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Effect of shade tree planting and soil management on rehabilitation success of a 22-year-old degraded cocoa (*Theobroma cacao* L.) plantation

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ABSTRACT

Since productivity of current cocoa plantations is stagnating or declining, increasing global demand for cocoa products puts pressure on tropical, primary forests to be cut for new plantations. To address this problem, sustainable increase of cocoa yield on current plantations is needed. On a 22-year-old, 61 ha cocoa plantation in peninsular Malaysia, shade tree planting and soil management treatments, including targeted mineral fertilization, intense organic fertilization and combinations of these with compost application and cover crop (*Centrosema pubescens*) planting, were assessed as a rehabilitation strategy of degraded cocoa plantations with sub-optimum yield. Treatment effects on cocoa yield and on proxy indicators soil fauna abundance and diversity, and soil nutrient status, was tested 3.5 years after implementation in four harvesting rounds between 28 November 2014 and 12 March 2015. Across all treatments, large differences were found in the yield of the two clones tested (PBC130 and PBC123). The effect of shade trees (mainly *Musa* sp., with some permanent shade trees) on yield interacted with the factor 'clone'. Mean wet bean yield of PBC123 trees in full-sun cultivation was 0.74 kg as compared with 1.08 kg for trees in the agroforestry system (46% increase). Mean wet bean yield of PBC130 trees, however, was 20% lower in the same agroforestry system (0.08 kg) in comparison with mean wet bean yield of trees in full-sun cultivation (0.10 kg). Soil management treatments did not result in clear yield improvement as compared with common-practice, control plots. However, cover crop treatment had a positive effect on proxy indicators soil nutrient status and endogeic soil fauna diversity. It is concluded that in the rehabilitation of degraded cocoa plantations, possible yield impact of applying a straightforward agroforestry system, as the one in our experiments, is high. Furthermore, it was shown that in a degraded plantation with a long history of intensive fertilization, improved soil management has little effect. Positive effects of shade trees on cocoa yield are therefore probably linked with the creation of an environment that improves cocoa crop physiology and reduces pressure of pests and diseases, rather than with the improvement of soil quality as a consequence of intercropping with trees.

1. Introduction

Global cocoa (*Theobroma cacao* L.) production increased almost linearly from 1.2 M t in 1961 to 4.6 M t of dry cocoa beans in 2013 (average annual production increase of 5.5%). Over the same period, annual cocoa area harvested increased from 4.4 M ha to 10 M ha (average annual increase of 2.5%) (FAO, 2015). As a result, average global productivity also steadily increased: from 269 kg/ha (1961) to 458 kg/ha in 2013. The latter increase, however, only shows a linear trend until 1989 (when average global yield was 479 kg/ha). Since then, annual yield has been fluctuating between 434 kg/ha and 513 kg/ha. At the same time, there are indications that global demand for cocoa is rising. Between 2006 and 2011, cocoa demand increased at an average rate of 1.7% per year (ICCO, 2014). Because of these stagnating yield figures, increasing cocoa demand puts additional pressure on primary forests where new cocoa plantations are often installed (Clough et al., 2009). The global cocoa sector consequently faces the challenge of both increasing cocoa production whilst avoiding unsustainable expansion of the area under cocoa by cutting down forests. A trade-off might then have to be found between so-called land sparing and

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land sharing strategies (Vaast and Somarriba, 2014). In cocoa, the former usually coincides with production intensification by removal of shade trees, and more intensive use of fertilization and chemical pest and disease control, whereas the latter integrates cocoa trees with other crop species, providing ecosystem services that compensate natural land taken by cocoa production.

In the past, the cocoa industry has advocated the use of full-sun, intensive cocoa production as a land sparing technique (Vaast and Somarriba, 2014). However, claims on the long-term productivity-enhancing effect of shade removal and fertilizer application are only based on a few studies of which the Ghana study of Ahenkorah et al. (1974) is frequently cited (Asare et al., 2014; Gockowski et al., 2013; Isaac et al., 2007; Lehmann et al., 2000; Schroth et al., 2000, 2002). In that 20-year experiment, it was shown that yield of cocoa plants without shade in combination with fertilizers was triple the yield of cocoa cultivation under shade without fertilizers (Ahenkorah et al., 1974). However, the shade was provided by only one, fast-growing pioneer species (*Terminalia ivorensis*), which might have competed with cocoa for light and soil nutrients, thus explaining its negative effect on cocoa yield. Since well-managed cocoa trees can remain productive for up to 60 years (Jagoret et al., 2011; Bisseleua et al., 2013), sustainability of shaded agroforestry cocoa systems versus that of fertilized full-sun systems should be assessed beyond a 20 year period as well. However, the experiment of Ahenkorah et al. (1974) was stopped after twenty years, just when the yield of plots without shade and with fertilizer application started to decrease and the yield of plots with shade and with fertilizer application started to increase.

Production of cocoa in agroforestry systems, that consist of a complex of shade tree species, is likely to be more sustainable in the long term because of (i) reduction of high air and soil temperatures (Beer et al., 1998); (ii) reduction of wind speed (Beer et al., 1998); (iii) reduction in fruit abortion, resulting from soil N addition through leguminous shade trees (Bos et al., 2007); (iv) protection against windborne spores of fungal diseases (Rice and Greenberg, 2000); (v) improved buffering of high humidity levels and soil moisture availability (Beer et al., 1998; Schwendenmann et al., 2010); (vi) improvement of light regulation and nutritional status of trees (Isaac et al., 2007); (vii) reduction of excessive vegetative growth (flushing) (Beer et al., 1998); (viii) reduction of nutritional imbalances and dieback of trees (Beer et al., 1998; Wessel and Gerritsma, 1994); (ix) weed growth suppression (Rice and Greenberg, 2000); and (x) increased overall insect biodiversity, which improves yield through natural control of pest populations and increased pollination services (Asare, 2006; Bisseleua et al., 2009; Bos et al., 2007; Sperber et al., 2004; Zuidema et al., 2005).

Cocoa agroforestry systems also have a positive impact on soil fertility, and reduce and prevent soil erosion (Beer et al., 1998; Duguma et al., 2001; Schroth et al., 2001a; Rice and Greenberg, 2000). Agroforestry enhances soil exploration by the trees' root system and the associated mycorrhizas. It also fosters litter fall and proliferation of soil organisms (fauna and microbes, including pest and disease antagonists), thus creating a soil with more favourable structure, and adequate organic matter and nutrient availability (Schroth and Krauss, 2006). In addition to litter from agroforestry trees, ground vegetation plays a vital role in maintaining soil moisture and appropriate bulk density, leading to improved nutrient mobilization as compared with these parameter levels under bare soil (Schroth et al., 2001b).

In addition to the agro-ecological benefits of shade trees, possible lower/ha yield of cocoa in agroforestry systems can be compensated by additional income from selling fruits from shade trees such as bananas (*Musa* sp.), citrus (*Citrus* sp.), avocado (*Persea americana*), coconut palm (*Cocos nucifera*) (Feintrenie et al., 2010; Koko et al., 2013; Osei-Bonsu et al., 2002) or other, local and often underutilized fruit tree species (Asare et al., 2014; Bisseleua et al., 2009; Sonwa et al., 2007; Vaast and Somarriba, 2014).

After more than 20 years of intense cocoa cultivation under full-sun conditions, which concerns around 30% of globally produced cocoa (Gockowski and Sonwa, 2011), the latter-type cocoa plantations have been shown to suffer from decreased yield due to soil deterioration, nutrient imbalances and increased incidence of pests and diseases. Whereas most agroforestry research focuses on characteristics of existing agroforestry practices, the present research investigates the effect on cocoa yield and soils of implementing agroforestry practices as an ex-post rehabilitation strategy of such sun-grown, degraded cocoa plantations. Replanting of deteriorated plantations in an agroforestry system would probably be the most efficient way of achieving cocoa production with low pest and disease pressure and sustained production in the long run. However, replanting entails a production stop of at least 4 years with economic consequences for the farmer. As a result we chose to investigate rehabilitation of existing trees. The present study will further shed more light on the poorly understood interaction between shade and soil management, and between the latter factors and cocoa genotype. We thereby hypothesize that apart from directly monitoring yield through production indicators such as number of pods or bean yield per tree, the positive effects of rehabilitation treatments can also be assessed by proxy indicators such as soil nutrient status and soil biodiversity indices.

2. Material and methods

2.1. Site description

Research took place at a 1100 ha rubber + 61 ha cocoa estate in Pahang Province of peninsular Malaysia (4°14′48″N, 101°59′8″E). Plots have a flat topography and are situated at 80 masl. Soils are haplic ferralsols according to a soil map (no reference) found at the estate. The plantation has a tropical rainforest climate (Af in Köppen's classification) with a mean annual precipitation of 2300 mm (average 2011–2014 of data recorded by a Onset™ U30 NRC Remote Monitoring weather station) which is equally distributed over the year. However, October–December are usually the wettest months (>260 mm per month on average). Annual mean temperature is 26 °C. Throughout the year, daily temperature and relative humidity vary between 20 and 35 °C and 40–100% (early morning), respectively.

2.2. Experimental design

Experiments were conducted in two 3.3 ha cocoa plots (separated by an East-West-oriented road and situated at the east of a large rubber (*Hevea brasiliensis*) plot), where 7 cocoa clones (PBC130, PBC131, PBC139, PBC123, PBC140, PBC159 and PBC113, all planted in 1989) occur in North-South-oriented rows (4 rows of each clone beside one another) in a monocrop cocoa system with trees spaced at 3 m × 3 m (1111 trees/ha). The pattern and succession of clone rows is repeated throughout the plantation. Annual cocoa yield at the plantation gradually declined from around 1300 kg of dry beans/ha recorded in 1999, to 630 kg/ha, recorded in 2011 (unpublished plantation records). Treatments were implemented between 8 and 26 August 2011.

Shade trees were planted on 1 ha of each of the 2 selected plots (i.e. the mid-section) as an agroforestry treatment. Two times two cocoa clones (PBC130 and PBC123) were selected for experiments (so that each clone occurred in both the agroforestry and monocrop areas). The four rows of each selected clone were divided into 8 subplots of 16–20 trees in both plots (each plot represents one replicate).

In each subplot, one or a combination of soil management practices were implemented as treatments. These practices consisted of various degrees of intensification and included (i) compound NPK fertilizer application; (ii) targeted (i.e. based on soil analysis and modelling) mineral fertilization, (iii) organic fertilizers, (iv) compost mulch, and (v) green manure (cover crop) (for details: cfr. infra). The eight treatments thus applied were: (i) common practice (=control); (ii) common practice + cover crop; (iii) mineral fertilizers; (iv) mineral fertilizers + cover crop; (v) mineral fertilizers + compost mulch; (vi) organic fertilizers; (vii) organic fertilizers + cover crop; and (viii) organic fertilizers + compost mulch. Experiments thus consisted of a full factorial $2 \times 2 \times 8$ split–split-plot design with two replicates, and with the agroforestry and monocrop plots as the first main plots, the rows with the two clones as the second main plot therein, and with 8 completely randomized subplots with different agronomic treatments nested within each clone x agroforestry/monocrop plot.

2.3. Clones

According to local estate management and based on information from the Malaysian Cocoa Board (MCB, 2012), under current common-practice cultivation factors (full-sun system with compound NPK fertilizer application) cocoa clones PBC130 and PBC123 represent the worst and respectively best available cocoa clone at the estate in terms of pest and disease resistance and yield. PBC130 trees are susceptible to both Vascular Streak Dieback (VSD) (*Ceratobasidium theobromae* P.H.B. Talbot and Keane) and Black Pod Disease (BPD) (*Phytophthora palmivora* E.J. Butler) and this clone has a seed index (number of dried beans per 100 g) of 78 (Lee et al., 1993) whereas PBC123 trees exhibit moderate resistance against VSD (Bong et al., 1996), intermediate resistance against BPD, and a seed index of 96 (Lee et al., 1993). Selection of these extremes allowed to thoroughly examine the interaction effects of the clone factor with all applied treatments.

2.4. Agroforestry

Agroforestry set-up was achieved by a two-tier approach: (i) planting of bananas (*Musa* sp., local variety 'Sematu') at $6 \times 6\,m^2$ for quick shade provision; and (ii) planting of 5 perennial shade tree species (*Peltophorum pterocarpum*,*Gliricidia sepium*, *Durio* sp., *Erythrina fusca* and *Parkia speciosa*) with either mostly ecological (i.e. all but *Durio* sp. are leguminous trees) or tangible economic benefits (durian fruits from *Durio* sp. and 'petai' or bitter bean from *P. speciosa*), at $12 \times 12\,m^2$. Each of the 5 trees were altered in the planting scheme in both the N–S as well as the E–W planting rows so that shade trees of each species were evenly distributed in the agroforestry plot. Coconut (*C. nucifera*) trees, spaced at $24 \times 24\,m^2$, had been planted 3–5 years prior to the experiment and were left in the field as additional shade trees in the middle between the newly planted trees. All shade trees were planted as locally purchased seedlings, apart from *Gliricidia* that was propagated by cuttings obtained from mature *Gliricidia* trees found elsewhere in the estate. Due to water logging, half of the banana corms planted had rotten following heavy rains in November 2011 and were replanted in April 2012. First bananas could be harvested on 1 November 2012 (15 months after planting).

2.5. Compost

Five compost baskets ($2 \times 2 \times 1.5\,m^3$) were constructed in between main experimental plots, using 4 wooden poles around which a fence mesh wire was attached, and filled with cocoa leaf litter, diseased pods or empty pod shells collected from all subplots. Following Dalzell et al. (1987), compost was further enriched with fresh cocoa leaves (from maintenance pruning), fresh pod shells (harvest waste), organic waste from a local vegetable trader, 10 kg per basket of commercially available chicken dung pellets and 10 kg per basket of top soil collected in the estate. Chicken dung pellets and top soil were only added once in the beginning of the composting experiment in order to improve the compost fermentation initiation. Each two weeks, diseased pods, pruned leaves (from both cocoa and banana plants) and organic waste from the vegetable trader were added to the compost baskets. One side of each compost basket was regularly opened by removing the mesh wire (every 1–2 months) for thorough mixing of the contents. Compost was applied once a year (in April). Contents of compost baskets were evenly spread in the respective subplots as mulch. In this way, 1500 l of compost was added to each subplot, so that each tree received between 8 and 10 l of compost, corresponding to between 4 and 5 kg of compost per tree, equivalent to between 4.4 and 5.5 t of compost/ha. Incorporation of the compost into the soil was not possible due to the soil's heavy clay structure.

2.6. Cover crop

The leguminous cover crop species *Centrosema pubescens* was sown in rows between cocoa tree rows, 1 m apart. Five to 10 seeds were planted in shallow pits every 50 cm. After 3 months, *C. pubescens* had formed a dense cover on the respective subplots. Since *C. pubescens* was vigorously twining (Skerman et al., 1988), it had to be regularly cut from cocoa and shade trees. Every two months, the upper leaves and branches of the dense cover crop mat were cut by brush cutters and left on the field as a green manure, following Dalzell et al. (1987).

2.7. Fertilization

2.7.1. Soil sampling

Fertilizer application doses were based on soil samples that were taken in June 2011, in both cocoa plots (each representing one replicate) used for experiments (for rate calculation, see below). Samples were taken by means of an Eijkelkamp Edelman Clay auger (ø 80 mm) at two depths (0–20 cm and 20–40 cm) and at two positions relative to cocoa tree stems (i.e. close to the trees and at middle distance between trees). Samples were mixes of soil obtained from drills at 12 evenly distributed spots (3 rows of 4) in each 3.3 ha plot. Eight mixed samples were thus obtained (2 plots × 2 depths × 2 positions relative to trees). Stones and coarse organic material were removed and large clay clumps were manually broken until a homogenous mass of small ($ø < 3$ mm) clay crumbs was obtained. Subsequently, from each mixed sample a subsample of 200 g was stored in sealed plastic bags in a refrigerator at 5 °C until transport to Belgium, where they were stored again at 5 °C until analysis (2 weeks after sampling).

2.7.2. Soil analysis

Soil parameters were analyzed at the Department of Soil Management (Ghent University, Belgium). Soil texture, pH–H_2O and pH–KCl, were determined following van Reeuwijk (2002). Total organic carbon (TOC) was assessed following ISO standard 10694:1995, whereas total N was determined using the Kjeldahl method (ISO 11261:1995). Total P, Ca, K, Mg, Na, Fe and Al were determined following ISO standard 11885:2009. Available P was determined after extraction with ammonium lactate (1.0 M, pH 7, 1:20 v/v soil:extractant ratio, 30 min extraction) (Egnèr et al., 1960) and acetate buffer, followed by colorimetric analysis, using a SpectrAA (Varian Inc.) spectrophotometer, following Scheel (1936).

2.7.3. Fertilizer requirements

In the common practice plots, 1.2 kg per plant of OPCOM65 (NPK 13.6: 0.96: 19.2) fertilizer was annually applied in three rounds (February, May and August), together with one round (March) of ground mineral limestone (GML) (16% MgO), applied at a rate of 0.5 kg per year.

For the targeted 'mineral fertilizer' treatment, requirements were calculated using the soil diagnostic method first proposed by Jadin and Snoeck (1985) and further developed at CIRAD (*Centre International de Recherche en Agronomie pour le D éveloppement*, Montpellier, France). Subsequently, this method has been used and refined in cocoa production experiments in Ghana (Afrifa et al., 2009; Snoeck et al., 2010) and Ivory Coast (Koko et al., 2009). The method uses standard values derived from earlier research on the relation between cocoa soil nutrient status and yield, and is based on the optimization of: (i) the *N*/exchangeable bases ratio, either by changing *N* or the exchangeable bases (Mg, Ca, K) levels (optimum relation is given by: $Y = 8.9X - 6.15$, in which Y = sum of exchangeable bases, and X = total *N* in ‰); (ii) the proportions of K, Ca and Mg concentrations to 8%, 68% and 24% of exchangeable bases, respectively; and (iii) *N*/*P* ratio (ideally 1.5; N in ‰; P is total P and expressed as P_2O_5 in ‰) (Jadin and Snoeck, 1985).

Soil analysis results (Table 1) from the samples taken in the position halfway between the trees (to avoid blurring of soil nutrient status as a result of residues from recent fertilizer applications) at 20–40 cm depth (cocoa root area) were fed into an algorithm programmed in Excel by CIRAD on the basis of the aforementioned optimum soil conditions. In order to obtain adequate fertilizer recommendations, a number of other field parameters were also entered into the algorithm: soil depth (0.20 m), apparent density (1200 kg m^{-3}, determined using the soil core cutting method (Aysen, 2002) with Eijkelkamp rings of 100 ml; mean of 3 samples), cocoa tree age (22 years), plant density (1111 trees ha^{-1}), and area fertilized per tree (9 m^2—i.e. assuming fertilizers are broadcast over full area). Application of the soil diagnostic method subsequently resulted in a recommendation of 400 g K_2O per tree for soil restoration (to be spread over 3 years; i.e. 135 g per tree per year) and 60 g K_2O per tree per year for compensation of exports by yield. As a result, 195 g K_2O per tree per year was applied during the first three years, and 60 g K_2O per tree per year in the fourth year of the experiment. Furthermore, addition of 350 g per tree of MgO for soil restoration over 3 years (=120 g MgO per tree per year during the first three years) and 12 g MgO per tree per year for compensation of yield export was also recommended. As a result, 132 g MgO per tree per year was applied during the first three years, whereas 12 g MgO per tree per year was applied in the fourth year of the experiment. Based on the results of the soil diagnostic method, N, P and Ca proved to be sufficiently available in the soil, so that addition was not necessary. K was applied as muriate of potash (MOP) (KCl) (60% of K_2O) (330 g per tree per year), whereas Mg was applied as kieserite ($MgSO_4$) (27% MgO) (490 g per tree per year). MOP and kieserite were applied in two rounds (February and August) each year.

Organic fertilizers consisted of chicken dung pellets with NPK at a ratio of 5:5:5. Application rate was 8 kg per tree per year, split over 2 applications of 4 kg per tree, as recommended by Konam and Namaliu (2008). Appropriate amounts of both mineral and organic fertilizers applied to trees were collected by calibrated cups and applied in a circle with a radius of 1 m around the tree stem, following Wood (1975).

Table 1
Results of soil samples analysis at two depths (0–20 cm and 20–40 cm) and at two positions relative to the cocoa tree stems (i.e. close to the trees and in middle between the trees). CEC=Cation Exchange Capacity, P_{avail} = available P, P_{tot} = total P.

Soil parameter	Unit	Close		Middle	
		0–10 cm	20–40 cm	0–10 cm	20–40 cm
Sand[a]	%	–	–	–	12
Silt[a]	%	–	–	–	26
Clay[a]	%	–	–	–	62
pH–KCl		3.7	3.6	3.7	3.6
pH–H_2O		4.4	4.2	4.4	4.3
Total OC	%	1.81	1.23	1.32	1.45
C.E.C.[a]	cmol/kg	–	–	–	12.5
N (tot)%	%	0.16	0.12	0.13	0.14
P_{avail}	mg/kg	183	60	25	69
P_{tot}	mg/kg	917	432	401	500
Ca	mg/kg	1019	577	365	734
K	mg/kg	67	47	22	48
Mg	mg/kg	109	39	27	54
Na	mg/kg	21	20	8	18
Fe	mg/kg	2912	2708	2992	3025
Al	mg/kg	934	804	379	785
C/N		11.6	10.6	10.1	10.7

[a] Soil texture and cation exchange capacity (C.E.C.) were only determined for the samples in the middle between the trees at a depth of 20–40 cm.

2.8. Data collection

2.8.1. Cocoa production

Between 21 November 2011 and 12 March 2015, cocoa production was evaluated every fortnight during harvest seasons (November'11–May'12; September'12–March'13; October'13–March'14; November'14–March'15). A total of 38 harvest rounds was thus monitored. In August 2011, prior to treatment implementation, in the centre of each subplot, 6 cocoa trees were selected and tagged. During each harvest round (i) number of harvested pods; (ii) number of harvested pods with CPB infestation symptoms; (iii) number of harvested pods with Black Pod Disease symptoms; and (iv) wet bean yield (g) were recorded per tree. From the latter variables, share of 'bad' pods per tree (%) (i.e. those pods that were harvested, but had lost commercial value due to pulp affected by pests and/or diseases) and wet bean weight per pod (g) were derived. Prior to statistical analysis, the share of bad pods was arcsin(x)-transformed to enhance data normality.

In order to evaluate the effect of treatments on cocoa production, only data collected during the last 4 harvest rounds (28 November 2014–12 March 2015) (main harvesting season of 2014–2015) was statistically analysed because similar analysis (unpublished) of all harvests up to March 2014 did not reveal significant differences between treatments in their effect on cocoa production parameters. Data were recorded in MS-Excel, and the parameter values of the last 4 harvest rounds were summed per tree and subsequently statistically analysed through a three-way analysis of variance (ANOVA) of the split–split-plot design in SAS 9.2. For multiple comparison of parameter means between treatments, Duncan's Multiple Range Test was used.

2.8.2. Soil nutrient status

Two years after treatment initiation (August, 2013), the effect of fertilization treatments on soil nutrient status was evaluated, hypothesizing that more fertile soils will eventually positively influence cocoa productivity. Only subplots with (i) common practices; (ii) organic fertilizers; and (iii) mineral fertilizers were considered. From all 8 of each of these treatment subplots (i.e. from all replicate × agroforestry treatment × clone combinations), two samples were taken: one at a depth of 0–20 cm, and the other at a depth of 20–40 cm, both in the centre of the subplot as well as in the middle between trees. The thus obtained 8 samples per treatment were mixed and transported to Belgium for analysis of pH–H_2O, pH–KCl, TOC, total N, total P, available P, Ca, K and Mg following the same methods as described in § 2.6.2.

In March 2014 (2.5 years after treatment initiation), effect of cover crop on soil nutrient status was assessed. In the subplots of

PBC130 under full-sun cultivation, 5 samples per replicate (randomly distributed over the subplot, avoiding borders) were taken in the middle between trees, at a depth between 5 and 25 cm. The 10 samples that were thus obtained per treatment were mixed and transported to Belgium for analysis of pH–H_2O, TOC, available P, Ca, K and Mg following the same methods as described in § 2.6.2. NH_4 and NO_3 contents were determined by continuous-flow auto-analysis (ISO standard 13395) (Carlson et al., 2008).

2.8.3. Soil fauna

Healthy soils maintain a number of functions essential in agricultural production as well as in providing ecosystem services. The latter functions include the ability of the soil to transform carbon, cycle nutrients, maintain structure and regulate pests and diseases. Their quality depends on the interaction between soil biotic and abiotic factors (Kibblewhite et al., 2008). Soil fauna improves soil structure and speeds up the process of decomposition of organic material (Rousseau et al., 2012). As a result, soil fauna abundance (in mass or volume) as well as diversity are indicators of adequate soil quality which is a pre-condition of sustainable cocoa production. It was demonstrated that agricultural intensification leads to loss of soil macrofauna and micro-organisms (De Beenhouwer et al., 2013; Ponge et al., 2013).

The effect of cover crop treatment on soil fauna was assessed following standard methods proposed by The World Agroforestry Centre (Swift and Bignell, 2001). Epigeic (i.e. soil-creeping) and anecic (i.e. burrowing, but surfacing for feeding) macro- (>2 mm) and mesofauna (0.1–2 mm), including earthworms, termites, ants and beetles, woodlice (Isopoda), millipedes (Diplopoda), insect larvae, collembolans (springtails) and mites (Moreira et al., 2008) were trapped by pitfalls. Endogeic (i.e. underground) macrofauna was assessed by monolith analysis. Two areas were selected: two adjacent subplots with cover crop (one with common practice and the other with organic fertilizer treatment, both in full-sun cultivation and with cocoa clone PBC123); and a second control area consisting of two adjacent subplots without cover crop (also one with common practice and the other with organic fertilizer treatment, both in full-sun cultivation and with cocoa clone PBC123). Per area, 2 transects (8 m apart) of 20 m were made (Fig. 1). Per transect, we placed 5 pitfall traps (4 m apart). The latter consisted of glass jars (15 cm ø, 2.5 cm deep) that were dug in the ground (mouth flush with soil surface) in the late afternoon of 7 August 2012 (±1 year after cover crop planting), filled with water and a few drops of detergent (in order to break the surface tension so that trapped organisms immediately drowned), and protected against rain and tree litter fall by inversed plant pot saucers (20 cm ø) that were supported by three satay sticks so that saucers were at ±15 cm above glass jars. Pitfalls were emptied and their contents evaluated 24 h later.

In the same areas, monoliths at 3 sampling sites (each 8 m apart) along the first transect, and at 2 sampling sites (8 m apart) along the second transect were isolated (Fig. 1). The latter was done by excavating by spade a trench of 20 cm wide and 30 cm deep around a quadrat of 25 cm × 25 cm. The monolith up to a depth of 25 cm was then put in bags and subsequently analysed by breaking down the soil and identifying the faunal taxa found. Individuals collected in both pitfall and monolith samples were photographed. Pictures were subsequently compared with online images for identification of taxa at least down to class level and where possible, to order, genus or species level. Species classified at a given level (e.g. order Araneae), with morphologically clear differences, but without further classification were considered as different taxa.

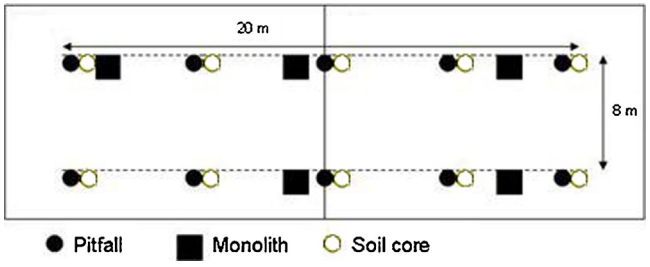

Fig. 1. Soil fauna sampling scheme, showing two 20 m transects, 8 m apart, stretched over 2 adjacent subplots with or without cover crop, one with common practice and the other with organic fertilizer treatment, both in full-sun cultivation and with cocoa clone PBC123.

Microfauna (nematodes) was assessed from 5 soil samples per transect per area that were taken by auger in the cocoa root strata (10–30 cm) (Fig. 1). Samples were put in bags, sealed to avoid desiccation, and transported to Belgium for analysis. Nematode quantification was done at the nematology department of the Diagnostic Centre for Plants at the Institute for Agriculture and Fisheries (ILVO) by passing 300 g soil diluted in 2 l of water through sieves of subsequently 50 mesh and 400 mesh after which nematodes were extracted by centrifugation and microscopically (for details see Swift and Bignell, 2001) quantified and identified down to genus level for plant parasitic nematodes and only quantified for the aggregated group of saprophagous nematodes (i.e. soil quality enhancing because feeding on dead or decomposing organic material).

Diversity of macro-, meso- and micro-fauna was assessed by calculating the species richness (R), Shannon (H') and Gini–Simpson ($1-\lambda$) indices (Pallman et al., 2012). Species richness (R) represents the total number of different species (or taxa) in a given dataset. The Shannon index (H') quantifies the uncertainty in predicting the taxon identity of an individual that is taken at random from the dataset. It is calculated as (1), in which R is species richness (see above) and p_i the proportional abundance of the ith taxon. The Gini–Simpson index ($1-\lambda$) equals the probability that two entities taken at random from a dataset represent different taxa; λ is computed as (2) in which R is species richness (see above) and p_i proportional abundance of the ith taxon. Diversity indices can be sensitive to abundances of rare, median and dominant taxa in populations (Beisel et al., 2003). Since in our samples 57% of endogeic and 93% epigeic and anecic fauna taxa were recorded only once or twice, the Pielou's Evenness (E_{Pielou}) index (3), which has a weak sensitivity to variations in rare taxa (Beisel et al., 2003), was also calculated. Nematode families can be ordered on a colonizer–persister (c–p) scale (ranging 1–5) which indicates the maturity of the soil in which they are found. The maturity index (MI) is then calculated as the weighted mean of the c-p-values of nematodes in a representative sample (Bongers and Ferris, 1999; Lei et al., 2015). Since our microfauna analyses distinguished plant parasitic from saprophagous nematodes (as a single group), the MI could not be calculated. Instead the Plant Parasitic Index (PPI) was computed, which is similar to the MI, but only includes plant parasitic nematodes and consequently indicates the soil carrying capacity of plants that are host to plant parasitic nematodes (Bongers and Ferris, 1999). C-p-values for the genera identified in our samples were obtained from Bongers (1990): 3 for *Helicotylenchus* spp., 3 for *Meloidogyne* spp. and 5 for *Xiphinema* spp.

$$H' = -\sum_{i=1}^{R} p_i \log p_i; \quad (1)$$

$$\lambda = \sum_{i=1}^{R} p_i^2; \quad (2)$$

and

$$E_{\text{Pielou}} = \frac{H'}{\ln(R)} \quad (3)$$

3. Results

3.1. Cocoa production

Of the initial 384 trees (6 trees per subplot × 8 subplots × 8 plots) that were selected for cocoa production monitoring, 43 (11%) had perished by the time they were evaluated (2 years and 4 months after experiment implementation) and were marked as missing values. Clear differences in number of perished trees prevailed between the different clones. In the plots with cocoa clone PBC123, only 3 and 4 trees had died under full-sun and agroforestry treatments over the treatment period, respectively. During the same period, in plots with cocoa clone PBC130, number of dead trees was 27 and 9, for trees under agroforestry and full-sun treatments, respectively.

Factor analysis (Table 2) reveals a highly significant ($p < 0.001$) effect of the main factor 'clone' on all parameters considered. The average PBC130 tree produced less than 1/10 of cocoa pods, and cocoa bean and pulp weight as compared with PBC123 trees (Table 3). Significant interaction effects were shown between factors clone and agroforestry for parameters 'wet bean weight' and 'share of bad pods' (Table 2). The agroforestry treatment had no effect on mean number of pods per tree for both clones, but increased mean wet bean weight per tree for cocoa clone PBC123 with 0.34 kg (46%), whereas it decreased mean wet bean weight per tree with 0.02 kg (20%). Furthermore, for trees under agroforestry, as compared with trees under full-sun, mean share of bad pods increased by 0.08 for PBC130 whereas for it decreased by 0.16 for PBC123 (Table 3) (Fig. 2).

Factor analysis further revealed significant ($p < 0.05$) differences between the main effects of the 8 soil treatments for parameters 'number of pods' and 'wet bean weight', but not for the factor 'share of bad pods' (Table 2). The best treatment (organic fertilizers + compost) resulted in double the mean number of pods produced and double the mean yield of trees in comparison with the worst-performing treatment (common practice + cover crop). However, the best performing treatment is not significantly increasing yield in comparison with the common practice (CP) control plot (Table 3).

3.2. Soil nutrient status

Soil acidity in the upper soil layer (0–20 cm) is (up to 1.5 units) higher in plots treated with organic and mineral fertilizers than in soil of common practice plots. In the lower (20–40 cm) layer, there is no effect of treatments on soil acidity levels. TOC, K, N and Mg contents of the upper soil layer treated with both organic and mineral fertilizers are higher in comparison with concentrations of these elements in soil of common practice plots. Contents of available P as well as Ca are higher in plots treated with organic fertilizers than in common practice control plots, but only in the upper soil layer. In the lower soil layer, contents of available P and Ca are substantially higher in plots treated with mineral fertilizers than in lower soil layers of common practice and organic fertilizer plots (Fig. 3).

C. pubescens as a cover crop increased the amounts of TOC, NO_3, available P, Ca, Mg and K in the 5–25 cm soil layer in comparison with control plots without cover crop. No increase in pH–H_2O or NH_4-contents was observed in plots which had the cover crop as compared with control plots (Table 4).

3.3. Soil fauna

In the 10 pitfalls installed in the subplots with cover crop, 16 different organisms were collected belonging to 9 different insect taxa. In the pitfalls of the control subplots, 29 organisms were found that belong to 19 different taxa (Table 5). Diversity indices R, H' and $1 - \lambda$ were higher in control subplots than in cover crop subplots, whereas E_{Pielou} was higher in cover crop subplots compared with control subplots (Table 6). Analysis of the 5 monoliths taken from the subplots with cover crop revealed 9 different taxa, whereas only 5 different taxa were observed in the monoliths of the control subplots (Table 5). Diversity indices R, H', $1 - \lambda$ and E_{Pielou} were higher in cover crop subplots than in control subplots (Table 6).

Among identified microfauna (nematode) species, *Helicotylenchus* sp. was most abundantly present, with a mean number of 67 individuals per sample. Two samples from the cover crop plots contained respectively 1 and 2 *Xiphinema* sp., and 1 sample from the control plot contained 1 *Meloidogyne* sp. (Table 5). Data on the number of saprophagous nematodes had one outlier (1968 individuals) in a sample of the cover crop plot. Removing the latter value and considering just two nematode groups (parasites and saprophagous nematodes), it was shown (T-test; $p > 0.5$) that nematode abundances did not differ significantly between cover crop plot samples (65 ± 18 (SE) parasitic and 27 ± 5 (SE) saprophagous nematodes) and control plot samples (69 ± 11 (SE) parasitic and 25 ± 6 (SE) saprophagous nematodes). Although not statistically tested, neither diversity indices R, H', $1 - \lambda$ and E_{Pielou} or the PPI were different between cover crop and control subplot samples (Table 6).

4. Discussion

Huge differences in production can be observed between the two cocoa clones (PBC123 and PBC130) in our study. Notwithstanding high weights (up to 691 g) reported for individual PBC130

Table 2
Factor analysis of the number of pods, wet bean weight (kg), and the arcsin(x)-transformed share of bad pods evaluated between 28 November 2014 and 12 March 2015 (i.e. between 2 and 3 years after experiment implementation). Where factors or interaction effects are significant at the 0.05 and 0.001 level, they are indicated by * and ** respectively.

Factor	Number of pods		Wet bean weight		Share of bad pods (transformed)	
	F	p	F	p	F	p
Clone	164.87	**0.00	116.59	**0.00	14.12	**0.00
Agroforestry	0.01	0.91	5.07	*0.03	3.61	*0.04
Soil Treatment	2.37	*0.02	2.03	*0.04	1.32	0.24
Clone × agroforestry	0.00	0.95	5.91	*0.02	3.80	*0.04
Clone × soil treatment	1.23	0.29	1.14	0.34	1.19	0.10
Agroforestry × soil treatment	0.84	0.55	0.72	0.65	1.01	0.43
Clone × agroforestry × soil treatment	1.21	0.30	1.23	0.29	2.55	0.06

Table 3
Mean (±SE) number of pods, wet bean weight (kg) and% of bad pods harvested between 28 November 2014 and 12 March 2015 (between 2.3 and 2.6 years after implementation of experiments) under factor combination clone x agroforestry (with significant interaction effects on wet bean weight and share of bad pods) (above) and main effects of the soil treatment factor (below). For the soil treatment factor, different lower-case letters indicate significant ($p < 0.05$) differences (revealed by Duncan's Multiple Range Test) between mean values. CP = common practice, OF = organic fertilizers, MF = mineral fertilizers.

		Number of pods	Wet bean weight (kg)	Share of bad pods
Clone × agroforestry				
Full-sun	PBC130	1.4 ± 0.4	0.10 ± 0.03	0.25 ± 0.06
	PBC123	17.2 ± 1.4	0.74 ± 0.07	0.32 ± 0.03
Shade	PBC130	1.5 ± 0.4	0.08 ± 0.02	0.33 ± 0.07
	PBC123	17.2 ± 1.7	1.08 ± 0.12	0.16 ± 0.02
Soil treatment				
OF + compost		13.9 ± 1.6a	0.73 ± 0.16a	0.30 ± 0.04a
CP		12.6 ± 1.7a	0.62 ± 0.17a	0.23 ± 0.05a
MF + cover crop		8.8 ± 1.8ab	0.53 ± 0.15ab	0.22 ± 0.04a
MF + compost		8.6 ± 1.9ab	0.57 ± 0.11ab	0.28 ± 0.04a
OF + cover crop		8.6 ± 1.7ab	0.50 ± 0.09ab	0.18 ± 0.04a
OF		7.7 ± 1.7b	0.44 ± 0.11ab	0.22 ± 0.05a
MF		7.3 ± 1.7b	0.44 ± 0.10ab	0.23 ± 0.05a
CP + cover crop		6.9 ± 1.7b	0.31 ± 0.08b	0.35 ± 0.07a

cocoa pods (Noordiana et al., 2007), total average yield (measured by mean wet bean weight per tree) of PBC130 trees in our experiments was just one tenth of that of PBC123 trees. Because the experimental plantation is highly infested with pests (mainly *Conopomorpha cramerella*, i.e. the Cocoa Pod Borer (CPB)) and diseases (mainly *C. theobromae*, i.e. Vascular Streak Dieback (VSD)) (Vanhove et al., 2015), observed yield differences might be attributed to the superior resistance against CPB of clone PBC123 (Teh et al., 2006). However, the latter hypothesis is not supported by our finding that although the mean number of PBC130 pods per tree is significantly lower (less than 1/10) than that of PBC123 pods, the share of bad pods was significantly higher for PBC123 trees in comparison with that observed on PBC130 trees. Also McMahon et al. (2015) reported highest cocoa yield for PBC123 trees among 12 local clones in Sulawesi, Indonesia. As a result, physiological differences rather than differences in tolerance or resistance against pests and diseases between PBC130 and PBC123 most probably explain yield differences between the latter clones. McMahon et al. (2015) further found significant interaction effect of clones and sites (cocoa trees from 3 different provinces were evaluated in their tests). In our experiment, we found an interaction effect of factors clone and agroforestry: the agroforestry treatment had a negative effect on yield of PBC130 trees, whereas a positive effect of the agroforestry treatment was observed on yield of PBC123 trees (see §3.1.).

Shade trees in cocoa agroforestry systems will compete with cocoa trees for nutrients and light, which can have a negative effect on cocoa yield/ha (Beer et al., 1998; Bisseleua et al., 2013; Clough et al., 2011; Somarriba et al., 2013; Waldron et al., 2012). Assuming that dry bean weight is 44% of fresh bean + pulp weight in cocoa pods (Braudeau, 1969; Deheuvels et al., 2012), we can extrapolate average yield in our cocoa agroforestry and full-sun control plots to 318 and 210 kg/ha, respectively. These numbers are below the world cocoa average yield, which was 458 kg dry beans/ha in 2013 (Vaast and Somarriba, 2014). In a study on 36 cocoa agroforests in Talamanca, Costa Rica, Deheuvels et al. (2012) also report low cocoa production rates (mean yield was 136 ± 8 (SE) kg of dry beans/ha) and found no significant differences in cocoa yield/ha between 4 agroforestry clusters with varying densities of cocoa versus shade trees. In our experiments, however, where shade trees (predominantly *Musa* sp.) were planted in between mature cocoa trees (not affecting the original cocoa density of 1111 trees/ha), the beneficial effect of shade on cocoa production outweighed potential competition with shade trees. Since shaded cocoa in Malaysia is reported to have a potential yield of 700–1000 kg/ha (Wessel and Gerritsma, 1994), and since the effect of the agroforestry treatment on mean number of pods per tree was not significant ($p = 0.91$), the significant ($p < 0.05$) effect on mean wet bean weight per tree might be explained by the significant ($p < 0.05$) reduction by the agroforestry treatment of bad pod% (Table 3) and thus by the pest-suppressing effect of our agroforestry treatment.

In Ghana, a positive and significant ($p < 0.001$) correlation was found between density of intercropped banana plants and number

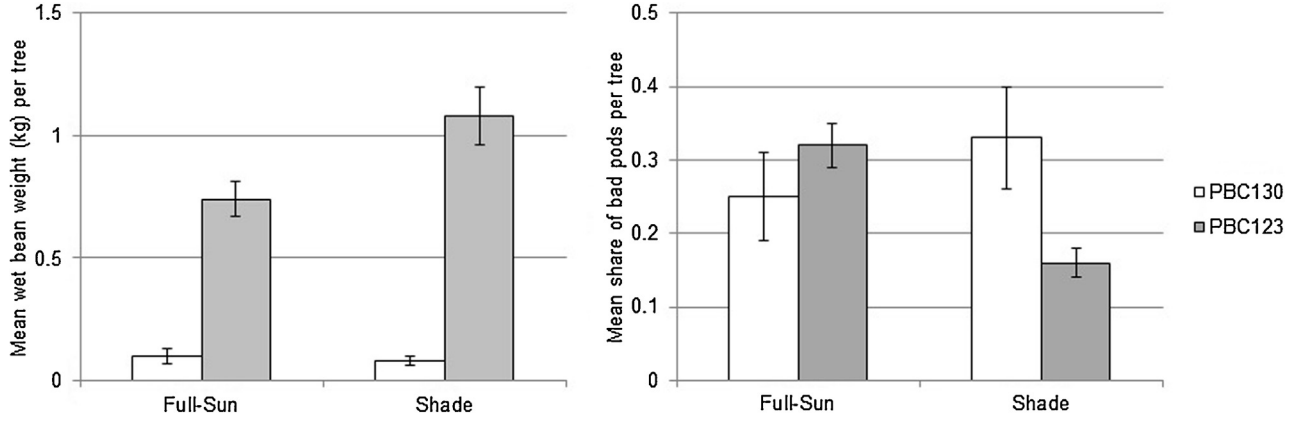

Fig. 2. Mean wet bean weight (kg) (±SE) per tree (left) and mean share of bad pods (±SE) per tree (right) of trees of cocoa clones PBC130 and PBC123 under full-sun and agroforestry cultivation.

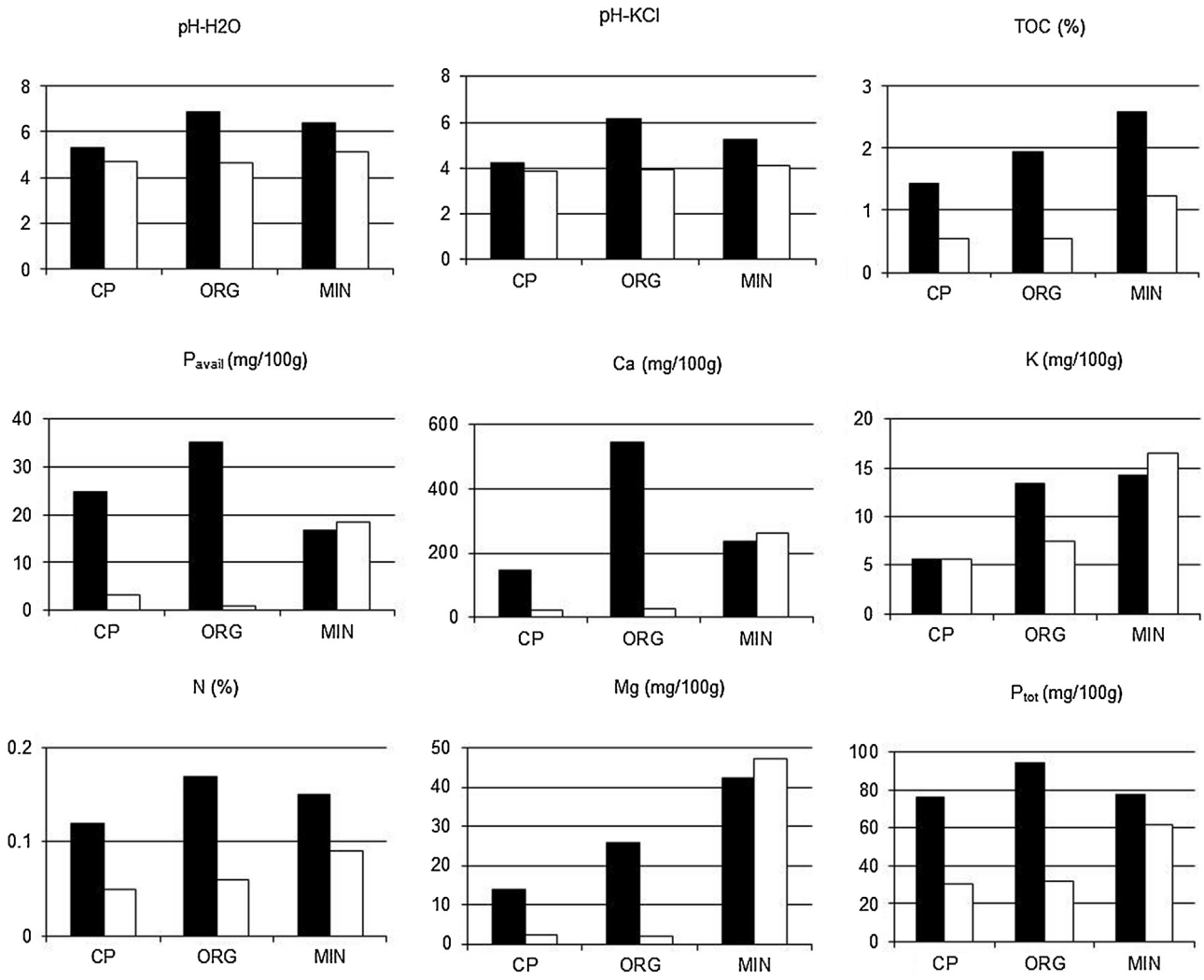

Fig. 3. Soil parameters evaluated 2 years after treatment initiation (August 2013), in the 0–20 cm soil layer (black bars) and the 20–40 cm soil layer (white bars) measured in common practice control plots (CP) and in plots treated with mineral fertilizers (MIN) and organic fertilizers (ORG). TOC = total organic carbon, P_{avail} = available P, P_{tot} = total P.

of trapped cocoa pollinating midges (Order Diptera, Family Ceratopoganidae) (Frimpong et al., 2011). Although Groeneveld et al. (2010) showed that increased pollination of cocoa flowers by 10–40% increases the number of mature pods and yield, we did not find a significant effect of the agroforestry treatment on the number of pods harvested per tree. More research is needed to reveal the links between rehabilitation by means of intercropping of shade trees, presence of pollinating midges, pod set and yield.

Post-hoc multiple comparison of the effects of 8 soil treatments on mean number of pods per tree and on mean wet bean weight per tree (Table 3) does not reveal clear differences between (groups of) treatments. The common practice control plot is ranked second for both production parameters whereas its effect does not significantly ($p < 0.05$) differ from the best-performing treatment of organic fertilizers in combination with compost. Despite that the soil diagnostic method (Jadin and Snoeck, 1985), which is based on measured soil parameters, has been hailed as a powerful tool in tailoring fertilization to specific needs of cocoa fields (Afrifa et al., 2009; Koko et al., 2009; Snoeck et al., 2007, 2010), the effect on yield of all mineral fertilizer treatments, either alone or in combination with cover crop or compost treatment, does not differ significantly ($p > 0.05$) from that of the common practice control treatment. The soil diagnostic method did not result in a recommendation for N or P fertilization. As a result, our addition of only K and Mg – despite increased levels observed after two years in the 20–40 cm zone in the mineral fertilizer plots in comparison with the common practice and the organic fertilizer plots (Fig. 3) – did not result in an increase in cocoa production in comparison with plots which received the common practice compound NPK treatment or with the organic fertilizer treatment. We suggest that the soil diagnostic method might be more effective in addressing fertilization needs of intensely weathered soils of West-African cocoa production systems (Snoeck et al., 2010) rather than in larger-scale cocoa plantations, such as that of the Selborne estate,

Table 4
Soil parameters evaluated 2.5 years of treatment initiation (March 2014) in the 5–25 cm layer in common practice control plots (CP) and in the common practice + cover crop plots (CP + COV). TOC = total organic carbon, P_{avail} = available P.

Treatment	pH (H_2O)	TOC (%)	N(NO_3) (mg/kg)	N(NH_4) (mg/kg)	P_{avail} (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)
CP	3.9	1.1	7.5	5.9	22.1	265.1	45.4	59.6
CP + COV	3.9	1.4	16.2	5.8	49.8	331.1	53.2	85.6

Table 5
Abundances of epigeic, anecic and endogeic macro- and meso-fauna taxa found in both cover crop as well as control cocoa subplots. Taxa were identified up to the most detailed level possible (Class, Order, Family, species). Taxa followed by different numbers were morphologically different, but were not further classified.

	Cover crop plot	Control plot
Endogeic fauna (monoliths)		
Termite (Order Isoptera)	495	1
Centipede (Class Chilopoda)	6	1
Millipede (Class Diplopoda)	1	
Earthworm (Order Megadrilaceae)	6	3
Ant (Fam. Formicidae)	128	333
Weaver ant (*Oecophylla smaragdina*)	2	
Silverfish (Fam. Lepismatidae)	1	1
Spider (Order Araneae)	1	
Earwig (Order Dermaptera)	2	
Total	642	339
Epigeic and anecic fauna (pitfalls)		
Termite (Order Isoptera)		1
Earwig 1 (Order Dermaptera)	2	1
Earwig 2 (Order Dermaptera)		1
True bug 1 (Order Hemiptera)	2	1
True bug 2 (Order Hemiptera)	2	
True bug 3 (Order Hemiptera)		1
Moth (Order Lepidoptera)	2	
Ant 1 (Fam. Formicidae)	2	6
Ant 2 (Fam. Formicidae)		1
Weaver ant (*Oecophylla smaragdina*)	2	1
Beetle (Order Coleoptera)	1	
True fly 1 (Order Diptera)	1	
True fly 2 (Order Diptera)	2	6
Spider 1 (Order Araneae)		1
Spider 2 (Order Araneae)		1
Spider 3 (Order Araneae)		1
Spider 4 (Order Araneae)		1
Spider 5 (Order Araneae)		1
Spider 6 (Order Araneae)		1
Spider 7 (Order Araneae)		1
Spider 8 (Order Araneae)		1
Spider 9 (Order Araneae)		1
Spider 10 (Order Araneae)		1
Total	16	29
Microfauna (nematodes)		
Helicotylenchus sp.	651	685
Xiphinema sp.	3	0
Meloidogyne sp.	0	1
Saprophagous nematodes	1938	245
Total	2592	931

which had been subjected to intense mineral (NPK) fertilization during several decades.

Soil nitrate concentration in plots with the *C. pubescens* cover crop is more than double that of soil in the common practice control plots (Table 4), which confirms findings of Schroth et al. (2001b) who found a significantly higher nitrogen mineralization in soils of cocoa plots with the leguminous *Pueraria phaseoloides* cover crop in comparison with monocrop cocoa or cocoa intercropped with rubber (*H. brasiliensis*) or peach palm (*Bactris gasipae*). Also available P concentrations in the soil of plots with cover crop were more than double that of soil in the common practice plots (Table 4), which can be explained by the fact that leguminous cover crops (i) mine P from deeper soils; (ii) incorporate previously occluded P into organic matter; and (iii) prime microbial-mediated P cycling in the upper soil horizons through root exudation (Fageria and Stone, 2006; Lambers et al., 2006). In a study on a Peruvian cacao agroforestry system, Hall et al. (2010) found a significantly ($p < 0.05$) higher amount of soil organic matter (SOM) in the 5–15 cm soil layer of plots with cover crop species *Canavalia ensiformis* (4.8%), *Calopogonium mucunoides* (5.2%) and *Callisia repens* (5.2%) than in the same soil layer of control plots (4.1%). According to Pribyl (2010), the SOM to TOC ratio is in most cases 2. Using the latter conversion factor, in our study we found a higher (but not statistically tested) amount of SOM in the 5–25 cm soil layer of cover crop (*C. pubescens*) plots (2.8%) than in control plots (2.2%).

Soil ecosystem health depends on biotic and abiotic soil factors. Although indicators of both factor types are often used as a proxy of soil health, some have a higher weight than others in indicating the capacity of the soil to maintain agricultural production and provide ecosystem services (Ekschmitt et al., 2003; Thomsen et al., 2012). Rousseau et al. (2012) report that in Costa Rican cocoa agroforestry systems, a limited set of soil quality indicators (bulk density, sum of bases, pH and TOC) correlated well with soil macrofauna abundance and is able to separate cocoa agroforestry systems into five distinct clusters along a low-to-high soil quality gradient.

Based on the latter study results and given that the cover crop used in our experiments improved 3 of the relevant indicators highlighted by Rousseau et al. (2012) (sum of bases, pH and TOC), a positive effect of our cover crop treatment on soil fauna was hypothesized in our experiments. The latter proved to be the case for endogeic but not for epigeic and anecic macro- and mesofauna found in monoliths and pitfalls, respectively (Table 6). In cocoa agroforestry systems in Bahia, Brazil, Moço et al. (2009) found that the cocoa litter layer contains significantly ($p < 0.05$) more invertebrate individuals in the litter (2.094/m^2) as compared with the soil (641/m^2), whereas Moço et al. (2010) report that soil and litter fauna richness is more sensitive to litter quality (defined by nutrient concentrations and palatability) than to soil quality. In our experiments, litter fauna is assumed to have also been recorded in the pitfalls so that the contrasting finding of lower epigeic an

Table 6
Diversity indices: species richness (R), Shannon (H'), Gini–Simpson ($1-\lambda$) and Pielou's evenness (E_{Pielou}) of epigeic, anecic and endogeic macro- and meso-fauna, and of microfauna (nematodes), and plant parasite index (PPI) of microfauna found in both cover crop as well as control cocoa subplots.

	Diversity index	Cover crop subplots	Control subplots
Endogeic fauna (monoliths)	R	9	5
	H'	0.29	0.05
	$1-\lambda$	0.37	0.03
	E_{Pielou}	0.13	0.03
Epigeic and anecic fauna (pitfalls)	R	9	19
	H'	0.94	1.14
	$1-\lambda$	0.88	0.89
	E_{Pielou}	0.43	0.39
Microfauna (nematodes)	R	3	3
	H'	0.25	0.25
	$1-\lambda$	0.38	0.39
	E_{Pielou}	0.23	0.23
	PPI	0.005	0.004

anecic macro- and mesofauna in the cover crop plot as compared with the control plot, is possibly explained by the creation by the cover crop of a more favourable environment for epigeic fauna, but whereby cover stems and leaves, rather than the soil surface is the preferred biotope of these species. As a result, increased abundance of epigeic fauna would have remained unnoticed by our monitoring method using pitfalls. More research is needed to confirm this hypothesis.

Tondoh et al. (2015) found that earthworm abundance and species richness in the soil of full-sun cocoa cultivation systems in Oumé department, Ivory Coast, increased with plantation age due to earthworm species adaptation to degraded lands, whereas Kilowasid et al. (2013, 2014),) did not found significant influence of plantation age (samples from plantations of 4, 5, 7, 10 and 16 years old) on abundance, species richness or Shannon diversity indices of endogeic fauna in smallholder cocoa plantations in Sulawesi, Indonesia. Although species richness is (10 on average) is in the range of our findings ($R = 9$ and 5 for endogeic fauna in the cover crop and control subplots, respectively) (Table 6); the Shannon diversity index is considerably lower ($H' = 0.29$ and 0.05 for endogeic fauna in the cover crop and control subplots, respectively) as compared with the average value of 2.5 in the study of Kilowasid et al. (2013). The latter difference is due to the relatively high abundance of ants and termites in our samples (Table 5). The treatment with cover crop did not result in differences in microfauna (nematode) abundances, diversity indices or Plant Parasitic Index (PPI) (Table 6). Considering saprophagous nematodes as a single group may have concealed microfauna diversity, however. Future research should therefore consider identification of all nematode trophic groups (bacterial-feeding, fungal feeding, plant feeding and omnivorous and predatory nematodes) (Lei et al., 2015).

Despite the recorded positive effects of the cover crop treatment on soil quality indicators, none of the cover crop soil treatments resulted in significant cocoa yield differences with the common practice control plots. Although compost application rates were below those (7.5 t/ha) recommended by Dalzell et al. (1987) for tropical crops, the effect on the number of harvested cocoa pods of the combination of compost with organic fertilizer treatment proved to be significantly ($p < 0.05$) higher than that of some other treatments without compost application (organic fertilizers, mineral fertilizers and common practice + cover crop) (Table 3). Nevertheless, no significant difference in the effect on yield parameters between any treatment that included compost application and that of the common practice without compost could be evidenced. Further research should investigate whether soil improving treatments such as compost application and cover crop planting require more time to have a significant effect on old, degraded cocFiguroa trees or whether rehabilitation of the latter trees is not possible by soil management alone.

5. Conclusions

In this paper we examined several combinations of agricultural interventions in an old, monocropped cocoa plantation in view of finding a sustainable increase of its production. The observed average yield gap between the best- and the worst-performing cocoa clone at the plantation was 90%, meaning that genetic improvement of cocoa plantations, by introducing clones that better resist pests and diseases and that are better adapted to local climate and soil conditions, can be an important element of rehabilitation of degraded cocoa plantations. Top working, by grafting improved clones on mature cocoa trees (Pranowo, 2012), can be a quick and cost-effective way of renewing cocoa plantation genotypic composition.

Our results on the effects of planting shade trees in between cocoa trees show that a simple agroforestry system with shade predominantly provided by banana plants, after 3.5 years already has positive effect on production. This means that despite economic incentives and cultural preferences for intensification practices (such as more targeted fertilization and pesticide application) (Steffan-Dewenter et al., 2007), shade tree planting can be relatively more rewarding to producers. The higher economic returns of the global cocoa agroforestry system in comparison with the monocrop cocoa systems (Ramírez et al., 2001) have not been quantified in our study, but selling products of shade trees would provide an additional incentive for cocoa growers to intercrop degraded cocoa plantations with shade trees. Given the fact that we found a significant interaction between shade treatment and considered clones in the effect on cocoa yield, cocoa breeding programmes should not exclusively focus on developing clones with high yield potential, high quality bean composition (e.g.% of butterfat) or resistance against pests and diseases, but also on clones that maintain these characteristics in shaded agroforestry systems, rather than in intensified, monocrop full-sun coco systems as is currently the general rule.

The 8 evaluated soil treatments did not result in the anticipated effect on cocoa yield. It is possible that it takes more than 1 year before new land use systems, such as those tested in our study, have a measurable effect on the production of perennial crops such as cocoa. More likely, factors other than soil quality have been responsible for the declining and currently low yield at the plantation. The latter factors might be related to pests and disease incidence, as well as to physiological stress conditions due to shade removal. Our results indicate that the latter constraints can be more effectively tackled by implementing simple agroforestry practices in combination with optimum clones, than with soil amendment practices. More research is needed to investigate whether rehabilitation of deteriorated plantations as investigated in our research, from an economic and ecological perspective outperforms cocoa replanting in agroforestry systems.

Conflict of interest

The authors state no conflict of interest.

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