Crop Protection 130 (2020) 105047

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Cacao agroforestry systems do not increase pest and disease incidence compared with monocultures under good cultural management practices

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ARTICLE INFO

Keywords:
Labour time
Long-term system comparison
Organic farming
Frosty pod rot
Phytosanitary inspection
Theobroma cacao
Yield
On-farm trial

ABSTRACT

Pests and diseases threaten cacao production worldwide. Agroforestry systems are traditionally seen by farmers as one of the causes of increased pest and disease incidence, in contrast with full-sun monocultures. Cultural management practices—e.g. regular tree pruning, frequent pod harvest, regular removal of infested pods, weed management—have been reported to be crucial for pest and disease management. We performed two experiments for the purpose of assessing the effect of (i) different cacao production systems, and (ii) the frequency of harvest and removal of infested pods on the incidence of pests and diseases and on the cacao yield. The first experiment was performed in a long-term system comparison trial in Bolivia, where data on pest and disease incidence were recorded for three years in five production systems: two monocultures and two agroforestry system under organic and conventional farming, and one successional agroforestry system, i.e. a high tree density multi-strata system. Pest and disease management did not differ between systems and relied on cultural management practices. Overall, the incidence of pests and diseases did not differ between production systems, which indicated they were not the driver of yield differences between them. Across production systems, only 14% of the pods were affected by pests and diseases; 70% of these were affected by frosty pod rot. More than 80% of the pods infected by frosty pod rot were removed before the sporulation phase. In the second experiment, the effects of the frequency of harvest and removal of infected pods—every 15 days versus every 25 days—on pest and disease incidence and yield were tested in four farmers' fields. Fortnightly harvest and diseased pod removal significantly decreased disease incidence and increased cacao yield, by 25% and 46% respectively. Our results show that cacao agroforestry systems do not increase pest and disease incidence compared with monocultures when good cultural management practices are implemented, which, in turn, can increase the productivity of the cacao plantations.

1. Introduction

Theobroma cacao L. is the tropical tree producing cacao beans, the raw material for the chocolate industry as well as for many other products derived from the beans. Cacao is mainly cultivated by smallholders in the tropical lowlands of Central and South America, West Africa, and South-East Asia (Franzen and Borgerhoff Mulder, 2007). Reliable productivity is therefore crucial for both the cacao industry and the livelihood of millions of cacao producers around the world. However, while global demand for cacao is increasing, cacao productivity is decreasing in many producing countries due to aging plantations, degraded soils, and pests and diseases, among other reasons (Blaser et al., 2018; Effendy et al., 2019). The most important fungal diseases, such as frosty pod rot (*Moniliophthora roreri*), black pod (*Phytophthora* spp) and witches' broom (*Cripinellis perniciosa*), cause annual yield losses of up to 40% (Ten Hoopen et al., 2012). Pests are also seriously limiting the cacao production, e.g. the cacao pod borer in Southern Asia (Day, 1989) and the swollen shoot virus in West Africa (Andres et al., 2017). In some cases, losses of up to 80–100% have been reported (Andres et al., 2017; Dorado Orea et al., 2017; Saripah and Alias, 2016; Soberanis et al., 1999). The lack of viable control methods have led to the abandonment of many cacao plantations (Krauss and Soberanis, 2001), a fact that worsens the situation by increasing the inoculum pressure on the surrounding fields.

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https://doi.org/10.1016/j.cropro.2019.105047
Received 30 September 2019; Received in revised form 29 November 2019; Accepted 7 December 2019
Available online 11 December 2019
0261-2194/

To minimise the impact of pests and diseases, different approaches have been implemented and tested: biocontrol (Ten Hoopen and Krauss, 2016), biotechnology (Mondego et al., 2016), improvement of disease resistance through breeding (Gutiérrez et al., 2016), precision engineering to improve the crop with CRISPR/Cas9 technology (Fister et al., 2018). However, the small size of the farms and the farmers' limited resources, particularly in access to labour, technology and financial capital, leave the producers vulnerable to the effects of environmental perturbations, mainly pests and diseases (Curry et al., 2015). In addition, most of the control methods developed are still quite unsatisfactory. For instance, most fungicides do not significantly improve yields or are not cost effective (Bateman et al., 2005) Biocontrol agents are sometimes reported to be effective only when other cultural management practices are applied (Ayala and Navia, 2008; Krauss and Soberanis, 2002; Krauss et al., 2003). Breeding programs (e.g. at CATIE in Costa Rica, at El Ceibo in Bolivia) have made significant progress towards developing cacao material that is resistant to various diseases (Phillips-Mora and Wilkinson, 2007). However, reducing the number of cacao varieties grown in the farms can change the flavour and aroma known and appreciated by the cacao industry (personal communication, Rapunzel Naturkost).

Farmers have only adopted cultural management practices, if any, as a way to manage pests and diseases. These practices include periodical removal of diseased pods, pruning of cacao and shade trees, maintenance of drainage systems, etc. (Soberanis et al., 1999). They are difficult and labour intensive, and farmers are usually discouraged and/or lack the labour force required to implement them, especially when cacao prices are low (Phillips-Mora and Wilkinson, 2007). However, cultural management practices have proved to be very efficient in reducing disease incidence (Soberanis et al., 1999), thus confirming the key role of management in preventing yield losses. On the other hand, recommendations on disease management are not well defined. In the case of frosty pod rot, for instance, pod removal frequency varies from fortnightly to weekly or even daily depending on the study (Soberanis et al., 1999).

In addition to cultural management practices, the type of cacao production system can also influence pest and disease incidence. For example, cacao agroforestry systems, which include fruit, palm, and/or timber trees together with the cacao trees, create certain microclimate conditions that differ from those of full-sun cacao monocultures: reduced light availability and wind speed, buffered temperatures, and increased relative humidity (Niether et al., 2018). These microclimate conditions in agroforestry systems are traditionally seen by most farmers as one of the causes of increased incidence of fungal diseases, compared with those of full-sun monocultures. However, research has reported contrasting results about the effect of agroforestry systems on pest and disease incidence (Blaser et al., 2018; Krauss and Soberanis, 2001; Mortimer et al., 2018). Microclimate conditions can stimulate sporulation of the diseases, but also of their antagonists (Mortimer et al., 2018). Moreover, the stimulation has been reported to be case-specific; in fact, the spatial structure of the shade trees, the identity of those shade trees, and the architecture and spatial arrangement of the cacao trees can all have an influence (Ngo Bieng et al., 2017; Gidoin et al., 2014). In addition, organic farming, which excludes the application of synthetic pesticides and fertilisers, in contrast with conventional management, can also influence pest and disease incidence. Cacao production under organic farming is still very limited, representing about 3.4% of the global harvested cacao production area (Willer and Lernoud, 2018), and, to our knowledge, no studies have been conducted yet to assess pests and diseases under organic farming (but see Riedel et al., 2019). Pest and diseases are considered to be one of the main reasons for the yield gap between organic and conventional farming (Röös et al., 2018), but recent research works indicate that organic farming can promote pest control (Muneret et al., 2018).

In this study, we aimed at testing the effect of different cacao production systems and of the frequency of harvest and diseased pod removal on the incidence of pests and diseases and on the cacao yield. For this purpose, two different experiments were conducted. The first one was performed in a long-term trial in Bolivia, where five different production systems were compared: two monocultures and two agroforestry systems under conventional and organic management, and one successional agroforestry system without any external inputs. The successional agroforestry system is a complex agroforest combining species of different strata and life cycle in high densities, including both crops and species that are typical of the natural succession of the forest. Data on pest and disease incidence, yield parameters and labour time were recorded over a period of three years (2015–2017). In this trial, good cultural management practices, i.e. fortnight harvest and removal of diseased pods, regular cacao and shade tree pruning and weed management, were implemented in all five systems. In the second experiment, at four farmers' fields, the frequency of harvest and diseased pod removal was increased from 25 days—the current practice, if performed, in the study region—to 15 days in order to test the effect on pest and disease incidence and on the cacao yield. In addition, this experiment aimed at validating the fortnightly phytosanitary inspection and diseased pod removal of the long-term trial in the farmers' fields, as well as at empirically demonstrating the importance of cultural management practices to the farmers. We hypothesised that good cultural management practices reduce the incidence of pests and diseases, while increasing cacao yields. Under this scenario, we did not expect any differences in pest and disease incidence between production systems, which, consequently, will not be the determinant of yield differences between systems.

2. Material and methods

2.1. Experiment 1. comparison of cacao production systems

2.1.1. Study site and experimental trial description

The study site (380 m a.s.l.) lies on an alluvial terrace in Alto Beni (department of La Paz), on the eastern foothills of the Bolivian Andes, 15° 27′ 36.60″ S and 67° 28′ 20.65″ W. The soils are Luvisols and Lixisols, and the natural vegetation is composed of nearly evergreen humid forests. The mean annual rainfall is 1439 mm, the mean temperature 25.2 °C, and the mean annual relative humidity 83%.

In 2009, a long-term trial was established to compare different cacao production systems, namely, full-sun monocultures and agroforestry systems under conventional and organic farming, and a successional agroforestry system without any external inputs. Successional agroforestry systems are complex, multi-strata systems based on the natural succession of species, combining species of different life cycle in high densities with other crops of economic interest (Milz, 2010). The principles and methods of the successional agroforestry systems were first developed by Götsch (1992). The complete list of trees can be found in Niether et al. (2018).

Each production system was replicated four times in a completely randomised block design. The size of the plots was 48 m × 48 m, with a net plot of 24 m × 32 m. The cacao tree spacing was 4 m × 4 m (625 trees ha^{-1}). In each plot, a total of 12 different cacao varieties were planted: four local selections, four commercial varieties (Imperial College Selection [ICS] and Trinidad Selection Hybrid [TSH]), and four hybrids (from the ICS and TSH). Detailed information on the management practices of each system can be found in Armengot et al. (2016). Chemical fertilisers and herbicides were used in the conventionally managed plots, while compost and manual weeding were applied in the organic ones. A perennial leguminous cover crop was sown in the organically managed plots.

In both the agroforestry systems and the successional agroforestry system, cacao trees grew together with timber and fruit trees (spaced 16 m × 8 m), leguminous trees (8 m × 8 m) and some palm trees. Bananas in the agroforestry systems, and plantains and bananas in the successional agroforestry system, were also planted (4 m × 4 m spacing).

Additionally, a mixture of tree seeds was dispersed around each banana tree and other seeds grew from the natural succession in the successional agroforestry system.

Microclimatic conditions differed between production systems (Niether et al., 2018). The mean annual relative humidity was 2.7% higher and the vapour pressure deficit (VPD) was 11 kPa lower in the agroforestry systems than in the monocultures (data from 2013 to 2014). The mean annual temperature did not differ between production systems, but the mean annual temperature amplitude was reduced by 1.1 °C in the agroforestry systems.

2.1.2. Data collection

From January 2015 to December 2017, data on pest and disease incidence at pod and tree level, as well as on cacao yields, were registered in the net plot (48 cacao trees) of each plot.

At pod level, a phytosanitary inspection was performed every 15 days, right before the harvest. During this inspection, all the pods with visible external disease infection symptoms on each tree were registered according to the identified disease and then removed. Diseased pods were left on the floor close to the tree trunk. In the case of frosty pod rot, the sporulation stage at which the pods were removed from the tree was also recorded in order to establish the potentiality of spore dispersal. Pods damaged by birds and/or small mammals were also recorded. At tree level, during the regular pruning of the cacao trees, the incidence of witches' broom, both in vegetative flushes and flowering cushions, was registered and the brooms removed. Also, the number of stem borers per tree was recorded and the tree was treated accordingly, i.e. stem borers were manually removed and the wounds made to the trees were covered with lime. The presence/absence of the cacao mirid (*Monalonion dissimulatum*) was also recorded at tree level, due to its low presence and in order to avoid double counting, since the pods were not removed from the trees.

Pest and disease management was only performed through cultural management practices; in other words, no chemical or biological control products were applied to any of the production systems. The working time devoted to the regular pod phytosanitary inspection and to any additional management measure (e.g. removing the stem borer) was also recorded. Time data were converted into days considering eight working hours per day.

Harvest was also carried out every 15 days during the whole year, although the production peak was between June and August. At each harvest date, all the ripe pods on each tree were harvested and registered. The pods were opened and the fresh bean weight per tree was registered. If a ripe pod without external symptoms of infection was opened and the symptoms were detected inside, the disease was recorded and the pod considered as non-healthy. The non-affected beans, if any, were pooled with the beans of the healthy pods in order to determine the yield per tree.

2.1.3. Data analyses

Hybrid cacao trees were not considered in the analyses because a very high percentage of those trees did not produce or only produced very few pods (57.5% of the hybrid trees produced 10 or less pods within the three years). In addition, given that they all were genetically highly heterogeneous (they were not clones as the other trees of the trial), we wanted to avoid any differences due to potential susceptibility of the genetic material. Apart from the hybrids, trees that were not producing or that died during the sampling period were also excluded (7.3%). In total, 1779 trees were considered (582, 578, 619 for, respectively, 2015, 2016 and 2017), an average of 29.7 trees for plot (from a potential of 32 trees per plot). The number of trees considered in the analyses did not differ between production systems (SS = 19.23, df = 4, P-value = 0.227).

For each year and plot, the total number of diseased pods (recorded during both the phytosanitary inspection and the harvest) and that of healthy pods were summed to calculate the total number of pods produced. The percentage of unhealthy pods, as well as of each disease and pest (frosty pod rot, black pod, witches' broom, and damaged pods), was calculated in relation to the total number of pods produced. At tree level, the incidence of witches' broom in vegetative flushes and flowering cushions was calculated as the average number of witches' broom per tree. The incidence of mirids was calculated as the average percentage of trees that had pods with mirids from the total cacao trees in each plot. The stem borer was only analysed for 2015, since only eleven trees in 2016 and one in 2017 were affected. The incidence of stem borers was calculated following the same procedure as for witches' broom. The fresh bean weight was converted into dry weight by applying the factor 0.33. Yields per hectare were extrapolated by multiplying the average yield per tree of each plot by the planting density factor (625 trees ha^{-1}). The dry weight per pod was estimated from the total number of pods and the total dry weight per tree.

The effects of the production system and year on the total number of pods harvested, the incidence of unhealthy pods and of each disease, the total dry weight and the dry weight per pod were all analysed through mixed-effects models, with the block as random factor. The same model was used to evaluate the effect of the production system on the percentage of trees affected by witches' broom in vegetative flushes and flowering cushions, and by stem borers and cacao mirids. Data were checked for normality and homoscedasticity of residuals and were log- or sqrt-transformed when necessary. The analyses were performed with R 3.1.10 (R Development Core Team, 2015), with the "lme4"package for mixed models (Bates et al., 2015) and the "lmerTest" to evaluate the significance of the effects (Kuznetsova et al., 2017).

2.2. Experiment 2. frequency of harvest and diseased pods removal

2.2.1. Study site

The study was performed in four farmers' fields in 'Brecha B', in the municipality of Palos Blancos (Alto Beni) in 2015/16. The mean altitude of this region is 450 m a.s.l., with a mean temperature of 26 °C and an annual precipitation of 1800 mm. The field sizes ranged from 0.7 to 1.5 ha; the cacao trees grew under agroforestry systems. The total number of agroforestry and by-crop trees ranged between 83 and 298, and the number of species between 26 and 37. Cacao tree spacing was 4 × 4 m. All four fields had a mixture of hybrid cacao trees, international clones (mainly ICS1, ICS6, ICS95 and TSH565) and some local selections. The age of the plantations was approximately 16 years. The management of both cacao and agroforestry trees was rather poor in all the sites, with seldom cacao and shade tree pruning, no phytosanitary inspections for pest and disease management, no regular harvest, occasional weed management, no fertiliser application. The cacao peak production in this area was between May and August.

2.2.2. Experimental design, data collection and analyses

In August 2015, the cacao trees were pruned in all four sites to have similar good starting conditions. In May 2016, each field was divided in half; one half was assigned to fortnightly harvest and the other half to harvest every 25 days, which is the common local practice. For each field and harvesting regime ten cacao plants were randomly selected in the centre of the plot.

At each harvest, all the ripe cacao pods were registered and harvested. The pods were classified into healthy or unhealthy, and in the latter case, the disease was identified and registered, and the pod was removed. The percentage of unhealthy pods, as well as of each identified disease, was calculated from the total number of pods harvested along the sampling period. Pods were split open and the fresh weight of the beans was recorded. Mature pods that had been infested at a late stage were also opened and any non-affected bean was pooled with the beans of the healthy pods in order to determine the yield per tree. Yields per hectare were extrapolated by multiplying the average yield per tree of each harvesting regime by the planting density factor (625 trees ha^{-1}). The fresh weight was converted into dry weight by applying the dry factor of 0.33. Together with the harvest, a phytosanitary inspection was performed. All the diseased pods detected were removed and registered.

The effect of the harvesting regime on the total number of pods harvested, the incidence of each disease and the total dry weight were analysed through mixed-effects models, with the farmer's field as random factor. Data were checked for normality and homoscedasticity of residuals. The analyses were performed with R 3.1.10 (R Development Core Team, 2015), with the "lme4″package for mixed models (Bates et al., 2015) and the "lmerTest" to evaluate the significance of the effects (Kuznetsova et al., 2017).

3. Results

3.1. Experiment 1. comparison of cacao production systems

3.1.1. Diseases and pests

Over the three years, a total of 58,775 pods were recorded, only 13.7% of which presented infection symptoms (Fig. 1a). The incidence of unhealthy pods did not differ between production systems, except for the higher values found in the successional agroforestry system as compared with those of the agroforestry systems (Table 1, Fig. 1b).

Frosty pod rot was the most important disease; an average of 10.3% of the total pods were affected by it (Fig. 1b). From the total pods infected by frosty pod rot, only 18.0%, 18.3% and 17.5%, respectively for 2015, 2016 and 2017, were removed during the sporulation phase. Most of the affected pods (an average of about 70%) were removed at the stage in which they present chocolate-coloured spots, and the rest when they presented deformations or premature ripening.

After the frosty pod rot, black pod and witches' broom had similar incidence (an average of 1.30 ± 0.13% for black pod, and of 1.40 ± 0.20% for witches' broom; Fig. 1b). No differences between production systems were found for the incidence of black pod, while incidence of witches' broom was significantly higher (by 60%) in monocultures than it was in the agroforestry systems ($P < 0.001$), just like in the organically managed agroforestry system when compared with the conventional one ($P = 0.028$, Table 1). Finally, pests had a very low incidence, only some pods damaged by birds and/or small mammals were detected. The number of pods damaged by small mammals and birds significantly increased from 0.4% in the monocultures to 0.93% in the agroforestry systems ($P = 0.013$), and to 1.57% in the successional agroforestry system ($P = 0.003$) (Table 1, Fig. 1b).

At tree level, the incidence of pests and diseases was also low. A lower incidence of witches' broom and stem borers was found in the successional agroforestry system as compared with the agroforestry systems ($P < 0.001$, $P = 0.02$), just like it was lower in the agroforestry systems than in the monocultures ($P < 0.001$, $P = 0.04$, Table 1, Fig. 2). No significant differences between production systems were found in the incidence of mirids.

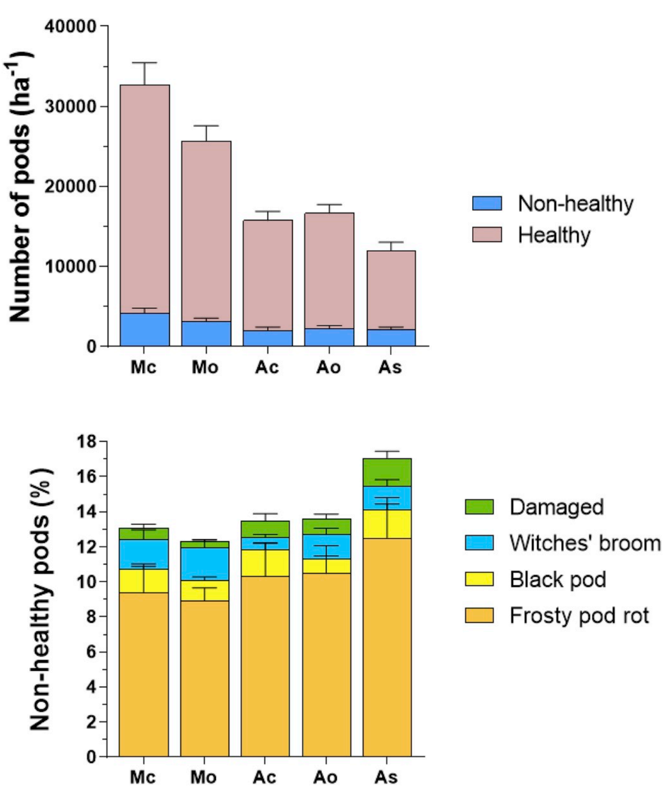

Fig. 1. Annual mean ± standard error from 2015 to 2017 of a) the total number of healthy and non-healthy pods produced, and b) the percentage of the different diseases and pests observed in the five cacao production systems, i.e., conventional monoculture (Mc), organic monoculture (Mo), conventional agroforestry (Ac), organic agroforestry (Ao), and successional agroforestry (As).

3.1.2. Cacao production

Both the total number of pods and the dry bean weight differed between production systems ($P < 0.001$, $P < 0.001$, respectively). The successional agroforestry system produced less pods ($P < 0.001$) and yield ($P < 0.001$) than the agroforestry systems, and the latter less than the monocultures ($P < 0.001$, $P < 0.001$, respectively for pods and yield). Less pods and yields were obtained in the organically managed monoculture than in the one conventionally managed ($P = 0.013$, $P < 0.001$), but no differences were detected between the two agroforestry systems ($P = 0.43$, $P = 0.55$, Table 2, Fig. 1a). The yield per pod was higher in the successional agroforestry system ($P < 0.001$) and the agroforestry systems ($P < 0.001$) than in the monocultures (Table 2).

3.1.3. Labour time

The time devoted to the regular fortnightly phytosanitary inspection (excluding the bi-annual cacao pruning) amounted to an average of 6.0 days ha^{-1} $year^{-1}$, which represents a 6.3% of the total time spent on all the on-field agricultural practices, mainly harvesting, weeding, fertilising and pruning, both the cacao and the agroforestry trees (data not shown). Less time was invested in the agroforestry systems than in the monocultures ($P = 0.004$), and in the monoculture under organic farming compared with the conventional one ($P = 0.016$). These results follow the same pattern as the total number of pods produced (Table 2).

3.2. Experiment 2. frequency of harvest and diseased pods removal

The total number of pods registered did not significantly differ between the two frequencies of harvest and diseased pods removal (Table 3). Overall, 24.8% of the pods were affected by any of the four diseases detected: frosty pod rot (8.38%), black pod (10.72%), witches' broom (5.27%) and anthracnosis (0.43%). Fortnightly harvest and diseased pods removal decreased the percentage of unhealthy pods ($P = 0.013$), as well as the incidence of frosty pod rot ($P = 0.011$) and, marginally, that of the black pod disease ($P = 0.096$) compared with the 25-day frequency (Table 3). No differences were observed for witches' broom and anthracnosis. However, a significantly higher cacao production was registered with the 15-day harvest frequency ($P = 0.043$).

4. Discussion

4.1. Overall pest and disease incidence

Fungal diseases were the major cause of pod losses in our long-term trial. Pests had only a minor role. These findings agree with those of previous studies considering fungal diseases a major cause of cacao loss; 40% of the annual cacao production is estimated to be lost by some of the most important fungal diseases such as frosty pod rot, black pod and witches' broom (Ten Hoopen et al., 2012).

Table 1
Results of the linear mixed-effects models assessing the effects of production system, year, and interaction between year and production system on the incidence of diseases and pests at pod and tree level in the long-term system comparison trial.

Fixed effects	Pod level										Tree level					
	Diseased pods (%)		Frosty pod rot (%) †		Black pod (%) †		Witches' broom (%) †		Pests (%) †		Witches' broom †		Stem borer †		Mirid	
	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*
System	1.71·	4	1.32	4	0.52	4	1.95 ***	4	2.54 *	4	9.94 ***	4	0.86·	4	542.36	4
Year	28.68 ***	2	28.04 ***	2	2.32 **	2	15.37 ***	2	5.90***	2	14.18 ***	2	–		2062.2 ***	2
Year × System	2.48	8	3.86	8	0.39	8	0.64	8	2.91	8	0.33	8	–		333.6	8
Orthogonal contrasts	*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*	
System As vs A	0.16 ± 0.05 **		0.13 ± 0.07•		0.044 ± 0.05		0.007 ± 0.04		0.18 ± 0.06 **		−0.258 ± 0.03 ***		−0.16 ± 0.06 *		−0.53 ± 1.28	
System A vs M	0.10 ± 0.07		0.14 ± 0.09•		−0.004 ± 0.06		−0.167 ± 0.04 ***		0.18 ± 0.07 *		−0.480 ± 0.05 ***		−0.16 ± 0.07 *		2.32 ± 1.56	
System Ac vs Ao	−0.06 ± 0.08		−0.03 ± 0.11		0.121 ± 0.08		−0.138 ± 0.06 *		−0.03 ± 0.09		0.004 ± 0.05		−0.04 ± 0.10		−2.72 ± 2.02	
System Mc vs Mo	0.03 ± 0.08		−0.01 ± 0.11		0.023 ± 0.08		−0.061 ± 0.06		0.11 ± 0.09		0.025 ± 0.05		−0.17 ± 0.10		−1.06 ± 2.02	

Above: ANOVA table showing the effect and the levels of significance of the fixed terms production system, year, and interaction between year and system. Below: coefficients of the orthogonal contrasts for the factor system comparing the successional agroforestry system (As) with the agroforestry systems (A), and the agroforestry systems (A) with the full-sun monocultures (M), as well as the farming management within each production system, i.e. conventional agroforestry (Ac) with organic agroforestry (Ao), and conventional full-sun monoculture (Mc) with organic full-sun monoculture (Mo).
At pod level, the results show the percentage in relation to the total number of pods produced. At tree level, the results show the percentage in relation to the total number of trees. For the mirid, data were collected as presence/absence per tree. For witches' broom and stem borer, the actual number per tree was used. Stem borer was only analysed for year 2015, since a very low incidence was detected in 2016 (eleven trees affected) and 2017 (one tree affected).
DF: degrees of freedom; SE: standard error; $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$; $^{\cdot}\ P < 0.1$; † sqrt-transformed.

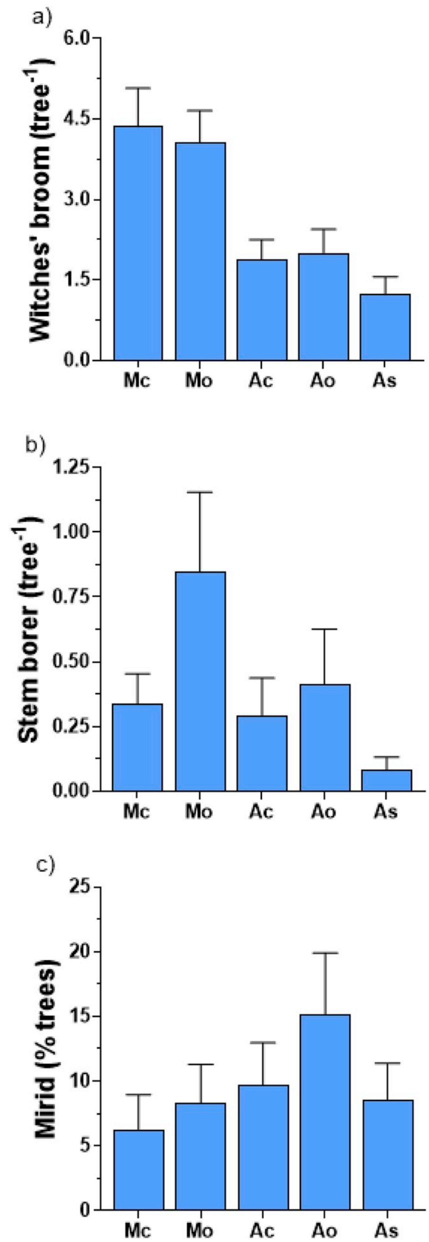

Fig. 2. Annual mean ± standard error from 2015 to 2017 of a) the number of witches' broom in floral cushions and vegetative flushes per tree, b) the number of stem borers per tree, and c) the percentage of trees with presence of mirids in the five cacao production systems, i.e. conventional monoculture (Mc), organic monoculture (Mo), conventional agroforestry (Ac), organic agroforestry (Ao), and successional agroforestry (As).
For stem borer, only data from 2015 are presented, since the incidence observed in 2016 and 2017 was very low.

Although pests and diseases are a main threat for the cacao production, the pod losses in our study were relatively low compared with losses reported in other studies (Krauss and Soberanis, 2001; Phillips-Mora and Wilkinson, 2007; Soberanis et al., 1999), even though in our trials only cultural management practices were performed, i.e. no pesticides or biological control products were applied. One explanation for this low percentage could be the diligence with which the cultural management practices were implemented in the whole plantation. These included the pruning of the cacao trees and the agroforestry trees (twice per year), frequent weed management, regular and continuous harvest throughout the year, and periodical removal of diseased pods. This is supported by the results of the second experiment, which proved that a shift from a periodical 25-day to a 15-day harvest and diseased pod removal decreased the number of diseased pods and increased the cacao yield. These finding are also in line with previous studies reporting a positive impact of cultural management practices on pest and disease reduction (Soberanis et al., 1999). Studies in many other countries, e.g. Perú (Soberanis et al., 1999), Costa Rica (Krauss et al., 2003) or Colombia (Cubillos and Aranzazu, 1979), have reported improved yields when increasing the frequency of diseased pod removal to weekly or fortnightly. However, in our study region, as in many other regions and countries, the vast majority of farmers do not practice this preventive management (Soberanis et al., 1999). The goal of this experiment was to prove that good cultural management practices could lead to low levels of pests and diseases in our long-term trial, but, most importantly, to empirically demonstrate the benefits of such management (in particular of fortnightly harvest and diseased pod removal) to farmers in their own plantations. However, time constraints condition the management of the plantations of most farmers in our study region, who commonly combine farming with other economic activities (taxi driving, shop management, etc.) to complement their living income. Good management practices, mainly tree pruning, are difficult and labour intensive. However, we have shown here that the time invested in this periodical inspection is very low (about 6%) in comparison with the rest of management practices performed. The cacao industry is demanding more production to meet the increasing demand for chocolate and other cacao products. Our study supports previous results showing that a better management of the cacao plantations increases their yields, and could also avoid further expansion of agricultural land and deforestation, two key aspects of biodiversity conservation and climate change mitigation (Clough et al., 2009). This should be stimulated by higher cacao prices, which would compensate the extra labour demand associated to the implementation of diligent cultural management practices. Moreover, Soberanis et al. (1999) showed that gains in gross return compensate the extra effort when traditional management is shifted to fortnightly and weekly diseased pod removal.

Among all the pests and diseases recorded, frosty pod rot had the highest incidence. This result is in agreement with previous studies that showed the disease to be more destructive and more difficult to manage than black pod and witches' broom, making it a major threat for cacao production in Latin America (Phillips-Mora and Wilkinson, 2007). Average cacao losses of 30% to frosty pod rot are usually reported, but they can affect the total yield loss under favourable conditions, often resulting in the abandonment of the cacao plantations. In comparison, the incidence manifested in our study was rather low (about 10% of pod losses). The fortnightly pod removal ensured that only about 18% of the pods were cut in the sporulation phase, which is lower than in other studies (Soberanis et al., 1999). Once diseased pods reach the sporulation phase, they become a major source of inoculum for further infections since they remain attached to the tree trunk. A diseased pod can produce over 7 billion spores that will be widely distributed by the wind (Phillips-Mora and Wilkinson, 2007). Pods are usually infected when they are young and, before the sporulation phase occurs (about 2–3 months after the infection), external symptoms such as water-soaked lesions, deformations, premature ripening and chocolate-coloured spots may be visible. The symptoms are not always easily recognised. In this sense, training for farmers is essential to prevent that the sporulation phase takes place in the pods still attached to the trunks.

4.2. Pest and disease incidence in different production systems

We did not find substantial differences in pest and disease incidence between production systems. Our production systems, whether monoculture or agroforestry systems, conventionally or organically managed, did not differ in pest and disease management. The low incidence of pests and diseases did not justify (economically or environmentally) the application of any external inputs. This means that we could test the effect of the production system itself (e.g. plant diversity and shade,

Table 2
Mean ± SE and results of the linear mixed-effects models assessing the effects of production system, year, and interaction between year and production system on the total number of pods, yield, yield per pod, and labour time devoted to control of pests and diseases in the long-term system comparison trial.

	Total pods (ha^{-1} $year^{-1}$)		Yield (t dw $ha^{-1}year^{-1}$)[b]		Yield/pod (g dw pod^{-1})		Labour time (h $year^{-1}$) [a]	
Mean ± SE								
As	10411 ± 1059.0		0.54 ± 0.05		52.36 ± 1.06		46.95 ± 4.35	
Ac	13996 ± 1174.9		0.66 ± 0.06		47.10 ± 0.52		44.92 ± 3.47	
Ao	14883 ± 1172.1		0.70 ± 0.06		47.08 ± 0.62		46.43 ± 4.53	
Mc	29273 ± 2907.6		1.26 ± 0.12		43.17 ± 0.52		55.26 ± 5.62	
Mo	23086 ± 1991.0		1.01 ± 0.09		43.78 ± 0.63		47.65 ± 3.30	
Statistical results								
Fixed effects	*SS*	*DF*	*SS*	*DF*	*SS*	*DF*	*SS*	*DF*
System	38344	4	5.52 ***	4	640.16 ***	4	3.54 **	4
Year	17535	2	4.18 ***	2	79.21 ***	2	46.18 ***	2
Year × System	2310	8	0.13	8	89.23 **	8	0.62	8
Orthogonal contrasts	*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*		*Estimate ± SE*	
System As vs A	−15.60 ± 1.68 ***		−0.20 ± 0.06 ***		2.83 ± 0.24 ***		−0.05 ± 0.06	
System A vs M	−28.93 ± 2.06 ***		−0.34 ± 0.03 ***		3.22 ± 0.29 ***		−0.23 ± 0.07 **	
System Ac vs Ao	−1.81 ± 2.66		−0.03 ± 0.04		0.01 ± 0.37		−0.04 ± 0.10	
System Mc vs Mo	9.64 ± 2.66 ***		0.10 ± 0.04 *		−0.30 ± 0.37		0.24 ± 0.10 *	

Above: ANOVA table showing the effect and the levels of significance of the fixed terms production system, year, and interaction between year and system. Below: coefficients of the orthogonal contrasts for the factor system comparing the successional agroforestry system (As) with the agroforestry systems (A), and the agroforestry systems (A) with the full-sun monocultures (M), as well as the farming management within each production system, i.e. conventional agroforestry (Ac) with organic agroforestry (Ao), and conventional full-sun monoculture (Mc) with organic full-sun monoculture (Mo).
DF: degrees of freedom; SE: standard error; ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; $^{\cdot}$ $P < 0.1$.
[a] sqrt-transformed.
[b] log-transformed.

fertilisation) on the incidence of pests and diseases, which was not hindered by any chemical or biological control treatment. The fact is that, although chemical and biological strategies for pest and disease control have been tested (Bateman et al., 2005; Krauss and Soberanis, 2001; Krauss et al., 2003), they are only rarely adopted by smallholder farmers (Phillips-Mora and Wilkinson, 2007), and they are usually effective only when combined with other cultural management practices (Ayala and Navia, 2008; Krauss et al., 2003; Krauss and Soberanis, 2002).

Overall, our results showed that agroforestry systems do not have more incidence of fungal diseases than monocultures. This contradicts the farmers' belief that agroforestry systems are more prone to fungal disease infections and, in our study area, it also challenges the recommendation of some technicians to cut down the agroforestry trees. Nevertheless, a better knowledge of the effect of agroforestry species on fungal communities is needed (Mortimer et al., 2018). Controversial results on the role of shade have been obtained for the main fungal diseases. For instance, black pod disease has been reported to decrease at high, moderate and low levels of shade (Beer et al., 1998; Blaser et al., 2018, and references in the review of Mortimer et al., 2018). Similar contradicting results have been released for frosty pod rot: both excessive shade and the lack of shade have been related to increased disease incidence (Krauss and Soberanis, 2001, and references in the review of Mortimer et al., 2018). The microclimate created in agroforestry systems, which is different than that of monocultures, but also those that emerge at the different strata of the agroforestry systems, could encourage populations of natural antagonists or stimulate fungus sporulation and favour autoinfection. The spatial structure of the shade trees, but also the density of the cacao trees in agroforests, have been reported to play a role in regulating frosty pod rot (Gidoin et al., 2014; Ngo Bieng et al., 2017). Cultural management practices could also have an influence on the different incidences of fungal diseases in full-sun and shade systems. However, this is not always easy to quantify, because management practices are not always fully reported in the literature. In our study, when the same good cultural management practices were implemented, we observed similar overall incidences of fungal diseases in monocultures and agroforestry systems. Likewise, Kieck et al. (2016) did not find any relation between system diversity and the percentage of unhealthy pods.

Looking at individual pests and diseases, we found that witches' broom had higher incidence both at pod and tree level in the monocultures when compared with the agroforestry systems, and the same tendency was observed for stem borers, although their incidence was hardly relevant in all systems (1.4%, 1.7% and 0.4% across production systems for witches' broom at pod and tree level, and stem borers, respectively). Evans (1998) reported that microclimates under shade favour natural antagonists of witches' broom, but Loguercio et al. (2009) found that both the disease and the antagonists are favoured

Table 3
Mean ± SE and results of the mixed-effect models analysing the effect of the harvest and phytosanitary frequency on the total number of pods harvested, the incidence of diseases, and the total cacao production at four farmers' fields.

	Every 25 days	Every 15 days	Estimate ± SE/P-value
Total pods (ha^{-1})	11546.88 ± 1248.1	17351.56 ± 3112.5	−0.35 ± 0.16 ·
Unhealthy pods (%)	28.32 ± 3.67	21.31 ± 3.84	7.01 ± 2.85 *
Frosty pod rot (%)	9.84 ± 1.19	6.93 ± 1.44	3.857 ± 1.25*
Black pod (%)	12.86 ± 3.36	8.58 ± 1.64	0.25 ± 0.16 ·
Witches' broom (%)	5.03 ± 1.04	5.51 ± 0.97	−0.48 ± 1.23
Anthracnosis (%)	0.58 ± 0.33	0.29 ± 0.10	0.29 ± 0.31
Yield (dw kg ha^{-1})	325.2 ± 25.06	475.4 ± 82.7	−0.29 ± 0.13 *

The percentage of unhealthy pods and the incidence of frosty pod rot (*Moniliophthora roreri*), black pod (*Phythophthora* spp.), witches' broom (*Crinipellis perniciosa*) and anthracnosis were calculated as a percentage of the total number of pods harvested. *$P < 0.05$; $P < 0.1$.

under shade. On the other hand, the higher pod losses due to small mammals and birds both in the successional system and the two agroforestry systems, compared with the monocultures, could be explained by the higher abundance and diversity of those production systems in our trial (Kazuya et al., 2017) and in other studies (Schroth and Harvey, 2007). In contrast with monocultures, agroforests can provide habitat for many other taxa, which can help preserve biodiversity and forest-dependent species (Bhagwat et al., 2008; Marconi and Armengot, 2020; Oke and Odebiyi, 2007). Thus, higher pod losses are compensated with the additional value of biodiversity conservation. However, it is worth mentioning that the percentage of pods lost due to pest was rather low (about 0.9%); if an increase is observed over the next years, addition management measures will be required to not threaten the cacao production.

The comparison of organic and conventional farming systems did not reveal significant differences in pest and disease incidence, apart from a marginal increase in witches' broom incidence in organic compared with conventional agroforestry. As previously mentioned, pest and disease management did not differ between these farming systems, but the systems themselves differed in fertilisation and weed management, among others aspects. It has been reported that fertiliser applications reduce the overall pathogen incidence, in particular of frosty pod rot, which is explained by the greater vitality of fertilised trees and the improved N supply for the production of secondary plant compounds against fungi (Kieck et al., 2016; Krauss and Soberanis, 2002). Our conventional systems received mineral fertilisation, while the organic systems received compost, but the agroforestry systems received half of the dose applied to the monocultures, and the successional agroforestry system was not fertilised at all. We can thus conclude that potential differences in cacao vitality due to different fertilisation management options did not lead to increased disease incidences in our agroforestry systems.

4.3. Pest incidence as driver of cacao yield

In our study, pests and diseases were not found to be drivers of the different cacao yields obtained in the various production systems, since, as discussed before, similar incidences of pests and diseases were observed in all production systems. This finding is in contrast with other studies reporting that pests and diseases are one of the main reasons for lower yields in organic compared with conventional agriculture (Röös et al., 2018). The higher total number of pods and higher yields of the conventional compared with the organic monoculture, and also of the monocultures compared with the agroforestry systems, can be explained, among other reasons, by competition for soil resources (Niether et al., 2019). Previous studies have shown as well a negative effect of agroforestry systems on cacao yield along a gradient of shade (Blaser et al., 2018), indicating competition for light. However, it has not been yet studied whether shade trees can increase the productive lifetime of cacao plantations by reducing premature aging, in contrast with full-sun monocultures (Blaser et al., 2018). It is noteworthy that the pods were bigger in the successional and agroforestry systems in comparison with monocultures, a fact that could be related to the lower total number of pods produced. Therefore, losing one pod due to pests or diseases in these systems implies a relatively higher yield loss, which may play a role in relation to the final yield. This makes an appropriate pest and disease management even more relevant in the process of minimising pod losses in agroforestry systems.

5. Conclusions

Our results show that cacao agroforestry systems and organic management have similarly low levels of pest and disease incidence to those of monocultures and conventionally managed systems under good cultural management practices and when no external input-based control treatments are applied. The cacao industry should incentive cultural management practices for pest and disease management by considering the extra labour time required to implement those practices in the price of cacao, a decision that would in turn increase productivity in the cacao plantations. Therefore, promoting cultural management practices and organic agroforestry systems is crucial to achieve two of the main goals of the cacao industry and the consumers: reducing deforestation and sourcing from sustainable cacao plantations.

Credit author section

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are thankful to the staff of the Sara Ana research station for their commitment in data collection, especially to Victor Soto. We also thank Claudia Vaderna for the preliminary analyses of the data. The study was financed by the Swiss Agency for Development and Cooperation (SDC), the Liechtenstein Development Service (LED), the Biovision Foundation for Ecological Development, and the Coop Sustainability Fund.

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