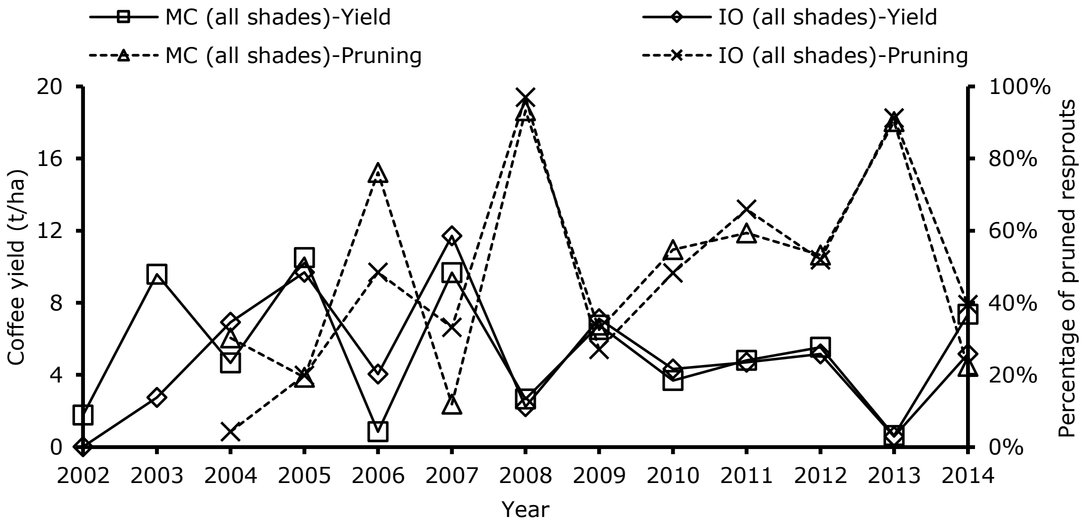
Fig. 1 Mean coffee yield and mean pruning intensity (%) of coffee resprouts per year under different managements and same shade types. A detailed contrast description can be found in Table 5.

Fig. 2 Mean coffee yield and mean pruning intensity (%) of coffee resprouts per year under different shade types and same managements. A detailed contrast description can be found in Table 5.

Fig. 3 Shade cover (% mean ± SD) under the different agroforestry systems in 2014.



(a)



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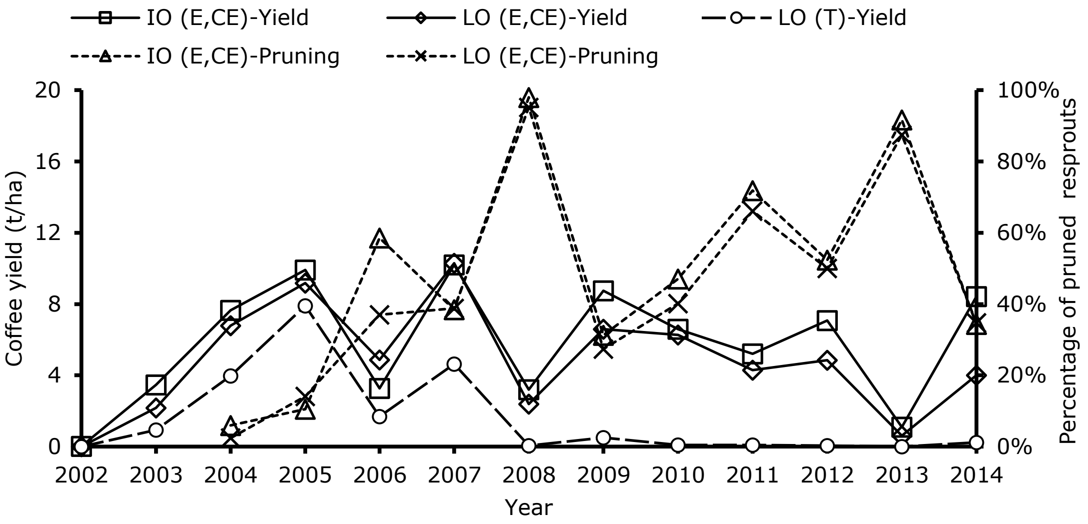

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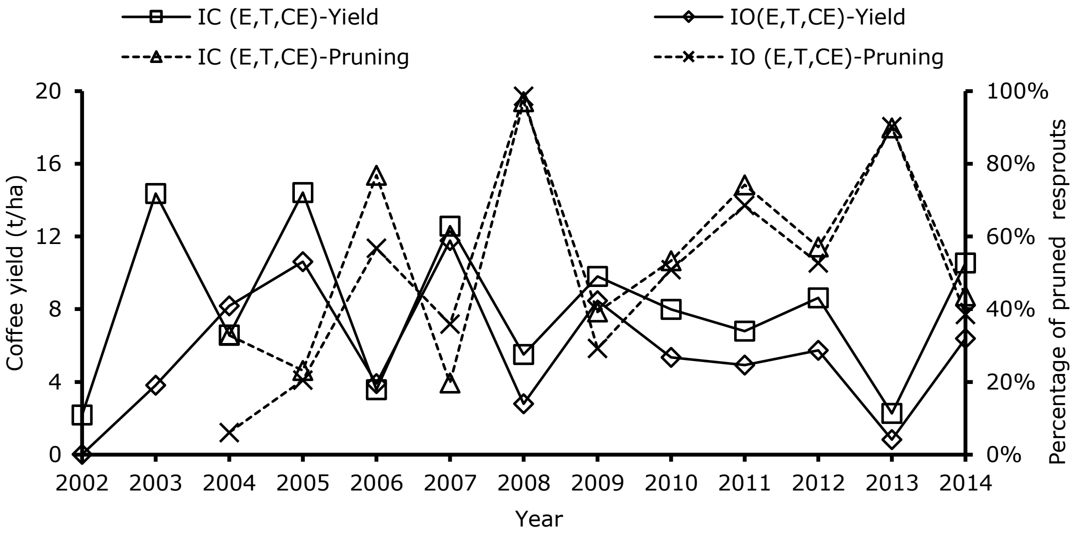
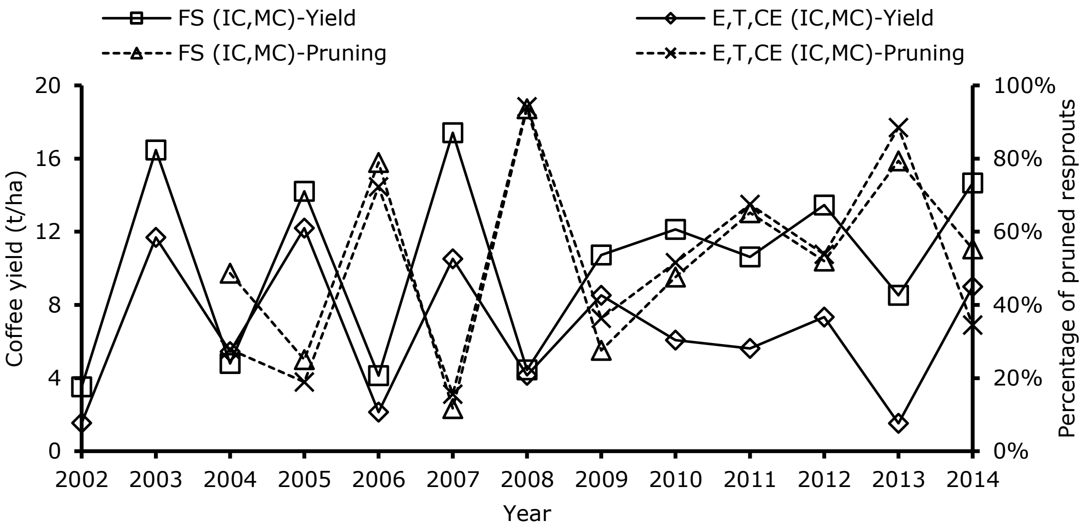
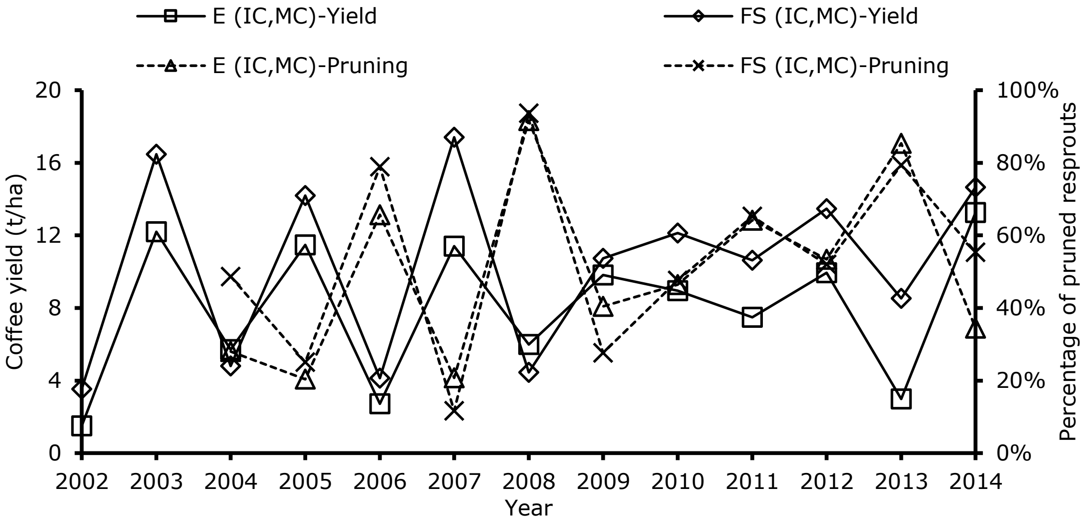


(d)

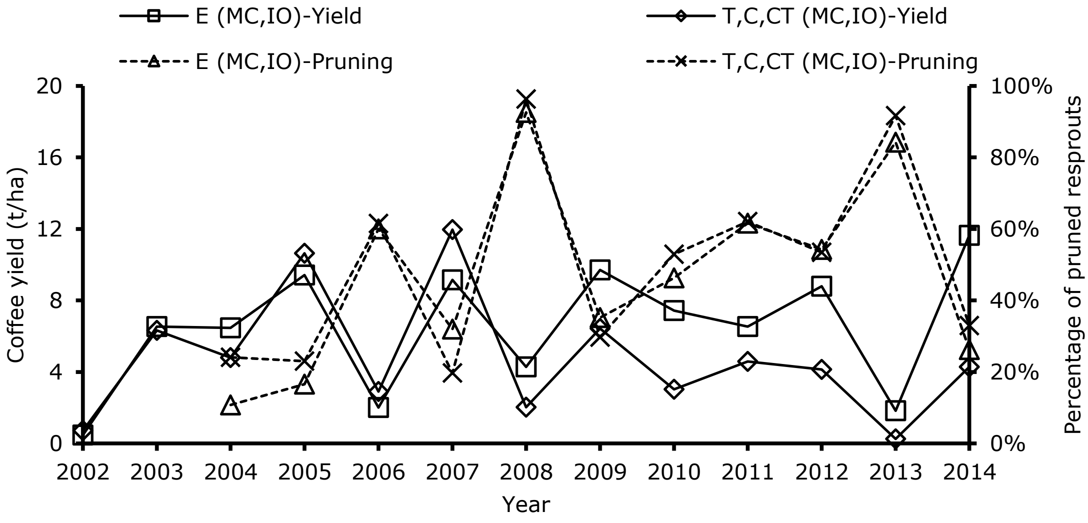
Fig. 1 Mean coffee yield and mean pruning intensity (%) of coffee resprouts per year under different managements and same shade types. A detailed contrast description can be found in Table 5.


FS (IC,MC)-Yield
E,T,CE (IC,MC)-Yield
FS (IC,MC)-Pruning
E,T,CE (IC,MC)-Pruning
Coffee yield (t/ha)
0
4
8
12
16
20
Percentage of pruned resprouts
0%
20%
40%
60%
80%
100%
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

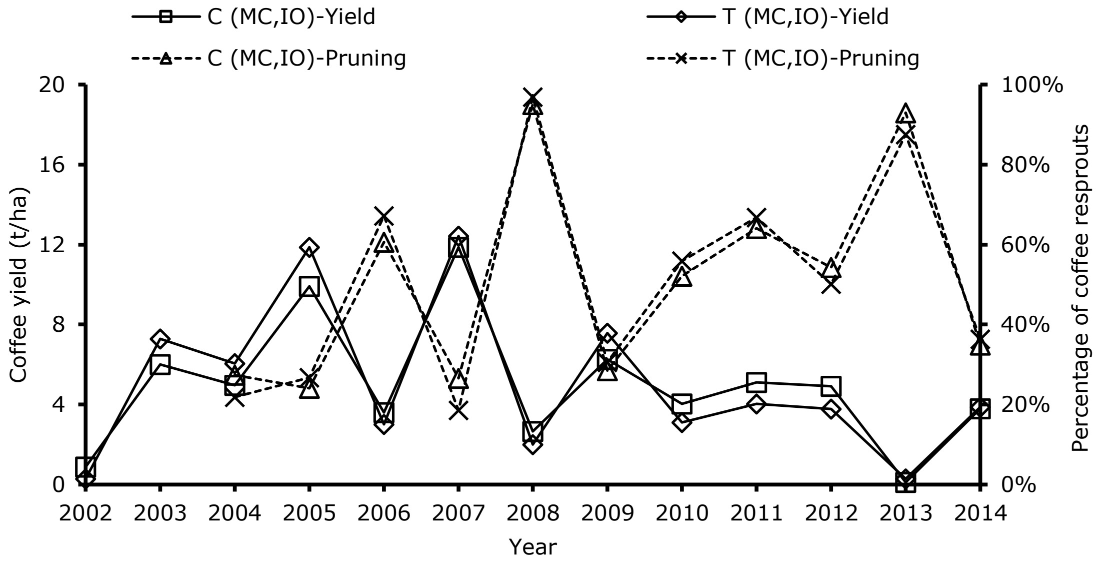
(a)


E (IC,MC)-Yield
FS (IC,MC)-Yield
E (IC,MC)-Pruning
FS (IC,MC)-Pruning
Coffee yield (t/ha)
0
4
8
12
16
20
Percentage of pruned resprouts
0%
20%
40%
60%
80%
100%
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

(b)


E (MC,IO)-Yield
T,C,CT (MC,IO)-Yield
E (MC,IO)-Pruning
T,C,CT (MC,IO)-Pruning
Coffee yield (t/ha)
0
4
8
12
16
20
Percentage of pruned resprouts
0%
20%
40%
60%
80%
100%
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

(c)



(d)

Fig. 2 Mean coffee yield and mean pruning intensity (%) of coffee resprouts per year under different shade types and same managements. A detailed contrast description can be found in Table 5.

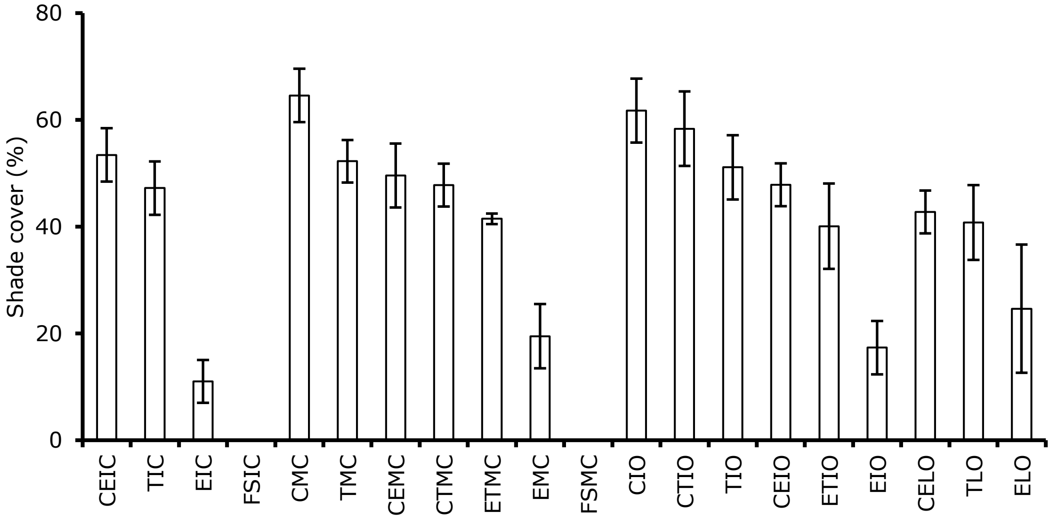


Fig. 3 Shade cover (% mean ± SD) under the different agroforestry systems in 2014.