1 **Shade trees have limited benefits for soil fertility in cocoa agroforests**

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13 Abstract

14 Agroforestry is often promoted as a sustainable agricultural practice that can
15 ameliorate causes of declining yields, such as soil degradation. However, despite the
16 often-stated potential of agroforestry, quantitative data on the benefits of shade trees
17 are limited to relatively few cropping systems, particularly maize and coffee.
18 Furthermore, agroforests are not cost-free and the benefits of agroforests might not be
19 sufficient to outweigh these costs in all cropping systems or environments. Here we
20 quantify costs and benefits of agroforests for cocoa production in Ghana, **West Africa**.
21 Specifically, we quantified the ability of shade trees to increase soil carbon stocks and
22 soil fertility (i.e. total soil carbon, nitrogen and phosphorus, available phosphorus and
23 potassium, cation exchange capacity, soil aggregation, pH, and foliar nitrogen and
24 phosphorus **concentrations**), and investigate if these benefits are sufficient to
25 outweigh the negative effects of shade trees on cocoa growth and yields. We
26 measured cocoa yields, soil fertility and carbon-sequestration under **individual** shade
27 trees, and in 30 x 30 m plots **that were distributed along** a gradient of shade-tree cover
28 **(plot-scale)**. We found localized positive effects of **individual** shade trees on soil
29 carbon and nitrogen content, as well as soil aggregation. **However, we found** no
30 evidence for positive effects of agroforests via improved soil fertility or carbon-
31 sequestration **with increasing shade-tree cover at the plot scale, a scale that** more
32 closely matches the scale at which agroforests are managed. Cocoa growth was lower
33 **under individual shade trees and decreased with increasing shade-tree cover in plots,**
34 and **cocoa** yields **also** decreased with increasing shade-tree cover. Our results indicate
35 that **the** benefits of agroforestry **for** soil fertility and carbon sequestration in cocoa
36 cultivation systems might not be as extensive as believed, and may not be sufficient to
37 compensate for short-term costs to production.

38 **Keywords**

39 agroforestry, carbon sequestration, cocoa **yield**, soil fertility, sustainable agriculture,

40 *Theobroma cacao*, ecosystem services.

1. Introduction

Agroforestry – the deliberate inclusion of trees in agricultural systems – is often believed to mitigate ongoing threats to agricultural production, while also maintaining essential ecosystem services (Jose, 2009; Tscharntke *et al.*, 2011). The benefits associated with agroforestry, including climate buffering, carbon sequestration, pathogen regulation, and improvements in soil fertility, are often taken to be broadly applicable to a wide range of cropping systems and climatic zones, but the majority of the quantitative evidence is concentrated in just a few, particularly coffee and maize (Sanchez, 1995; Rhoades, 1996; Kwesiga *et al.*, 2003; Jose, 2009; Nair and Nair, 2014). The extent to which the benefits of agroforestry are transferrable to other systems is largely unknown but important given that agroforests are widely promoted (Tscharntke *et al.*, 2011; Vaast *et al.*, 2016).

One of the more significant crops for which production in agroforests is promoted is cocoa. Worldwide demand for cocoa continues to increase even as production declines as a consequence of multiple factors including pests and disease, declines in soil fertility, and an increasingly hotter and drier climate (Franzen and Borgerhoff Mulder, 2007; Clough *et al.*, 2009; Läderach *et al.*, 2013; Vaast and Somarriba, 2014). Given these ongoing threats, implementing cocoa production in agroforests would seem to make intuitive sense but data that is specific to cocoa systems is limited. Furthermore, agroforests are not cost-free and the benefits of agroforests might not be sufficient to outweigh these costs in all cropping systems or environments. Most critically, agroforests often result in reductions in short-term yields (Sanchez, 1995; Tscharntke *et al.*, 2011), which is a major reason it is difficult to encourage their implementation. This is particularly the case among small-holder cocoa farmers in Africa (Ruf, 2011). If agroforests are to best meet future

sustainability needs it is necessary to demonstrate that the benefits are sufficiently large to justify their implementation.

One of the major proposed benefits of agroforests is their ability to mitigate the worst effects of soil degradation by maintaining soil fertility. Such a benefit would be particularly important for cocoa systems, which tend to be nutrient-depleted because nutrients exported from the system with each crop are generally not replaced through fertilization (Appiah *et al.*, 1997; Hartemink, 2005). While there is some anecdotal evidence from interviews with farmers that shade trees improve soil fertility in cocoa systems (e.g. Anglalaere *et al.*, 2011; Atkins and Eastin, 2012; Dumont *et al.*, 2014), the existing empirical evidence is limited and equivocal. With respect to soil carbon (C), Ofori-Frimpong *et al.* (2007) showed increases, while Gockowski and Sonwa (2011), Jacobi *et al.* (2014), and Mohammed *et al.* (2016) showed no effect of shade trees. With respect to mineral nutrients essential for plant growth, Ofori-Frimpong *et al.* (2007) showed increases in nitrogen (N), phosphorus (P) and potassium (K) in a fertilized, research station trial; Isaac *et al.* (2007) showed increases in one soil exchangeable nutrient (K) but not in others (N and P), but generally increased foliar nutrient levels of cocoa under **individual** shade trees. Given these limited and contrasting results, it remains an open question whether shade trees generally increase soil fertility and perhaps more importantly, whether these increases are sufficient to sustain yields. Moreover, to our knowledge no study has quantified the effects – positive or negative – of shade trees on an array of soil fertility parameters in cocoa agroforestry systems as implemented by farmers themselves; that is, in existing low-input, small-holder fields and along a continuum of shade-tree density.

An additional benefit of agroforests rests on their potential to sequester carbon. Agroforests have long been considered a greenhouse gas mitigation strategy,

91 including under the Kyoto Protocol, and the climate mitigation potential of
92 agroforests remains a major motivation for promoting their implementation (Nair *et*
93 *al.*, 2009). While it is clear that agroforests can store substantial C in above-ground
94 biomass (Gockowski and Sonwa, 2011; Jacobi *et al.*, 2014; Obeng and Aguilar,
95 2015), substantial questions remain about the ability of agroforests to enhance C-
96 sequestration in soils. In particular, while soil C tends to be higher in cocoa systems
97 compared to annual production systems (Guo and Gifford, 2002; Dechert *et al.*,
98 2004), it is unclear if the addition of shade trees in cocoa systems provides any
99 additional C-sequestration benefit (see contrasting results in Ofori-Frimpong *et al.*
100 (2007), Gockowski and Sonwa (2011), Jacobi *et al.* (2014), and Mohammed *et al.*
101 (2016)). Furthermore, it is also important to understand the extent to which C-
102 sequestration in cocoa agroforests compares with the C-sequestration ability of the
103 natural forests that they have replaced (Guo and Gifford, 2002; Leuschner *et al.*,
104 2013; Obeng and Aguilar, 2015).

105 To further our understanding of the extent to which agroforests might improve
106 the sustainability of cocoa production, we addressed the following question: do shade
107 trees in cocoa agroforests increase soil carbon stocks and soil fertility, and are these
108 benefits sufficient to result in net positive effects of shade trees on cocoa growth and
109 yield? Importantly, we investigated these questions using two commonly used
110 sampling approaches. First, we determined the effect of individual shade trees on soil
111 fertility. To quantify the effects of individual shade trees we chose shade trees that
112 were growing with cocoa but isolated from the canopy of other shade trees. (Fig. 1).
113 Second, we extended our assessment to determine if the effects of individual shade
114 trees can be used to understand effects of larger numbers of trees across plots of larger
115 size (plot-scale, Fig. 1). Both sampling approaches (individual-tree and plot-scale

assessments) are commonly used to study tree-understory-interactions, but the outcome of tree-understory interactions can manifest differently depending on the approach used (Riginos *et al.*, 2009). Comparing these different approaches for assessing the effectiveness of shade trees on cocoa production is important because we need to know if assessments of the effects of individual shade trees can provide adequate information for farm management at larger scales.

2. Materials and methods

2.1 Study site

The study was done in one of the major cocoa growing regions in Africa, in the moist semi-deciduous tropical zone of the Ashanti Region of Ghana, around the villages Gogoikrom, Katatwoa and Akonkyi, located in the Atwima district (06°40' N and 01°57' W). The soils in the area are dominated by Acrisols. Mean annual precipitation ranges between 1700-1850 mm with rains occurring in two separate rainy seasons (March to July and September to November). Mean monthly temperatures range between 27-31° and mean relative humidity is generally high throughout the year (75-87%, Anglaaere *et al.*, 2011). The study area contains a large number of cocoa farms with variable shade-tree cover (including monocultures), as well as a selectively-logged natural forest remnant.

2.2 Assessing the effects of individual shade trees

2.2.1 Selection of individual shade trees

To assess the local effects of individual shade trees on soil fertility parameters and cocoa growth, we selected 32 individual shade trees across eleven cocoa farms in May 2014 (Fig. 1, Table A). All of the selected shade trees in this sampling approach were surrounded by cocoa and had cocoa growing in their subcanopy, however, each

individual shade tree was isolated from the canopy of other shade trees by at least 30 m. This approach allowed us to quantify the local effects of individual shade trees within cocoa farms. Each selected shade tree represented a different shade-tree species commonly found in cocoa farms in the Atwima district (cf. Anglaaere *et al.*, 2011, personal observation). Our selection included most species recommended for use in Ghanaian cocoa farms (Opoku-Ameyaw *et al.*, 2010). Species were not replicated because we were interested in general effects of shade trees across the full range of species commonly found in Ghanaian cocoa farms. In the rest of the manuscript we will refer to these trees as “individual shade trees”.

For each individual shade tree we assessed effects on soil fertility and cocoa growth parameters by taking measurements directly under the shade-tree canopy (‘subcanopy’) and in open control areas where cocoa grows in the absence of shade trees (‘open’; Fig. 1). Subcanopy areas and open areas for each shade tree were sampled as pairs within the same farm, so that each shade tree had its own paired control location. Open areas were sampled within cocoa but away from the influence of the focal shade tree, at a minimum distance of twice the radius of the canopy from the trunk of the shade tree, or at a minimum distance of 12 m from the canopy edge if the canopy radius was less than 5 m. Sampling procedures for each parameter are described in the sections below (section 2.2.2 and 2.2.3).

2.2.2 Soil sampling and analysis

In May 2014, we collected two soil samples in the subcanopy area, and two soil samples in the open areas away from shade trees, around each individual shade tree. Sampling was done under the canopy of cocoa trees, in both subcanopy and open areas (Fig. 1). All subcanopy soil samples were collected, at a distance of half the

radius of the canopy from the base of the trunk of each shade-tree. The purpose of this sampling approach was to ensure samples were always taken in the subcanopy area of shade trees and resulted in an average sampling distance from the trunk of each shade tree of 2.93 ± 0.2 m.

Soils were sampled at three depths after carefully removing the litter layer; topsoil samples (0-15 cm) were sampled with a hammer corer ($\varnothing$ 5.5 cm), and subsoil samples (15-30 cm and 30-50 cm) were collected using a soil auger. Soil bulk density was calculated based on the weight of topsoil core samples after correcting for soil moisture and the mass and volume of roots and stones (Culley, 1993). Topsoils were then gently sieved through an 8 mm sieve and air-dried. After drying, soil samples were composited for each location (subcanopy/open) and soil-layer combination. This resulted in two composited soil samples per focal shade tree ($n=64$, 32 pairs) for each soil depth.

A subsample of 80 g of all composited topsoil samples was fractionated by means of wet sieving to determine the aggregation status of soils as described by Six et al. (2000). We then calculated the mean weight diameter (MWD) of aggregate distributions as:

$$MWD = (2 * LM) + (1.125 * sM) + (0.1515 * m) + (0.0265 * (s + c))$$

where LM represents the percentage of large macroaggregates, sM the percentage of small macroaggregates, m the percentage of microaggregates, and $(s + c)$ the percentage of unaggregated silt and clay in each soil sample. All aggregate fractions were subsequently dried, ground, and total C and N contents of each aggregate fraction were determined using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN).

The remaining composite samples from all soil layers were then dried to

constant weight at 105° C, passed through a 2mm sieve and ground. At the Soil Research Institute in Ghana (CSIR-SRI) we determined pH potentiometrically in 0.01 M CaCl₂ solution (Houba *et al.*, 1995). Cation exchange capacity (CEC) was determined at pH 7 with ammonium acetate following Chapman (1965) and soil texture was determined by the hydrometer method (Anderson and Ingram, 1993). Extractable P and K was determined using Bray I extraction (Bray and Kurtz, 1945). Subsamples were transported to ETH Zurich and analyzed for total C and N contents using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN). Total P contents were determined colorimetrically after Kjeldahl digestion using a continuous flow injection analyzer (AutoAnalyzer 3HR; Seal Analytical, Hampshire, U.K.). For the purpose of this paper, here-after we use the general term “soil fertility” when we wish to refer to general effects across all measured parameters (total soil C, N and P, available P and K, CEC, soil aggregation and pH as well as foliar N and P concentrations as described in section 2.2.3).

2.2.3 Foliar sampling and assessment of cocoa growth

To assess the effects of individual shade trees on the potential nutrient uptake of cocoa plants we collected one young, but fully expanded cocoa leaf from each individual cocoa tree growing in the subcanopy, as well as from eight cocoa trees in open areas without shade trees (Fig. 1). In most cases, we collected leaves from 4 or 5 cocoa trees in the shade-tree subcanopy, but this was not possible for shade trees with narrow crowns because there were fewer cocoa trees under the subcanopy of these shade trees. Therefore, in these few cases we collected two leaves from each cocoa tree under the subcanopy of narrow-crowned shade trees. For the eight cocoa trees sampled in open areas, we chose the four cocoa trees closest to the two open soil

sampling locations that served as the open control locations for each shade tree (Fig. 1; four cocoa trees × two open sampling locations = eight cocoa trees). Leaves were pooled within each location (subcanopy and open), resulting in two composite foliar samples per focal shade tree (n=64, i.e. 32 subcanopy/open paired samples).

Foliar samples were dried to constant weight at 60°C, ground and analyzed for total C and N concentrations using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN). Total P concentrations were determined colorimetrically after Kjeldahl digestion using a continuous flow injection analyzer (AutoAnalyzer 3HR; Seal Analytical, Hampshire, U.K.).

To assess the effects of individual shade trees on cocoa growth, we measured diameter at breast height (DBH) of the same cocoa trees in both the subcanopy and open area as used for foliar sampling.

2.3 Assessing the effects shade trees in plots along a shade-tree cover gradient ('plot-scale')

2.3.1 Selection of shade-tree cover gradient

To assess effects of increasing abundance of shade trees, we selected 26 cocoa plots (30×30m) along a shade-tree cover gradient ranging from monoculture to dense agroforestry plots (0-90 % cover). We limited our selection to low-input cocoa farms that contained mature cocoa trees (12-20 years), and that had not experienced any recent changes in shade-tree cover (determined by communication with local farmers). Our 26 plots were distributed across 22 smallholder farms in three villages, over an area of approximately 40 km². Four out of the 22 farms contained two plots because these farms contained areas with different levels of shade-tree cover, which was the independent variable in our study.

The shade trees found in each plot represent a mixture of the species most commonly found in agroforestry plots in the study area. We estimated the shade-tree canopy cover by subdividing the whole plot into 5×5 m subplots and visually estimating the area covered by shade trees in each 25 m² subplot. Cover estimates for subplots were cross-checked between two observers and individual estimates were then summed to determine the cover of the whole plot.

Densities of both cocoa trees and shade trees were recorded by counting individuals in each plot and we estimated the basal area of shade trees by measuring their diameter at breast height (DBH). Shade-tree cover was strongly correlated with both shade-tree density ($r = 0.82$) and basal area ($r = 0.6$), and for this reason we subsequently use only shade-tree cover as a measure for shade-tree abundance in our analyses. In order to compare the effects of shade trees on soil properties in cocoa farms to the soil properties of natural forest areas, we randomly selected three natural forest plots (30×30m) in a selectively logged, natural forest patch within the study area.

2.3.2 Soil sampling and analysis

In May 2014, we collected soil samples from nine locations within each 30 × 30 m plot along the cover gradient (N= 26 plots), as well as in three forest plots (N= 3 plots). Individual sampling locations within each plot were distributed at regular points 10 m apart along three parallel transects (which were themselves 10 m apart), with three sampling locations per transect (3 transects × 3 sampling locations = 9 sampling locations per plot; Fig. 1). At each sampling location, soils were sampled at three depths after carefully removing the litter layer; topsoil samples (0-15 cm) were sampled with a hammer corer (Ø 5.5 cm), and subsoil samples (15-30 cm and 30-50

cm) were collected using a soil auger.

Soil bulk density was calculated based on the weight of topsoil core samples after correcting for soil moisture and the mass and volume of roots and stones (Culley, 1993). Topsoils were then gently sieved through an 8 mm sieve, air-dried and composited for each plot. A subsample of 80 g of all composited topsoil samples was fractionated by means of wet sieving to determine the aggregation status of soils as described in section 2.2.2.

Soil samples taken from each plot were composited for each soil layer, dried, ground and analyzed for total C, N and P concentrations, extractable P and K, CEC, pH, soil texture as described in section 2.2.2. We also determined total C and N contents of each aggregate fraction using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN).

2.3.3 Foliar sampling and analysis

To assess the nutritional status of cocoa plants at the plot-scale we collected young, but fully expanded cocoa leaves from 30 randomly selected cocoa trees along three transects within each plot along the cover gradient (Fig. 1). Foliar samples were dried to constant weight at 60°C, ground and analyzed for total C, N and P concentrations as described in section 2.2.3.

2.3.4 Cacao growth and yield

To assess the effects of shade trees on cocoa growth, we measured DBH of 30 randomly selected cocoa trees along three transects within each plot along the cover gradient (we used the same cocoa trees as used for the foliar sampling, section 2.3.3).

To assess cocoa yield, from September to December 2014 we harvested all

ripe cocoa pods within the boundaries of our 30×30m plots at fortnightly intervals. Only 21 of the 26 plots could be harvested because not all farmers made their plots available for these assessments. We separated diseased and healthy pods and extracted cocoa beans from all pods. Beans from healthy pods were mixed, put in a heap, covered with banana leaf and left to ferment for 7 days (heap method; Opoku-Ameyaw *et al.*, 2010). We recorded the weight of fermented beans and sundried a subsample of 1 kg to constant weight to calculate dry bean yield.

2.4 Statistical analyses

For our assessments of the effects of individual shade trees, consistent with our paired sampling design we used two-sided, paired t-tests. These tests were used to assess differences in soil fertility and productivity parameters between subcanopy and open areas around individual shade trees. The inclusion of either shade-tree age or size (DBH) using linear mixed-effect models did not increase model fit over simpler models that only compared subcanopy and open areas and so we did not include these independent variables in our final analyses.

For our plot-scale assessments, we used linear regression to assess how soil fertility parameters and yields change along the shade-tree cover gradient. Including other variables such as soil texture, fertilizer input (determined by communication with local farmers) and pH as covariates to account for additional variability between plots did not modify the observed influence of shade-tree canopy cover on soil fertility parameters in our results and were therefore not included in the final analyses. Furthermore, we compared soil fertility parameters in agroforestry plots with those in forest plots using t-tests. Finally, to describe the dominant factors influencing cocoa yields, we performed a principal component analysis (PCA), on a subset of 12

variables (yield, canopy cover, DBH, C, N, P, K, CEC, MWD, sand, silt and clay content). All statistical analyses were done using R version 3.2.4 (R Core Team, 2016).

3. Results

3.1 Effects on soil and foliar characteristics of individual shade trees

The total soil C and N concentrations as well as soil aggregation (MWD) in topsoils (0-15 cm) were significantly higher under shade trees than in open areas (Fig. 2a-c). On average, subcanopy areas contained 20 % (3.27 g kg⁻¹) more C, 16 % (0.30 g kg⁻¹) more N and aggregates were 11 % (0.11 mm) larger than in open areas. We found no significant difference for total P (Fig. 2d), extractable P, extractable K (Fig. 2e), pH, CEC and soil texture between subcanopy and open areas in the topsoils (Table B in the Supplementary material). Soil parameters in the lower soil layers (15-30 cm and 30-50 cm) did not differ between subcanopy and open areas (Table B).

Nutrient concentration in cocoa foliage showed increased levels of C (paired t-test, $t=2.499$, $df=30$, $p=0.018$) and P (paired t-test, $t=2.34$, $df=30$, $p=0.026$), but no difference in N (paired t-test, $t=-0.86$, $df=30$, $p=0.39$).

Soil aggregate-size distribution in both subcanopy and open areas were dominated by macroaggregates (250-2000 μm and $>2000\mu\text{m}$), which on average accounted for 68 % of the dry soil weight in subcanopy and 62 % in open areas (Fig. A, panel a. in the supplementary material). Subcanopy areas had a higher proportion of large macroaggregates and a lower proportion of microaggregates and free silt and clay particles than in open areas (Fig. A. panel a., supplementary material). We found significantly higher aggregate C and N concentrations in all aggregate size classes in subcanopy soils (Fig. A. panel b. supplementary material; data for N not shown).

Together the observed aggregate size distribution and enrichment patterns lead to increased C and N stocks in macroaggregates (Fig. A. panel c. for C, data for N not shown). In both the subcanopy and open areas, more highly aggregated soils (higher MWD values) contained significantly more C, N, and P (subcanopy C: $R^2=0.37$, $p<0.001$; N: $R^2=0.53$, $p<0.001$; P: $R^2=0.16$, $p=0.03$; open C: $R^2=0.46$, $p<0.001$; N: $R^2=0.54$, $p<0.001$; P: $R^2=0.21$, $p=0.008$).

3.2 Effects on soil and foliar characteristics at the *plot-scale*

In contrast to the effects of *individual shade trees*, at the *plot-scale* we did not find any effect of *increasing* shade-tree cover on soil fertility parameters at any soil depth (Fig. 2f-k, Table B in the supplementary material). Soil fertility parameters were also unrelated to the age of cocoa trees (data not shown). The lack of significant effects at the *plot-scale* remained when we controlled for differences in soil texture, pH and fertilizer use (determined by communication with local farmers) between plots (data not shown). As observed *under individual shade trees*, more-highly aggregated soils generally contained more C, N, and P (C: $R^2=0.52$, $p<0.001$; N: $R^2=0.36$, $p<0.001$; P: $R^2=0.19$, $p=0.03$), *but aggregation did not increase with increasing shade tree cover (Fig 1h)*. Foliar C, N and P *concentrations in* cocoa foliage were also not related to the shade-tree cover (C: $R^2=0.06$, $p=0.2286$; N: $R^2=0.006$, $p=0.71$; P: $R^2=0.10$, $p=0.11$).

The comparison with forest plots showed that soil C, N and aggregation levels in agroforests were significantly lower than levels found in forests, even under dense shade-tree cover (on average C: -49 %, N: -53 % and MWD: -14 %; Fig. 2f-h, Table B). P concentrations in cocoa farms did not differ from levels found in forest plots (Fig. 2i, Table B). Aggregate-size distribution in cocoa and forest soils were dominated by macroaggregates (250-2000 μm and $>2000\mu\text{m}$), which on average

accounted for 77 % of the dry soil weight in cocoa and 85 % in forest plots. Forest soils had a higher proportion of large macroaggregates and a lower proportion of microaggregates and free silt and clay particles than in cocoa soils (data not shown).

3.3 Effects of shade trees on cocoa growth and yield

The mean DBH of cocoa trees was significantly lower under individual shade trees than in open areas (Fig. 3a). Similarly, at the plot-scale, higher shade-tree cover was associated with significantly smaller cocoa trees (Fig. 3b). Cocoa yields in plots along the cover gradient decreased significantly with increasing canopy cover (Fig. 3c). Yields were also significantly negatively related to cocoa age ($R^2=0.26$, $p=0.02$), but older plots did not have more shade cover ($R^2=0.02$, $p=0.49$).

3.4 Relationships between yield, soil fertility and shade at the plot-scale

The first and second axes of the PCA explained 37.9 % and 18.4 % of the total variance of cocoa plots studied (Fig. 4). Total soil C, N and P were the main contributors to the first axis (PC1). Canopy cover of shade trees, cocoa DBH and cocoa yield as well as sand content were the main contributors to the second axis (PC2). The projection showed that soil fertility parameters (total C, N, P and extractable K and CEC) are unrelated to shade-tree cover and yields, whereas the canopy cover of shade trees is negatively related to cocoa yields and DBH of cocoa trees.

4. Discussion

Our work demonstrates that individual shade trees can have localized positive effects on some important soil fertility parameters. In particular, soil C, N, and soil

aggregation are higher directly under **individual** shade trees (Fig. 2a-c). However, our results suggest that localized increases in soil fertility directly under **individual** shade trees do not necessarily translate into uniform benefits in soil fertility at the **plot**-scale (Fig. 2f-k). In particular, higher densities of shade trees did not result in greater improvements in soil fertility at the **plot**-scale (Fig. 2f-k). The difference **in the effects of individual shade trees versus shade trees within larger plots** is important because cocoa trees in agroforests are not generally grown **only** directly under **individual** shade trees, but are instead grown haphazardly with respect to the shade trees in an agroforest. That is, we found limited benefits of agroforests on soil fertility at the scale at which cocoa is **planted and managed in West African cocoa farms**. Finally, we found that the growth and yield of cocoa decreases both under **individual** shade trees and with increasing shade-tree canopy cover (Fig. 3). In sum, our results suggest limited beneficial effects of shade trees on soil fertility and yields in cocoa agroforests, especially at the **plot**-scale.

4.1 Individual shade trees increase soil fertility

In line with the common perception that shade trees in cocoa systems increase soil C stocks and soil fertility (Isaac *et al.*, 2007; Jose, 2009), our results show that **individual shade** trees locally increase C and N concentration, as well as soil aggregation in topsoils (Fig. 2a-c). Increased aggregation should physically protect soil organic matter, improve nutrient retention and reduce runoff and erosion, thereby **causing** beneficial effects on soil organic matter dynamics and nutrient cycling (Six *et al.*, 2000; Six *et al.*, 2004). Observing these positive effects of **individual shade** trees implies that the general benefits of **shade** trees on soil fertility observed in other agroforestry systems (e.g. maize, sorghum, coffee (Sanchez, 1995; Rhoades, 1996; Jose, 2009)) are also operating in cocoa systems. However, observed effects were

small relative to observed variability at the **plot**-scale (Fig. B in the Supplementary material) and restricted to the topsoil layer (Table B).

With respect to readily available nutrients for plant growth, however, our soil data suggests that shade trees do not increase extractable K or total and available P under their subcanopy (Fig. **2d-e**). This is a potentially important result because these are likely to be the soil nutrients that most strongly limit cocoa production (Hartemink, 2005). The absence of an effect of on extractable K or total and available P could suggest that shade trees are unable to sustain sufficient levels of P and K for cocoa production, but it could also result from rapid uptake of **any** available K and P by cocoa trees. **Consistent with the results of Isaac et al. (2007), we did observe higher P levels in cocoa foliage collected under individual shade trees, which would be consistent with rapid uptake, although we can't be certain that the higher foliar nutrient levels are attributable to the presence of shade trees.**

*4.2. Shade trees have limited effects on soil nutrients at the **plot**-scale*

Surprisingly, the localized benefits on soil fertility directly under **individual** shade trees did not translate into **increasing** benefits **with increasing shade-tree cover** at the **plot**-scale. In particular, we found no increase in any soil fertility parameter or foliar nutrient concentrations with increasing shade-tree cover (Fig. **2f-k**). Our findings are consistent with other studies that find no difference in soil C stocks between agroforests and monocultures in cocoa (Gockowski and Sonwa, 2011; Jacobi *et al.*, 2014; Mohammed *et al.*, 2016) or in coffee systems (Souza *et al.*, 2012; Noponen *et al.*, 2013). Given that the nutrient balance in many cocoa farms is negative, especially for K (Appiah *et al.*, 1997; Hartemink, 2005), and that shade trees alone are unlikely to be able to sustain sufficient levels of P and K for cocoa production, our results

suggest that growing cocoa in agroforests is unlikely to completely obviate the need for the addition of inorganic fertilizers. Together, these findings suggest that shade trees might ultimately have limited benefits for soil C sequestration and soil fertility at the level of the cocoa farming system.

The absence of clear beneficial effects of shade trees at the **plot-scale** could occur because cocoa is itself a small (5-8 m in height), perennial tree. Cocoa trees already produce substantial amounts of litter and might therefore contribute substantially to the formation of soil organic matter regardless of the presence of shade trees. Cocoa litter has been shown to increase soil C more than intercropped rubber trees (Monroe *et al.*, 2016) and this could also be the case with respect to other species of shade trees. This situation is quite different from the inclusion of shade trees in annual cropping systems where shade trees ensure constant input of organic matter that would otherwise be absent if annual crops were grown in monoculture (Haggar *et al.*, 1993).

We have two possible explanations for the somewhat surprising result that the effect of **shade** trees locally (i.e. effects **observed under individual shade trees**) do not scale up **to generate benefits for soil fertility** at the **plot-scale**. First, effects of shade trees might not be evident at the **plot-scale** because effects of **individual shade** trees on soil fertility parameters are small compared to the long-lasting spatial heterogeneity of the former forest soils in which cocoa is grown (Supplementary material Fig. B, Døckersmith *et al.*, 1999; Diekmann *et al.*, 2007). **Differences may emerge for individual shade trees because such a sampling approach implicitly relies on the strong and somewhat simplified contrast between locations directly under and well away from individual shade-trees.** But under more realistic levels of variability at the **plot-scale** the relative small effects of **individual shade** trees might be swamped by the

heterogeneity inherent to the system (Fig. B). A second reason why local effects of shade trees do not scale to plot-wide benefits could be that local increases in soil fertility under individual shade trees might occur simply as a consequence of the redistribution and local accumulation of nutrients already accessible to cocoa (e.g. uptake via lateral shade-tree roots from surrounding surface soil layers) and not as an absolute increase in the accessible nutrient pools per se (e.g. uptake via deep shade-tree roots from deeper soil layers not accessible to cocoa, Riginos *et al.*, 2009).

Irrespective of the cause, it is clear from our results that the benefits for cocoa of individual, isolated shade trees cannot be used to accurately estimate the magnitude of the collective effect of larger numbers of shade trees at the plot scale, which more closely represents the scale at which farmers implement and manage their agroforests. This finding suggests that shade trees may not increase soil fertility and soil C sequestration in smallholder cocoa farms to a level that can contribute to the long-term sustainability of these systems. In this context, we believe it is important that future assessments of the benefits of shade trees focus on on-farm measurements at larger scales rather than at the scale of individual, isolated shade trees. In doing so, it should be possible to provide data that will be more relevant for assessing the effectiveness of agroforestry in cocoa growing regions, given that this is the scale at which cocoa is grown and managed.

4.3. Agroforests are unlikely to restore soil carbon stocks to the level of natural forests

Our data at the plot-scale showed a net loss of 49 % in soil organic matter relative to forest soils, but no changes in soil organic matter levels related to cocoa age (12-20 years). The C accumulation potential of cocoa agroforestry systems therefore seems to

be limited and it is unlikely that agroforests can either maintain soil C stocks at the levels of natural forests, or restore C stocks to the level of natural farms over the lifetime of a cocoa farm. This finding confirms other studies that emphasize that cocoa agroforestry systems are a poor substitute for natural forests in terms of their C sequestration potential (Guo and Gifford, 2002; Hartemink, 2005; Leuschner et al., 2013). In this context it seems clear that sustainable intensification of cocoa production through improved integrated management practices on existing farms, and the avoidance of further expansion of cocoa systems into native forest ecosystems, would be a stronger mitigation alternative at the landscape scale, than the inclusion of shade trees alone.

4.4. Shade trees negatively affect cocoa growth and yield

Not only does our data suggest limited benefits of agroforests for soil fertility, but it also demonstrates that the inclusion of shade trees comes at the cost of lower cocoa growth and lower short-term yields. We found reduced growth of cocoa trees under individual shade trees (Fig. 3a) and reduced growth and yield of cocoa trees at the plot-scale with increasing shade-tree cover (Fig. 3b, c). Our empirical results are in line with the findings of Wade et al. (2010) and Clough et al. (2011) who reported decreasing yields with increasing shade-tree abundance based on data obtained from interviews with farmers.

If soil fertility improvements by shade trees (i.e. increased C and N concentrations and higher soil aggregation) were to increase yields, we would expect to find higher yields in plots with higher soil fertility. However, our data showed that existing differences in soil fertility between our study plots were unrelated to yields (Fig. 4). This indicates that soil fertility is unlikely to be the factor most limiting

yields in our study area. Instead, yields were more strongly affected by shade cover (Fig. 4), which could be due to increasing competition for light as shade canopy cover increases (Zuidema *et al.*, 2005; Lin, 2007). Yields were also positively affected by sand content in soils, although it is unlikely that shade trees affect soil texture directly. If shade trees are to be included in cocoa cropping systems, a combination of low shade-tree density and pruning may limit the effects of competition, while maintaining other benefits of shade trees such as microclimate buffering, for example.

Based on the evidence provided by our results, it appears difficult to justify the implementation of agroforests for the long-term sustainability of cocoa yields based on improvements in soil fertility. However, the effect of shade trees on growing conditions for cocoa may depend on the species of shade trees included in agroforests (Beer *et al.*, 1998). It is therefore possible that the inclusion of particular species of shade trees in agroforests may be more effective in improving soil fertility, which is the subject of ongoing research. It is important to note, however, that our data should be representative of the effects of agroforests as they are currently most commonly implemented in West Africa.

4.5. Shade trees could have other benefits for cocoa production

In this study we concentrated on the effects of shade trees on soil fertility, soil C-sequestration and short-term yields. However, we note that agroforests may influence the sustainability of cocoa production via other mechanisms including climate buffering (Abou Rajab *et al.*, 2016; Vaast *et al.*, 2016), pathogen regulation (Bisseleua *et al.*, 2009; Clough *et al.*, 2009; Bisseleua *et al.*, 2013), improved pollination services (Abou Rajab *et al.*, 2016), and could support higher levels of biodiversity (Bisseleua *et al.*, 2009; Clough *et al.*, 2009; Clough *et al.*, 2011).

Furthermore, the inclusion of shade trees may improve a systems' overall economic performance over the long term by providing alternative incomes (Obiri *et al.*, 2007; Rahman *et al.*, 2016). Indeed, informal interviews with farmers suggest that many of the shade-tree species investigated in our study are used for timber and fruit production and these interviews also suggest that farmers believe there is a benefit provided to cocoa through the provision of shade. Given the multiple potential benefits of shade trees it is clear that the potential for agroforests to improve the sustainability of agricultural production should not be judged on the basis of any single result, or assessment with respect to any single mechanism. It is in this context that our results should be considered. Nevertheless, our results strongly suggest that not all of the benefits commonly ascribed to agroforests can be considered to generally apply.

5. Conclusions

Improvements in soil fertility have long been considered one of the major benefits of growing crops in agroforests. Our results suggest that this may not be the case in all cropping systems. Furthermore, our results indicate that assessments of the effectiveness of agroforests based on the effects of individual shade trees may be misleading. Future assessments of the benefits of agroforests should concentrate on the effects of shade trees measured across larger spatial scales, as this more appropriately represents the scales at which farmers manage crop production within agroforests.

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Figure captions

Figure 1 (a) Schematic profile view of the sampling design around a representative individual shade tree growing together with cocoa trees. Individual shade trees were isolated from the canopy of other shade trees by at least 30 m. Sampling was done under the canopy of cocoa trees, both under ('subcanopy') and away ('open') from the canopy of each shade tree. Vertical black arrows show the position of the soil sampling within these areas. (b) Schematic aerial view of four representative 30 × 30 m plots along a gradient of increasing shade-tree cover (left to right: zero- to high-shade-tree canopy cover). Solid green areas represent the areas covered by the canopies of shade trees. Importantly, cocoa trees were present in all plots but are not shown in (b) for clarity in order to emphasize differences in the independent variable in this study (shade-tree cover). Soil sampling, and measurements of cocoa DBH and foliar sampling, occurred along three parallel transects arranged 10 m apart in each 30 x 30 m plot. There were three soil sampling locations arranged 10 m apart along each transect (black dots in (b)).

Figure 2 (a-e) Effects of shade trees on total soil carbon (C), nitrogen (N) concentrations and mean weight diameter of soil aggregation (MWD) as well as total soil phosphorus (P) and extractable potassium (K) in topsoils (0-15cm) sampled under (sub) and away (open) from individual shade trees and (f-k) in plots along a cover gradient ('plot-scale'). Different letters indicate significant differences between subcanopy and open areas under individual shade trees. Cocoa plots at the plot-scale are represented as black dots, the reference forest plots as open diamonds. No significant patterns were found across the canopy-cover gradient at the plot-scale.

Figure 3 (a) Effects of shade trees on cocoa diameter at breast height (DBH) under (sub) and away (open) from individual shade trees and (b) in plots along a cover gradient ('plot-scale'), as well as (c) dry cocoa bean yields harvested at the 'plot-scale'. Different letters in panel a) indicate significant differences between subcanopy and open areas at the tree-scale. Regression lines were drawn where linear relationships were significant ($p < 0.05$, panel b-c).

Figure 4 Principal component analysis (PCA) results showing 21 plots in cocoa farms along a cover gradient at the plot scale (black dots) in relation to environmental gradients. Blue vectors illustrate the significance and strength of the relationships between environmental gradients, the black circle represents a "circle of equilibrium contribution". 'Canopy.Cover' = shade-tree canopy cover, 'Silt' = soil silt content, 'MWD' = mean weight diameter of soil aggregation (MWD), 'P' = total soil P, 'N' = total soil N, 'C' = total soil C, 'K' = exchangeable K, 'CEC' = cation exchange capacity, 'DBH' = diameter at breast height of cocoa trees, 'Yield' = cocoa yield, 'Sand' = soil sand content, 'Clay' = soil clay content.

(a) Individual shade trees

(b) Plot-scale (aerial view)

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790 **Figure 1**

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792 **Figure 2**

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794 **Figure 3**

795
796 **Figure 4**

(a) Individual shade trees

(b) Plot-scale (aerial view)

Highlights:

- Effects of shade trees were assessed using two sampling approaches.
- Shade trees have localized positive effects on soil fertility.
- Effects of individual trees do not translate to benefits across larger areas.
- Benefits of agroforests on soils do not offset costs for cocoa production.