Plant Soil (2020) 453:87–104
https://doi.org/10.1007/s11104-018-03921-x

REGULAR ARTICLE

Soil fertility and *Theobroma cacao* growth and productivity under commonly intercropped shade-tree species in Sulawesi, Indonesia

Ariani C. Wartenberg · Wilma J. Blaser · James M. Roshetko · Meine Van Noordwijk · Johan Six

Received: 16 July 2018 / Accepted: 18 December 2018 / Published online: 16 January 2019

Abstract

Background and aims Trade-offs between ecological benefits and potential yield and growth reductions associated with the inclusion of shade trees in cocoa agroforests remain poorly understood. In this study we investigate interactions between shade and cocoa trees in cocoa agroforests in terms of soil fertility and cocoa productivity.

Methods We quantified the effects of individual shade trees from 11 commonly intercropped species on cocoa growth (aboveground biomass) and yield and soil fertility indicators (total soil carbon, nitrogen, phosphorus contents and soil aggregation) at field sites in Southeast Sulawesi, Indonesia.

Results Shade trees had a net positive effect on soil fertility in cocoa agroforests, with a 6% increase in soil carbon, a 4% in soil nitrogen and a 24% increase in mean weight diameter (used as an indicator for median soil aggregate size), under shade tree canopies compared to open areas. We found that shade trees had a net negative effect on cocoa tree growth and no net effect on cocoa yields. We were not able to link costs versus benefits with specific shade tree traits, but nevertheless observed significant differences between shade tree species. *G. sepium* (gliricidia) had significantly positive effects on yields, soil carbon and aggregation. *N. lappaceum* (rambutan) and *D. zibethinus* (durian) had significantly positive effects on soil carbon and nitrogen contents and on aggregation, but not on yields.

Conclusions Our findings confirm the potential for soil improvements under shade trees and suggest that the inclusion of individual shade trees does not always constitute a direct trade-off for farmers in terms of yield losses.

Keywords Agroforestry · Soil fertility · Yields · *Theobroma cacao* · Shade trees

Abbreviations

AGB	Above-ground biomass
C	Carbon
LM	Large macroaggregates
m	Microaggregates
MWD	Mean weight diameter
N	Nitrogen
P	Phosphorus
sM	small macroaggregates
s + c	silt & clay particles
SOM	Soil organic matter

Responsible Editor: Remi Cardinael.

A. C. Wartenberg · W. J. Blaser · J. Six
Department of Environmental Systems Science, ETH Zürich, Zurich, Switzerland

A. C. Wartenberg (✉)
Department of Environmental Science, Policy & Management, Mulford Hall, UC, Berkeley, CA 94720, USA
e-mail: ariani.wartenberg@gmail.com

J. M. Roshetko · M. Van Noordwijk
World Agroforestry Centre, ICRAF Southeast Asia Regional Office, Bogor, Indonesia

Introduction

On a global scale, smallholder *Theobroma cacao* (cocoa) cultivation systems are facing increasing production pressures related to factors such as soil degradation or pest and disease outbreaks (Vaast and Somarriba 2014). The inclusion of shade trees in cocoa agroforests has been heralded as a solution to these issues, with proposed benefits ranging from increased livelihood sources to improved nutrient cycling processes and increased ecosystem resilience (e.g. Beer et al. 1998; Somarriba et al. 2013). However, shade trees are also likely to compete for light and/or nutrient resources with neighboring crops (Sanchez 1995), and to date it remains unclear to what extent the benefits versus disadvantages associated with shade trees ultimately impact soil fertility and yield productivity in cocoa agroforests.

In the humid tropics, plot-scale studies of the inclusion of shade trees in cocoa cultivation systems have shown positive contributions for carbon storage, biodiversity and afforestation (Clough et al. 2009; Jagoret et al. 2012; Schroth et al. 2015), but also evidence of trade-offs in terms of competition for light, water and nutrients and yield productivity (Abdulai et al. 2018; Asare et al. 2017; Blaser et al. 2018). The overall outcome of trade-offs from interactions between shade and crop trees can be difficult to pinpoint at systems scales. A better understanding of tree effects at individual tree scales could inform farmers' selection of shade trees in cocoa agroforests, providing them with improved adaptation strategies to climate change and food and income insecurity (Graefe et al. 2017).

In cocoa agroforests, the effects of isolated trees on soil fertility and nutrient storage dynamics have been documented to some extent (Blaser et al. 2017; Isaac et al. 2007b). However, species-related effects of isolated shade trees on soils remain understudied. In particular, studies of shade tree effects on soil aggregate stability, an important indicator for long-term soil fertility, remain scarce both in tropical and temperate agroforestry systems and do not investigate differences between species (Blaser et al. 2017; Lehmann et al. 2001). In diverse cocoa agroforests, litter and root residue from shade trees constitute a significant source of organic matter inputs (Schneidewind et al. 2018). Soil aggregate structures play an important role in soil organic matter (SOM) storage and turnover as they physically protect organic matter compounds from mechanical or microbial degradation over time (Tisdall and Oades 1982). As aggregates degrade over time, nutrients are released and become available for uptake by main cropping trees (e.g. cocoa). Shade trees are thus thought to contribute to soil fertility through improved aggregate formation, although field data on these effects remain lacking.

In the context of cocoa agroforests, costs and benefits associated with shade trees are highly dependent on selected tree species and local climate (Beer et al. 1998; Isaac et al. 2005). High variability in morphological traits of common shade trees, such as canopy and root system architecture, or litter and root chemistry, might lead to a range of effects on cocoa growth and productivity. First, shade tree canopies can impact light resources and limit cocoa yields, particularly in environments where nutrient availability is not a limiting factor (Beer et al. 1998; Isaac et al. 2007a). Second, the quality and quantity of litterfall can vary substantially between tree species (Hobbie et al. 2006; Sariyildiz et al. 2005). In cocoa agroforests, the inclusion of shade trees is therefore likely to affect litter inputs and nutrient cycling in cocoa farms. Third, shade-tree roots and root-associated fungi, another important source of soil organic matter in agroforests (van Noordwijk et al. 2004), are similarly likely to impact below-ground interactions in mixed cocoa agroforest. And fourth, trees with deeper roots are known to access and recycle water and nutrients from deeper soil layers (Bayala et al. 2008; Van Noordwijk and Purnomosidhi 1995), although there are also risks of significant root competition for moisture and nutrients between cocoa, which has shallow roots, and other shade trees (Beer 1987). While some tree-associated traits, such as extensive shallow rooting systems and dense spreading canopies, are thought to lead to direct resource competition between trees and crops, others, such as nitrogen-fixing (N-fixing) capacity, are thought to improve soil fertility and therefore provide indirect benefits to understory crops (Rhoades 1996). Ultimately, the cumulative outcome of potential costs and benefits of shade trees has rarely been documented, and on-farm studies of soil fertility parameters under shade trees remain scarce, particularly in cocoa agroforests.

An improved understanding of the interactions between shade trees and cocoa trees in cocoa agroforests would contribute valuable knowledge needed to optimize the sustainability and resilience of tropical agroforestry systems. The principal goal of our study was to quantify the effects of individual shade trees on soil fertility and cocoa productivity in Southeast Sulawesi, Indonesia, for the most common species found in the region. Indonesia is currently the 3rd biggest producer of cocoa globally (FAOSTAT 2011). Cocoa is cultivated across about 1.5 million ha and constitutes one of Indonesia's most important agricultural export products, generating about $1.2 billion annually. Approximately 71% of the country's cocoa supplies are currently produced on the island of Sulawesi (Witjaksono 2016).

We tested whether observed differences in the effects of shade trees might be linked to specific functional traits (absolute height, canopy height, canopy area, litter nutrient contents and aboveground biomass (AGB)). We hypothesize that soil fertility increases (as indicated by total carbon (C), nitrogen (N), phosphorus (P) and soil aggregation (MWD)) will vary under different shade tree species. We further investigate under which tree species trade-offs between predicted soil fertility benefits and competitive effects for other resources are minimized, leading to positive effects on cocoa productivity (as indicated by AGB and yields).

Materials & methods

Description of the study area

We conducted our study in the Konawe province of Southeast Sulawesi, Indonesia (3.58°S, 122.30°E), where cocoa is the most prevalent cash crop. Cocoa production systems in SE Sulawesi range from monoculture to diversified agroforests integrating cocoa with shade, fruit and timber trees (Janudianto et al. 2014; Wartenberg et al. 2017). Farmers in SE Sulawesi do not conduct specific soil or tree management in their cocoa systems due to farmers' limited capital, inputs and labor. Fertilizer management in cocoa AFS varies from none to very low levels of (mostly NPK) application around cocoa tree trunks (personal communications with farmers). The lack of intensive management approaches is related to the fluctuating market price for cocoa in the region, along with limited access to market information and low market transparency (Janudianto et al. 2014; Mithöfer et al. 2017).

Fifty-six experimental plots were selected around individual shade trees located in smallholder farms in the community of Wonuahoa, where soils are predominantly *orthic acrisols* (FAO-UNESCO 1979). Mean annual precipitation is 2080 mm (1982–2012) and highly seasonal, with most rain falling from January to June. Mean daily temperatures range is 25 °C to 28 °C, depending on time of the year and elevation (Climate-Data.org 2016).

Shade tree selection and characterization

Cocoa farms at the study location were mostly lightly shaded agroforests. In SE Sulawesi, recommended spacing for shade tree species varied from 3 × 3 m (for cocoa and coconut) to 10 × 10 m (for rambutan, langsat, durian and mango). While farmers followed recommended spacing for cocoa, actual spacing of shade-tree species varies greatly across farms and tends to be much wider than these recommendations. Gliricidia was the most commonly intercropped shade tree species in these systems; other species were represented more sporadically.

We selected 11 of the most commonly intercropped shade tree species found in cocoa farms in Southeast Sulawesi: *Gliricidia sepium* (gliricidia), *Nephelium lappaceum* (rambutan), *Lansium domesticum* (langsat), *Durio zibethinus* (durian), *Artocarpus heterophyllus* (jackfruit), *Anthoccephalus cadamba* (jabon), *Psidium guajava* (guava), *Mangifera indica* (mango), *Parkia speciosa* (petai), *Cocos nucifera* (coconut), and *Gmelina arborea* (gmelina) (Table 1). *Theobroma cacao* (cocoa) trees were included in our analyses. All individual trees selected for this study were located close to each other in cocoa farms of similar ages (7 to 12 years since establishment on land cleared from primary forest).

As we were interested in the effect of individual shade tree species, we selected 3–5 replicates of separate species occurring in the area (Table 1). Our sampling methodology was adapted from Isaac et al. (2007b): at each sampling site we selected isolated shade trees within cocoa farms, which were separated from the edge of adjacent shade canopies by at least 10 m. Sub-plots were delimited around each site to represent two sampling distances from the shade tree trunk: 1)

Table 1 Description of shade tree species and their functional traits: rooting depth, canopy architecture (tree and canopy height, canopy area and above-ground biomass (AGB)) and litter nutrient concentrations (litter C, N, P, Ca^{2+}, and C:N). The values displayed are mean values ± standard deviations

Species	Family	Common name	No. of Replicates	Tree Height (m)	Canopy Height (m)	Canopy Area (m^2)	AGB (kg)	Litter C (g kg-^{1})	Litter N (g kg-^{1})	Litter P (g kg-^{1})	Litter Ca (g kg-^{1})	Litter C:N
1. *Theobroma cacao*	Malvacea	Cocoa	5	5.3 ± 0.9	2.4 ± 1.0	20 ± 7	21 ± 14	431 ± 18	16.4 ± 4.4	1.4 ± 0.3	6.4 ± 3.0	27.7 ± 7.5
2. *Gliricidia sepium*	Fabaceae	Gliricidia	5	10.5 ± 1.6	3.4 ± 1.7	40 ± 30	56 ± 38	464 ± 6	27.2 ± 1.7	1.8 ± 0.2	9.7 ± 0.7	17.1 ± 1.0
3. *Nephelium lappaceum*	Sapindaceae	Rambutan	5	12.7 ± 1.9	3.9 ± 0.8	69 ± 24	332 ± 229	469 ± 10	11.0 ± 2.7	1.8 ± 0.6	13.6 ± 2.3	44.6 ± 10.4
4. *Lansium domesticum*	Meliaceae	Langsat	5	16.7 ± 3.3	3.2 ± 1.1	41 ± 13	495 ± 211	418 ± 16	15.0 ± 2.7	1.4 ± 0.2	9.9 ± 3.8	28.6 ± 5.4
5. *Durio zibethinus*	Malvacea	Durian	5	12.8 ± 2.2	3.5 ± 0.3	33 ± 16	537 ± 316	459 ± 7	17.3 ± 1.3	1.8 ± 0.4	8.6 ± 1.6	26.7 ± 2.0
6. *Artocarpus heterophyllus*	Moracea	Jackfruit	5	14.0 ± 3.9	3.7 ± 1.6	63 ± 48	526 ± 434	391 ± 9	13.0 ± 2.9	1.2 ± 0.2	8.9 ± 2.1	31.1 ± 6.1
7. *Neolamarckia cadamba*	Rubiacea	Jabon	5	21.6 ± 5.1	7.2 ± 1.9	136 ± 72	1262 ± 785	503 ± 19	15.9 ± 1.4	1.5 ± 0.1	5.4 ± 1.6	31.9 ± 2.9
8. *Psidium guajava*	Myrtaceae	Guava	5	6.8 ± 1.9	2.1 ± 0.4	40 ± 25	84 ± 108	484 ± 10	10.4 ± 0.9	1.5 ± 0.1	7.0 ± 2.5	46.7 ± 3.5
9. *Mangifera indica*	Anacardiacea	Mango	5	11.2 ± 4.6	4.1 ± 2.0	41 ± 25	348 ± 387	415 ± 25	12.1 ± 3.8	1.3 ± 0.3	9.3 ± 2.1	36.3 ± 8.2
10. *Parkia speciosa*	Fabaceae	Petai	3	13.5 ± 0.8	6.7 ± 0.9	64 ± 25	138 ± 30	NA	NA	NA	NA	NA
11. *Cocos nucifera*	Arecaceae	Coconut	5	10.2 ± 5.4	3.5 ± 2.3	39 ± 18	300 ± 283	468 ± 14	13.2 ± 2.8	1.5 ± 0.2	3.1 ± 1.5	36.5 ± 6.2
12. *Gmelina arborea*	Lamiacea	Gmelina	3	14.4 ± 4.9	4.8 ± 1.8	60 ± 26	322 ± 288	435 ± 27	11.8 ± 3.4	1.5 ± 0.2	9.3 ± 1.0	38.5 ± 8.0

[1] References: Hartemink 2005 (cocoa); Van Noordwijk and Purnomosidhi 1995 (gliricidia, rambutan, langsat, jackfruit, guava, mango, petai); Wahid et al. 2000 (coconut); Ruhigwa et al. 1992 (gmelinawhite teak)

"canopy" samples were collected under the shade tree canopy but outside of the canopies of cocoa trees (and up to a maximum distance of 5 m from the central shade tree trunk); 2) "no canopy" samples were located in open areas (and at a maximum distance of 10 m from the central shade tree trunk) (Fig. 1). Because cocoa farmers generally determined the planting locations of shade trees based on species-specific spacing recommendations from extension agents, the selection of shade trees which were planted in microsites with favorable soil properties is highly unlikely. All sampling sites were located on flat terrain in the same valley around Wonuahoa village and on soils with similar texture (clay loam). Sites were selected on adjacent farms which were managed similarly in terms of shade tree pruning practices and fertilizer application.

Shade-tree and cocoa tree metrics

For all shade trees, we recorded diameter at breast height (D; in cm) and tree height (H; in m), measured with a Haglöf ECII hypsometer. Specific wood density (ρ) was determined based on ICRAF database values (Harja et al. 2018). Where no data was available we applied an average ρ value for all species. We estimated above-ground biomass (AGB) based on ρ, D and H for each individual shade tree according to the following pantropical allometric equation developed by Chave et al. (2014):

$$AGB_{est} = 0.0673 \times \left(\rho \times D^2 \times H\right)^{0.976}$$

We additionally recorded lower canopy height (m) for each shade tree. Canopy area (m^2) was estimated based on radius (m) measurements in four directions from each shade tree trunk. While cocoa, gliricidia and rambutan may be deciduous during the dry season, in more humid locations like the study area they may not lose their leaves. We collected litter samples under each individual shade tree in April through May 2015, using 50 × 50 cm mesh litter traps placed directly under tree canopy at 50 cm above the ground. Litter samples were collected 2 to 3 weeks after installation of the traps, and then air-dried and ground in a coffee grinder. Samples were then transported to ETH Zürich and analyzed for C- and N-contents using dry combustion (CN-2000; LECO Corp., St Joseph, MN). Litter micro-nutrient concentrations (P, Ca^{2+}) were determined using wet digestion with HNO_3 and H_2O_2 and emission spectroscopy (ICP-OES 5100, Agilent Technologies, Santa Clara, CA).

Within each sampling site we marked all "canopy" and "no canopy" cocoa trees (Fig. 1a). For all selected cocoa trees, we recorded the

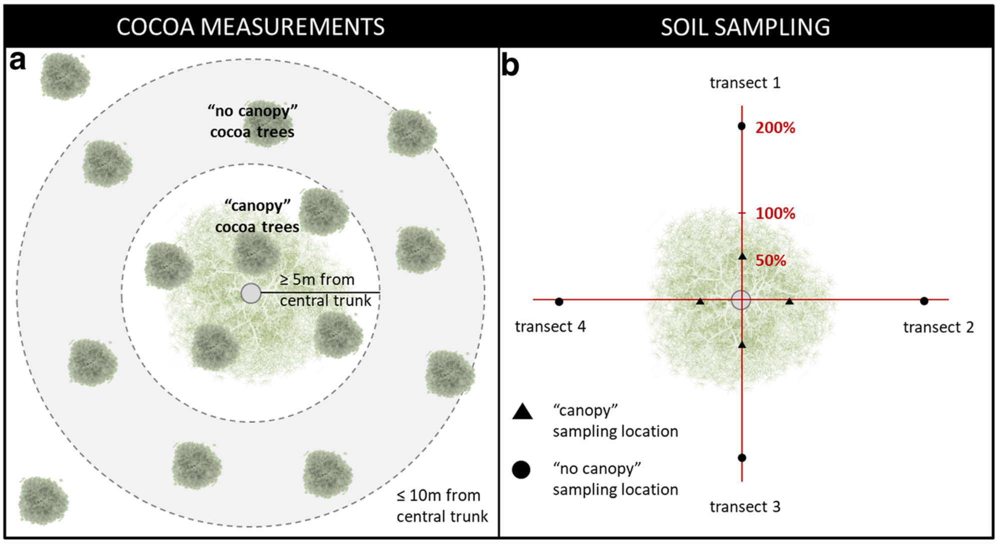

Fig. 1 Visual representation of the field design for **a**) measurements of cocoa productivity and **b**) soil sampling

distance of each cocoa tree from the central shade tree trunk, as well as D and H. AGB was estimated based on the specific allometric equation for cocoa developed by Smiley and Kroschel (2010):

$$\mathrm{AGB}_{\mathrm{cocoa}} = 0.202\, kg \times D^{2.112}$$

Potential yields for each individual cocoa tree ($N =$ 898) were determined by pod counts in April–May 2015, between the end of pod maturation and the start of cocoa harvest in Sulawesi.

Soil sampling and analysis

At each individual shade tree site, as well as for the cocoa control sites, we laid out four perpendicular transects radiating out from the central tree trunk (Fig. 1b). We collected four topsoil (0–15 cm depth) samples each for two locations: at 50% of shade-canopy diameter ("canopy"), and at 200% of shade-canopy diameter in open areas ("no canopy"). Samples were composited to obtain one sample per location ("canopy" and "no canopy") for each individual shade tree, processed through an 8 mm sieve to remove rocks, macro-fauna and large organic material, and then air-dried. All samples were then transported to ETH Zürich, where they were passed through a 2 mm sieve and finely ground for subsequent analysis.

For the five most common tree species (gliricidia, langsat, rambutan, durian, jackfruit) and for cocoa plots, we collected 4 intact cores (0–15 cm) per location ("canopy" and "no canopy") for aggregate fractionation using a hammer corer (Ø 5.5 cm). Weight, soil moisture content and bulk density were determined for each individual core. Cores were then carefully sieved through an 8 mm sieve by gently breaking soil clumps along natural planes of weakness (Six et al. 1998), and composited, yielding one sample per location. All samples were air-dried and packed in solid containers to avoid disrupting aggregate structure during transport to ETH Zurich. Sub-samples of 80 g were then fractionated using wet sieving methodology adapted from Elliott (1986) and described in Six et al. (2000) to determine stable aggregate size-distribution. Mean weight diameter (MWD), which we used as an index for median aggregate size, was calculated based on the proportions of large macroaggregates (LM; >2000 μm), small macroaggregates (sM; 250–2000 μm), microaggregates (m; 53–250 μm), and free silt and clay (s + c; <53 μm) particles according to Van Bavel (1950):

$$\mathrm{MWD} = 5(\mathrm{LM}) + 1.125(\mathrm{sM}) + 0.1515(\mathrm{m}) + 0.0265(\mathrm{s+c})$$

Soil nutrient concentrations were determined for "canopy" and "no canopy" composite samples under 11 species and cocoa ($N = 12$ Species * 2 Locations * 3–5 Replicates = 112), as well as for "canopy" and "no canopy" aggregate fractions under 5 species and cocoa ($N = 6$ Species * 2 Locations * 5 replicates * 4 aggregate fractions = 240). Total soil C and N concentrations were determined at ETH Zürich, using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN). Total soil P was determined colorimetrically after heat digestion with H_2O_2, H_2SO_4, Se and Li_2O_4S extraction (method adapted from Anderson and Ingram (1994)).

Statistical analyses

We used linear mixed models to analyze how shade trees in cocoa agroforests affect soil nutrient contents (total C, N and P, and C- and N-within-aggregate-fractions), soil aggregation (indicated by MWD), and cocoa above-ground biomass (cocoa AGB) and yields. We specifically tested i) differences in soil parameter values under shade tree "canopy" locations, relative to "no canopy" open reference positions ("tree effect"), and ii) whether the magnitude of this effect differed between the selected shade tree species ("species effect"). Linear mixed-effects models were fit using the *lme* function developed for R (Pinheiro et al. 2016). We used location and shade tree species as our fixed variables and assigned replicates for each shade tree species as random effects. For each response variable, we subsequently ran two-tailed t-tests to assess whether the "tree effect" under each shade tree species was significantly different from zero. To visualize the magnitude of the effects on soil C-, N- and P-contents, and MWD, we calculated the difference between measured "no canopy" and "canopy" values.

We performed linear regressions to assess i) whether cocoa AGB and yields changed with increasing distance from the trunks of shade trees; and ii) whether differences in cocoa AGB and yields were directly related to changes in soil N- and P-contents. For both analyses shade tree species was used as a covariate.

To assess whether observed differences in the effects of different tree species could be ascribed to shade tree functional traits, we further carried out multiple linear regressions to explore interactions between the effects of shade trees in cocoa agroforests and variation in the shade tree traits selected for our dataset (Table 1). We first tested for relationships between relevant shade tree traits (litter nutrient contents, tree and canopy height, canopy area and AGB) and cocoa AGB and cocoa yields. We then similarly tested for significant relationships between litter nutrient contents and soil nutrient contents and aggregation. Model assumptions for normality and homoscedasticity were checked for all analyses using both visual and statistical tests; robust models were chosen to control for the influence of outliers, using the *robustbase* (Rousseeuw et al. 2015) package in R (R Development Core Team 2014, version 3.1.1).

Results

Shade-tree-effect and species-effect on cocoa biomass and yield

There was a significant negative effect of shade trees on mean cocoa AGB, which was on average decreased by 19% under shade trees compared to open areas. The magnitude of this "tree effect" differed significantly between species but was not significantly different from zero for any of them (Table 2, Fig. 2a). We observed a slight but significant increase in cocoa AGB with increasing distance from the shade tree trunk ($r^2 = 0.11$, $p < 0.001$).

Differences in average yields across all sites were not statistically significant under shade tree canopies and open areas and differences between species were only marginally significant (Table 2). At the species level, yields under were significantly lower under durian canopy than under "no canopy". Yields were marginally lower under rambutan and marginally higher under gliricidia canopies, compared to "no canopy" areas. (Fig. 2b). We found no correlation between cocoa yields and distance from shade tree trunk ($r^2 = 0.07$, $p = 0.2$).

We found no significant relationship between cocoa AGB and yields ($r^2 < 0.01$, $p = 0.7$), or between cocoa AGB and yields and soil fertility variables (Appendix Table 4). We also found no significant relationships between variation in shade tree traits (tree height, lower canopy height, canopy area, AGB and litter nutrient contents) and changes in cocoa AGB or cocoa yields (Appendix Table 5).

Shade-tree-effect and species-effect on soil total C, N and P contents and soil moisture

Overall, shade trees had a positive effect on total soil C concentrations (Table 2), which significantly increased by 6% under shade trees relative to open areas. However, the magnitude of this "tree effect" significantly differed between shade tree species. Mean soil C was marginally higher under gliricidia and significantly higher under rambutan (3.6 g C $kg^{-1} \pm 1.1$ g C kg^{-1} compared to 1.5 g C kg^{-1} or less for all other species; Fig. 3a).

Similarly, total soil N was significantly increased under shade trees compared to adjacent open areas by about 4% on average across all species (Table 2). The magnitude of this "tree effect" significantly differed between shade tree species but was not significantly different from zero for any of the shade tree species. We did observe that soil N was marginally higher under rambutan and mango (Fig. 3b). Soil N contents under shade trees were not correlated with shade tree litter N contents.

Neither the mean "tree effect" nor the mean "species effect" on soil P content were statistically significant (Table 2). Nevertheless, soil P was significantly higher under jabon canopies than in open areas (Fig. 3c). Soil P contents were not correlated with shade tree litter P contents.

While there was no significant overall effect of shade trees on soil moisture, variation between

Table 2 Results from linear mixed effect model analysis examining the changes in total soil carbon (C), nitrogen (N) and phosphorus (P), soil aggregation (MWD), soil moisture; and cocoa above-ground biomass (AGB) and yields (Yield), associated with shade-tree presence ("tree effect") and differences between shade tree species ("species effect"). Abbreviations are: between group (numerator) degrees of freedom (Num DF); within group (denominator) degrees of freedom (Den DF); F-value (F); *P* value (P)

Response variables	Explanatory variables	Num df	Den df	F	P
Cocoa Above-Ground Biomass (kg)					
Tree		1	84	5.3	0.02
Species		11	84	2.2	0.02
Tree x Species		11	84	0.3	0.97
Cocoa Yield (# fresh pods)					
Tree		1	84	3.4	0.15
Species		11	84	1.5	0.07
Tree x Species		11	84	0.9	0.56
Total soil C (g kg^{-1})					
Tree		1	84	6.3	**0.01**
Species		11	84	2.4	**0.01**
Tree x Species		1	84	0.7	0.72
Total soil N (g kg^{-1})					
Tree		1	44	4.3	**0.04**
Species		5	44	6.1	**< 0.001**
Tree x Species		5	44	0.8	0.66
Total soil P (g kg^{-1})					
Tree		1	84	0.6	0.52
Species		11	84	1.1	0.37
Tree x Species		11	84	0.3	0.99
Mean Weight Diameter (mm)					
Tree		1	84	26.0	**< 0.001**
Species		11	84	2.7	**0.002**
Tree x Species		11	84	7.0	**< 0.001**
Soil Moisture (% H_20)					
Tree		1	84	0.3	0.60
Species		11	84	4.9	**0.001**
Tree x Species		11	84	0.5	0.81

Bolded P-values indicate statistical significance

species was statistically significant (Table 2). Soil moisture was significantly increased under langsat (0.016% $H_20 \pm 0.009\%$ H_20 compared to 0.006% H_20 or less for all other species).

Shade-tree-effect and species-effect on soil aggregation

We found a significant positive "tree effect" as well as a significant "species effect" on MWD, which was increased by an average of 24% under shade trees compared to open areas. We also found a significant interaction between tree and species effect on MWD (Table 2). The increase in MWD under shade trees was significantly different from zero under gliricidia, rambutan and durian (Fig. 3d). MWD was positively correlated with soil C ($r^2 = 0.34$, $p < 0.0001$) and soil N ($r^2 = 0.21$, $p < 0.0001$), and was positively related with Ca^{2+} contents of shade tree litter ($r^2 = 0.27$, $p = 0.03$). We further observed a positive correlation between canopy area and MWD ($r^2 = 0.18$, $p = 0.02$).

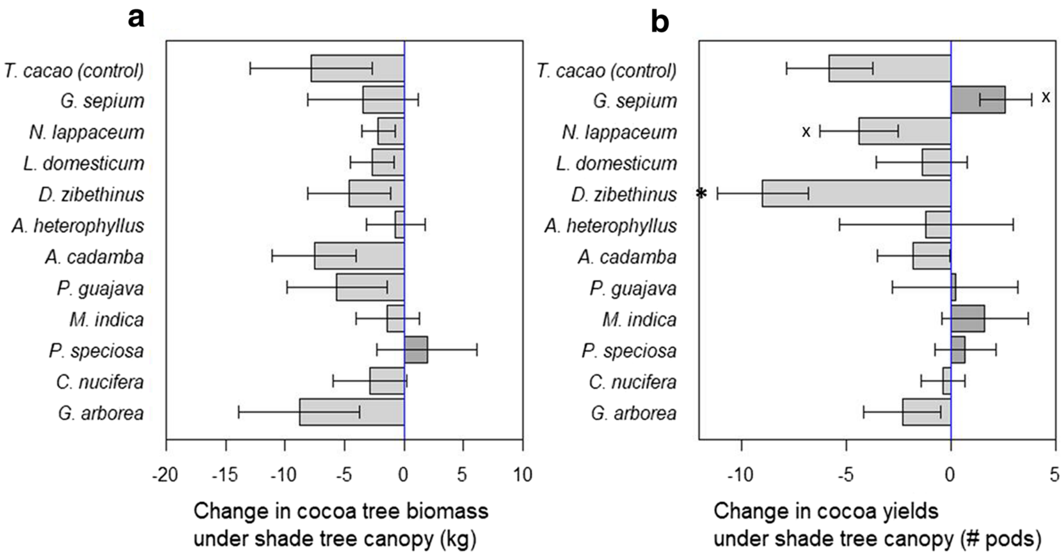

Fig. 2 Mean difference in cocoa tree **a**) yields (No. of pods) and **b**) above-ground biomass (AGB) under shade-tree canopy for 11 different shade-tree species intercropped with cocoa. Values under cocoa-only cultivation ("control" plots) are shown for reference. Mean differences for each species were calculated as the difference between mean cocoa AGB and cocoa yields measured under the canopy of individual shade trees and paired open locations. Bars represent one standard error of the mean. For each species, asterisks (*) indicate a "tree effect" significantly different from zero ($p \leq 0.05$); crosses (x) indicate marginal significance of "tree effect" ($p \leq 0.10$)

An analysis of different soil aggregate size classes showed a positive "tree effect" as well as a significant "species effect" on large macroaggregate (LM) and microaggregate (m) proportions, and C- and N-contents within LM and m fractions. Variations in small macroaggregate (sM) and silt-and-clay (s + c) fractions were not correlated with shade tree presence or shade tree species. The mean proportion of LM ($F = 10.9$, $p = 0.002$) and m ($F = 7.1$, $p = 0.01$) fractions significantly increased under shade trees. The increase in LM proportion under shade tree canopy compared to open areas was significant under gliricidia and rambutan, and marginally significant under durian (Fig. 4a). C-content within LM fractions ($F = 12.2$, $p = 0.001$) also increased under shade trees. The increase in C-content within LM was significant under rambutan and durian compared to open areas (Fig. 4b). Similarly, N-content within LM ($F = 10.6$, $p = 0.002$) and m ($F = 11.3$, $p = 0.002$) fractions increased under shade trees relative to open areas. The increase in N-content within LM fractions was significant under gliricidia and rambutan, and marginally significant under durian, compared to open areas (Fig. 4c).

Discussion

Isolated shade trees increase soil fertility

Soil C and N, as well as soil MWD, were significantly increased under shade trees (Fig. 3). These results echo previous studies which have found that isolated trees in acacia agroforests or savanna ecosystems contribute to increased total C and N pools in the topsoil (Pandey et al. 2000; Radwanski and Wickens 1967; Zinke 1962), and confirm that shade trees can have measurable positive effects on soil fertility even in perennial systems. Increased soil C- and N-contents under shade trees could be linked to increased organic inputs from litterfall (Beer 1988), buffered microclimates under tree canopies and resulting increases in litter decomposition rates (Belsky et al. 1989; Steffan-Dewenter et al. 2007), and increased root activity (Schroth 1998) under shade tree canopies.

Increased SOM content and changes in microclimate conditions can further lead to increased substrate availability and changes in soil moisture levels. These changes can influence microbial activity and hence SOM decomposition rates (Bending et al. 2002; Swift et al.

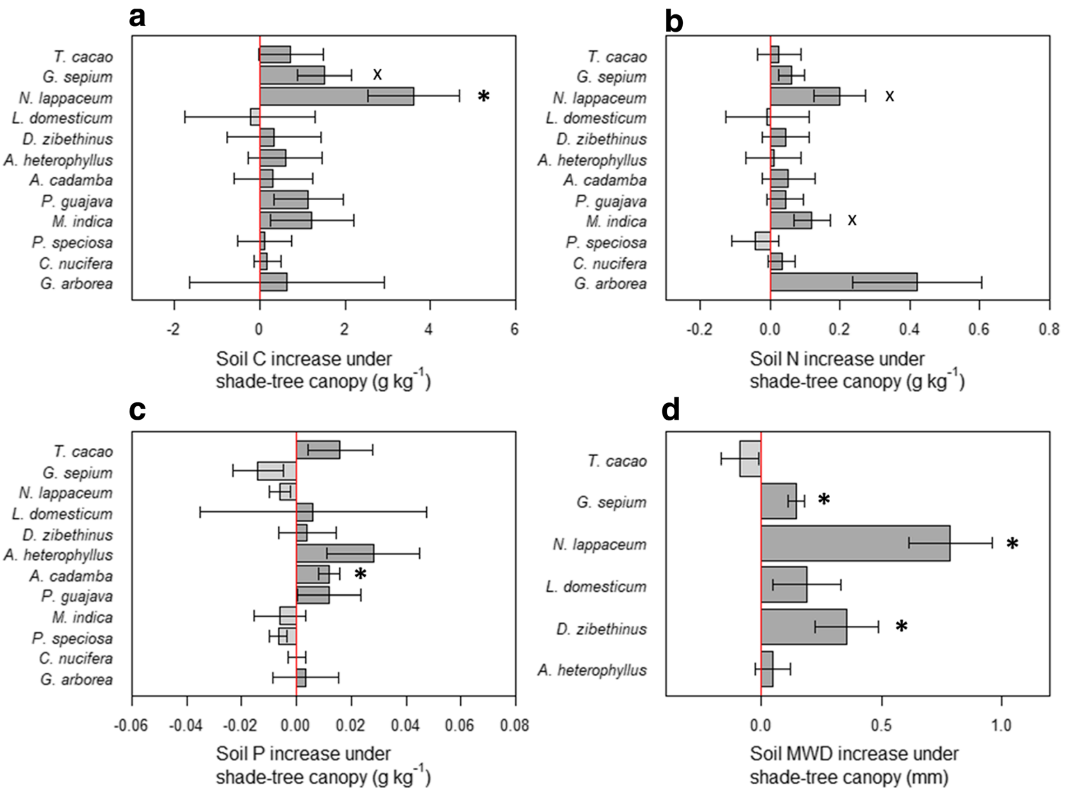

Fig. 3 Mean difference in soil **a**) carbon (C), **b**) nitrogen (N) and **c**) phosphorus (P) content and **d**) mean weight diameter (MWD) in the topsoil layer (0–15 cm) under shade-tree canopy for 11 different shade tree species and the control species cocoa. Mean differences were calculated as the differences between mean soil parameter values measured under the canopy of individual shade trees and paired open locations. Bars represent one standard error of the mean. For each species, asterisks (*) indicate a "tree effect" significantly different from zero ($p \leq 0.05$); crosses (x) indicate marginal significance of "tree effect" ($p \leq 0.10$)

1979; Zaman and Chang 2004). Soil aggregate formation is known to be driven by mechanisms related to the interaction of soil micro- and macro-fauna and plant roots and exudates (Fonte et al. 2012; Six 2014), as well as to the overall availability of SOM in the system (Kong et al. 2005). In our study, the observed increase in soil aggregate size (indicated by MWD) under tree canopies therefore may suggest improved long-term OM storage and increased availability of N and P under shade trees.

Shade trees negatively affect cocoa growth, but have limited effects on yields

Our findings also shed some light on the costs and benefits associated with shade tree inclusion in cocoa farms. We found that overall, shade trees had a significant negative effect on the growth of cocoa trees as cocoa tree AGB decreased by an average of 19% under shade canopy compared to open areas (Fig. 2a). While these results confirm observations by Blaser et al. (2017) or Koko et al. (2013) they contrast with those of Isaac et al. (2007a), who found increased cocoa AGB under individual shade trees. This discrepancy might be related to species-specific differences between the shade trees investigated in the two studies. Similarly to Koko et al. (2013), we found that cocoa AGB increased with planting distance from shade trees, confirming that close proximity to shade trees has a negative effect on cocoa tree growth, likely due to resource competition.

However, this negative effect on cocoa AGB did not directly translate to cocoa yields, which did not significantly decrease under shade trees. This suggests that in terms of yield productivity, the positive effects of shade trees on soil fertility may have outweighed resource competition at our

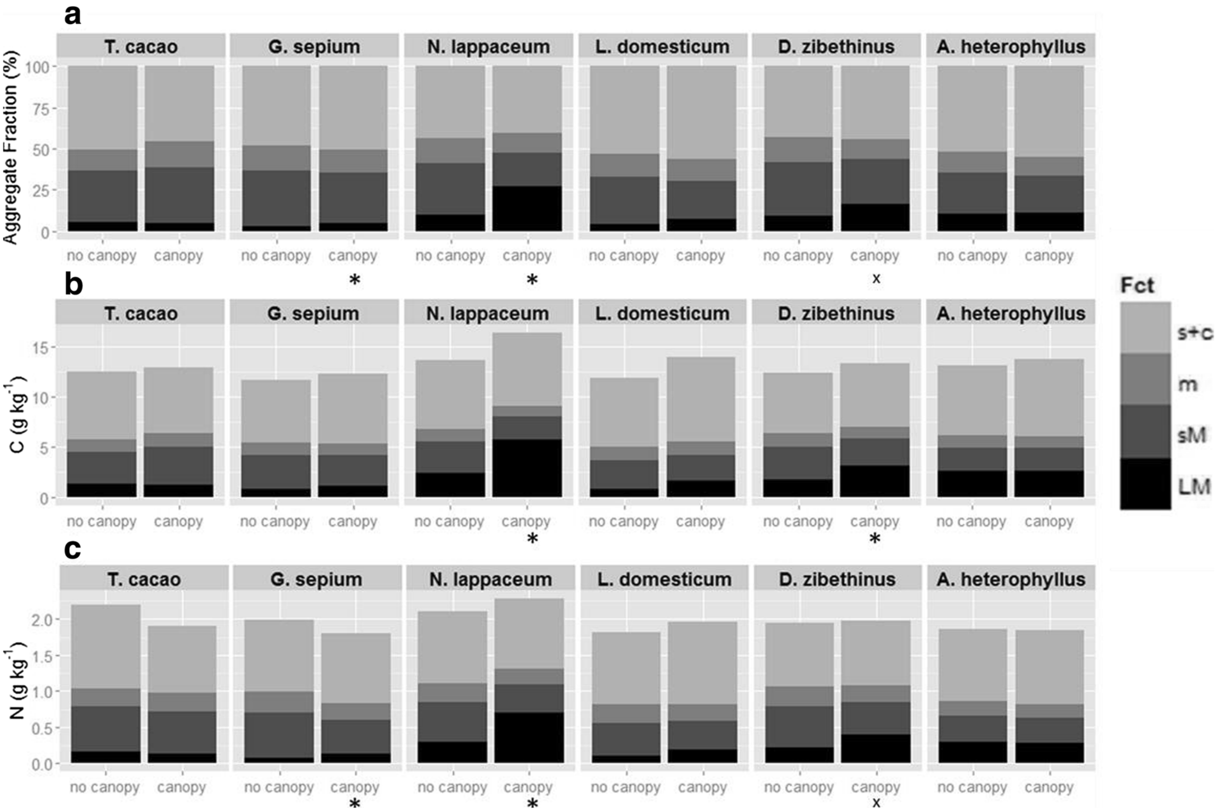

Fig. 4 Mean distribution across fraction sizes for **a**) aggregate fraction proportions, **b**) C- contents of aggregates and **c**) N-contents of aggregates for five shade tree species commonly intercropped with cocoa in Sulawesi, Indonesia. The different fractions (Fct) represented are: large macroaggregates (LM; >2000 µm), small macroaggregates (sM; 250–2000 µm), microaggregates (m; 53–250 µm), and free silt and clay (s + c; <53 µm) particles. For each species, asterisks (*) indicate a "tree effect" significantly different from zero ($p \leq 0.05$); crosses (x) indicate marginal significance of "tree effect" ($p \leq 0.10$). Both significant and marginally significant effects are indicated for the LM fraction only

study sites. Based on our results, individual shade trees might thus have less of a direct negative influence on yields than often assumed, although the extent to which negative effects do occur are likely dependent on differences in competition for light and nutrient resources across individuals and species.

Existing studies examining relationships between shade trees and cocoa at the systems scale document significant negative relationships between shade tree density and cocoa yields (e.g. Blaser et al. 2018; Clough et al. 2011; Waldron et al. 2015), indicating potential negative effects of high shade-canopy densities. However, no direct relationship has been shown between increased shade tree diversity and yields in cocoa agroforests (Clough et al. 2011; Wartenberg et al. 2017). While it remains unclear how our results would scale up, flexible inclusion of diverse shade trees at low densities within cocoa plots might be an effective approach for farmers to minimize trade-offs, although more research is needed to corroborate this at the systems scale.

Shade tree effects on soil fertility are highly variable between shade tree species

We observed high variability in the net change in soil nutrient concentrations and MWD under different shade tree species (Fig. 3), which is consistent with existing literature (Bossuyt et al. 2001; Giardina et al. 2001; Lehmann et al. 2001). Neither canopy architecture (tree height, canopy height, canopy area), tree size (AGB), nor litter nutrient contents were correlated with variation in soil nutrient contents. This is consistent with the results of Vivanco and Austin (2008), who reported that differences in litter quality and decomposition rates between tree species in Argentina did not translate to differences in SOM concentrations. Our results ultimately highlight the complexity of plant-soil interactions and the difficulty of disentangling direct relationships between tree species and soil nutrient cycling mechanisms in farmed landscapes (Vivanco and Austin 2008).

Our results do, however, provide some insights regarding soil aggregation mechanisms under different tree species. MWD increases, indicative of soil aggregate formation, were maximized under shade trees with large canopy area and median-height of 10–15 m, which most likely provide moderate levels of shade compared to shorter trees or trees with smaller canopy areas. This then suggests that soil aggregation was optimized under moderate levels of shade. Changes in soil temperature and moisture content are directly related to changes in foliage density across species (e.g. Isaac et al. 2007a). Because soil microbes are highly sensitive to environmental changes (Paul 2014), differences in microclimate between shade trees with different canopy structures most likely affected soil aggregate formation (Miller and Jastrow 2000; Tisdall and Oades 1982).

Macroaggregate fractions (> 2000 μm) degrade faster than microaggregate fractions (53–250 μm) occluded within them. High concentrations of nutrients contained in LM fractions therefore might be an indicator for increased aggregate turnover rates. We found that both MWD and large macroaggregate (LM) proportions were significantly higher (Fig. 4a) under the canopies of rambutan, which had elevated litter calcium levels compared to other species (Table 1). Calcium has been shown to catalyze the formation of physical bonds and to stimulate microbial activity (Chan and Heenan 1999; Six et al. 2004) by altering soil acidity (Reich et al. 2005), and has been recognized as a driver of soil aggregation and SOM stabilization processes (e.g. Muneer and Oades 1989). We thus hypothesize that increased litter calcium may have contributed to increased long-term aggregate stabilization under rambutan.

C- and N-distributions in aggregate fractions under tree canopies also varied between species. Under rambutan, gliricidia and durian trees, there was a significant increase in C- and N-storage in LM fractions compared to open areas (Fig. 3). We measured elevated litter CN ratios and high calcium levels only in rambutan litter (Table 1) and found that changes in total soil C and N pools in the whole soil were not reflected in C- and N-storage-within-aggregate dynamics, except under rambutan (Figs. 3 & 4). We did not find increased total N contents under gliricidia. The high litter quality of gliricidia trees, as indicated by low CN ratios (Table 1), may have contributed to increased aggregate turnover rates (e.g. Six et al. 2001) under gliricidia canopies. Under gliricidia, increased aggregate turnover rates may have led to increased short-term, rather than long-term, N-storage within macroaggregates. Under rambutan and durian, aggregate formation and C-stabilization within LM fractions might also have been related to changes in soil biological activity (Naher et al. 2013; Smith et al. 1998), although more data is needed to corroborate this.

Interactions between shade-tree functional traits and implications for cocoa productivity

While we found effects of shade trees on cocoa tree performance and soil fertility, we also found that the magnitude of these effects differed significantly between shade tree species. We were not able to directly link this variation to specific shade tree traits but recognize that our study was limited by a lack of data regarding relevant traits such as shade tree canopy density, rooting depth, root-associated microbiota and microclimate and light-levels under shade tree canopies. Documenting these traits for the species selected in our study, as well as for other common tropical shade trees, would further inform their impacts on cocoa growth and productivity. We found minimal differences in topsoil soil moisture between species apart from langsat. Deeper soil moisture measurements, combined with additional information regarding rooting depths, might further be useful to better understand below-ground competition dynamics for water resources in cocoa agroforests.

Nevertheless, we suggest that certain traits have a more dominant effect than others. For example, gliricidia trees are often cited as beneficial in agroforestry settings due to their N-fixing capacity (e.g. Tscharntke et al. 2011). Our results largely confirmed this, as we found significantly increased MWD and N contents within large macroaggregates in soils under gliricidia (Figs. 3 & 4). While on average, cocoa AGB was decreased under most shade tree species including gliricidia, (Fig. 2a), in contrast to most other trees gliricidia had a positive effect on cocoa yields (Fig. 2b). Under gliricidia, which has a relatively light canopy compared to other species, it appears that positive effects on soil N and aggregation may have outweighed resource competition trade-offs and led to increased cocoa yields.

A comparison of the effect of different species on cocoa yields showed that durian had the most negative effect on yields (Fig. 2a). In contrast, the measured increase in soil aggregation under durian trees indicated a significant improvement in soil structure. Similarly, rambutan had a net negative effect on both cocoa AGB and yields but a significantly positive effect on soil C and MWD, indicating a potential for soil fertility improvement. The individual durian and rambutan trees in the cocoa plots selected for this study had relatively high AGBs and low canopy heights (Table 1), indicating relatively dense canopies – this might have led to reduced light availability for nearby cocoa trees. Under durian and rambutan, potential benefits to cocoa trees from increased soil fertility (Figs. 3 & 4) might have thus been canceled out by light competition, although more data is needed to corroborate this. As we found decreased cocoa yields under both species, management recommendations targeting improved cocoa farming practices would have to address the potential adverse effects of these two species on productivity. However, durian and rambutan trees produce fruit commonly consumed throughout Southeast Asia. In light of discussions regarding the benefits of complex agroforests for soil restoration or climate mitigation activities (Schroth et al. 2015), the establishment of durian- or rambutan-based plantations or agroforestry systems might constitute an interesting alternative to cocoa for farmers. However, future research would have to address the optimization of incentive schemes and access to markets.

Conclusions

In Southeast Sulawesi, shade trees had a positive net effect on soil fertility but a negative net effect on cocoa tree growth. However, we found that cocoa yields were not significantly decreased under shade trees. Shade tree traits such as litter quality or tree morphology were also found to have significant effects on aggregate formation and the stabilization of nutrients in different aggregate-size classes, confirming the potential for soil improvements under shade trees. Our results indicate that shade tree inclusion in perennial cropping systems is a viable approach to increase the sustainability of cocoa cultivation systems, particularly when planted at low densities. While our study provides insights regarding the 11 selected shade tree species, which are all commonly found in cocoa agroforests of Sulawesi, our findings do not allow to draw strong conclusions regarding recommendations of specific species or traits. This highlights the need for further research to better understand inter-species interactions in cocoa agroforests and to inform shade tree planting guidelines based on general morphology and functional traits – a potentially important resource for farmers. In the meantime, we recommend that targeted evaluations of the costs and benefits associated with local shade tree species in tropical agroforests could help generate relevant planting recommendations for farmers in different regions.

Acknowledgements This research was supported by ETH Zürich, as well as by ICRAF. We would like to thank ICRAF's AgFor team in Bogor for their advice and logistical support, the AgFor Kendari team, Husrin Laode and Pak Sabri for their invaluable organizational and technical support in the field, and the farmers who participated in our study - in particular Pak Ibrahim and Pak Susi. We also thank Britta Jahn, Camille Rubeaud and Mathias Gebhard for their assistance with laboratory work at ETH Zürich and Engil Pujol Pereira for her comments on an earlier version of the manuscript.

Appendix

Table 3 Variation in soil properties across individual shade-tree sites. The values displayed are mean values ± standard deviations

Species	Common name	No. of replicates	“no canopy”				“canopy”			
			Soil C (g kg^{-1})	Soil N (g kg^{-1})	Soil P (g kg^{-1})	MWD (mm)	Soil C (g kg^{-1})	Soil N (g kg^{-1})	Soil P (g kg^{-1})	MWD (mm)
1. Theobroma cacao	Cocoa	5	13.0 ± 0.7	1.9 ± 0.1	0.20 ± 0.02	0.91 ± 0.27	13.7 ± 1.3	1.9 ± 0.2	0.21 ± 0.04	0.81 ± 0.21
2. Gliricidia sepium	Gliricidia	5	11.7 ± 1.1	1.6 ± 0.2	0.20 ± 0.04	0.73 ± 0.10	13.3 ± 1.3	1.7 ± 0.2	0.19 ± 0.02	0.88 ± 0.18
3. Nephelium lappaceum	Rambutan	5	13.8 ± 2.6	1.9 ± 0.3	0.24 ± 0.07	1.01 ± 0.31	17.4 ± 1.1	2.1 ± 0.2	0.23 ± 0.06	1.84 ± 0.46
4. Lansium domesticum	Langsat	5	13.6 ± 3.2	1.8 ± 0.2	0.22 ± 0.05	0.84 ± 0.19	13.4 ± 0.8	1.7 ± 0.1	0.23 ± 0.05	1.03 ± 0.28
5. Durio zibethinus	Durian	5	13.5 ± 1.0	1.9 ± 0.1	0.20 ± 0.03	0.99 ± 0.21	13.4 ± 1.7	1.9 ± 0.2	0.21 ± 0.02	1.34 ± 0.17
6. Artocarpus heterophyllus	Jackfruit	5	13.9 ± 1.7	1.8 ± 0.2	0.20 ± 0.02	1.15 ± 0.37	14.5 ± 1.2	1.8 ± 0.1	0.23 ± 0.05	1.20 ± 0.32
7. Neolamarckia cadamba	Jabon	5	13.0 ± 1.8	1.7 ± 0.2	0.20 ± 0.02	NA	13.3 ± 1.1	1.8 ± 0.2	0.21 ± 0.03	NA
8. Psidium guajava	Guava	5	13.0 ± 2.4	1.7 ± 0.2	0.21 ± 0.03	NA	14.2 ± 4.0	1.8 ± 0.3	0.22 ± 0.04	NA
9. Mangifera indica	Mango	5	12.0 ± 1.1	1.6 ± 0.1	0.22 ± 0.02	NA	13.2 ± 1.7	1.7 ± 0.2	0.21 ± 0.03	NA
10. Parkia speciosa	Petai	3	13.7 ± 1.8	1.7 ± 0.1	0.20 ± 0.02	NA	14.8 ± 0.9	1.7 ± 0.0	0.19 ± 0.02	NA
11. Cocos nucifera	Coconut	5	12.1 ± 0.7	1.6 ± 0.1	0.21 ± 0. 03	NA	12.2 ± 1.1	1.6 ± 0.1	0.20 ± 0.02	NA
12. Gmelina arborea	Gmelina	3	13.8 ± 1.4	1.9 ± 0.4	0.22 ± 0.02	NA	14.5 ± 4.1	2.4 ± 0.5	0.22 ± 0.03	NA
All	--	56	13.0 ± 1.8	1.8 ± 0.2	0.21 ± 0.03	0.95 ± 0.27	13.9 ± 2.1	1.8 ± 0.3	0.21 ± 0.04	1.18 ± 0.44

Table 4 Results of linear regression analysis between i) difference in cocoa AGB and yields and ii) changes in soil N- and P-contents under shade trees, using shade-tree species as a covariate. Shown are R^2 values

	Cocoa AGB	Cocoa Yield
Soil N	< 0.01	< 0.01
Soil P	< 0.01	0.02

(*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$,. $p < 0.1$)

Table 5 Results of linear regression analysis between i) cocoa AGB and yields and ii) shade-tree (ST) attributes and litter nutrient contents. Shown are R^2 values

	Cocoa AGB	Cocoa Yield
ST Crown Height	< 0.01	< 0.01
ST Lower Canopy Height	0.02	< 0.01
ST Canopy Area	0.02 *	< 0.01
ST AGB	< 0.01	< 0.01
ST Litter C	< 0.01	< 0.01
ST Litter N	< 0.01	< 0.01
ST Litter P	< 0.01	< 0.01
ST Litter Ca	< 0.01	< 0.01
ST Litter CN	< 0.01	< 0.01

(*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$,. $p < 0.1$)

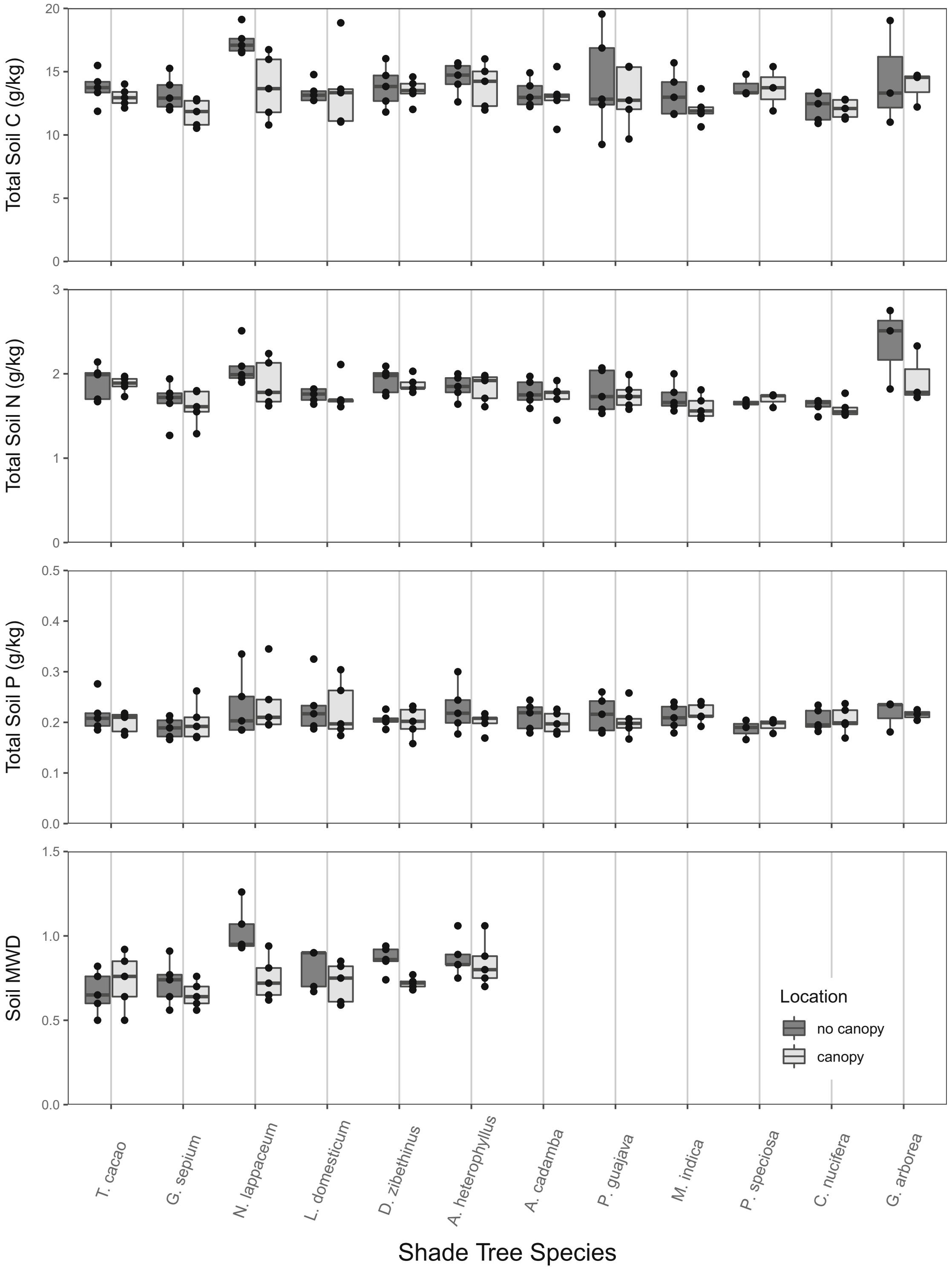

Fig. 5 Soil carbon (**a**), nitrogen (**b**), and phosphorus (**c**) contents; and mean weight diameter (or MWD) (**d**) in the topsoil layer (0–15 cm) obtained under shade-tree canopy (under canopy) and in open areas (no canopy) for 11 different shade-tree species and our control cocoa. The data is displayed as boxplots with dark horizontal lines representing the mean, the box representing the 25th and 75th percentiles, the whiskers the 5th and 95th percentiles, and dots representing outliers

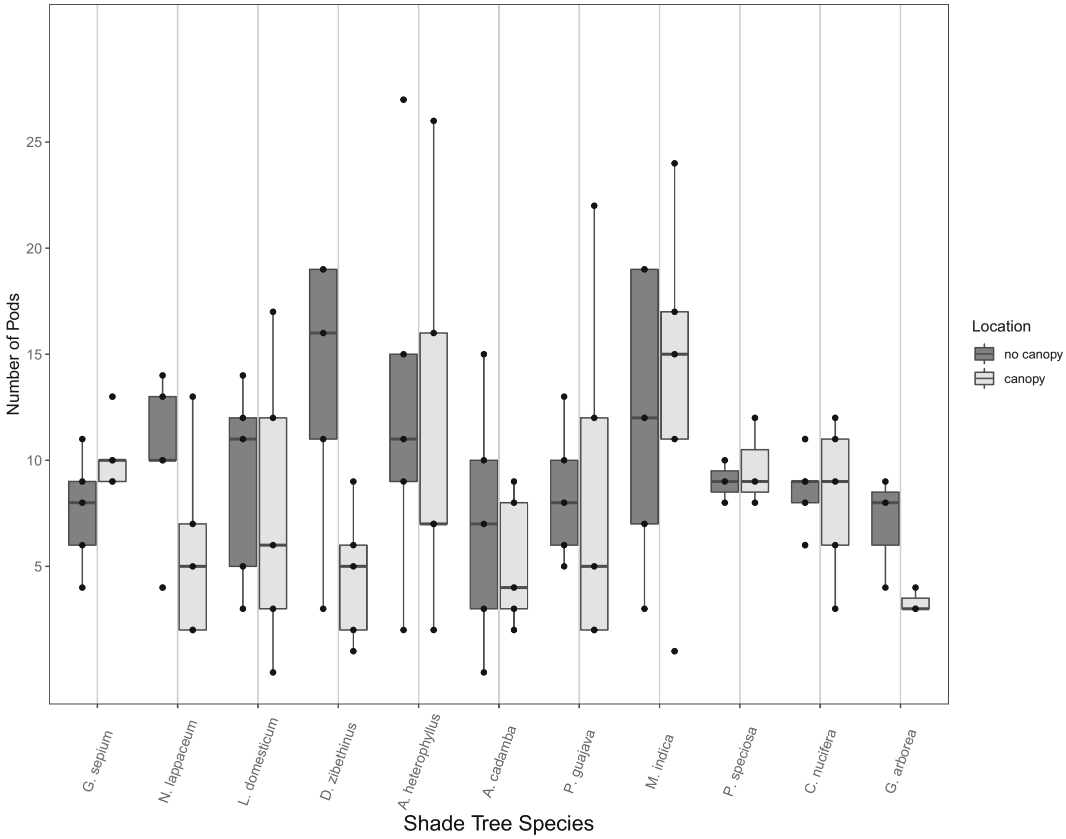

Fig. 6 Mean number of pods counted on cocoa trees located under shade-tree canopy (under canopy) and in open areas (no canopy) for 11 different shade-tree species. The data is displayed as boxplots with dark horizontal lines representing the mean, the box representing the 25th and 75th percentiles, the whiskers the 5th and 95th percentiles, and dots representing outliers

References

Abdulai I, Vaast P, Hoffmann MP, Asare R, Jassogne L, Van Asten P, Rötter RP, Graefe S (2018) Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. Glob Chang Biol 24:273–286

Anderson JM, Ingram J (1994) Tropical soil biology and fertility: a handbook of methods. Soil Sci 157:265

Asare R, Asare RA, Asante WA, Markussen B, Ræbild A (2017) Influences of shading and fertilization on on-farm yields of cocoa in Ghana. Exp Agric 53:416–431

Bayala J, Heng LK, van Noordwijk M, Ouedraogo SJ (2008) Hydraulic redistribution study in two native tree species of agroforestry parklands of west African dry savanna. Acta Oecol 34:370–378

Beer J (1987) Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. Agrofor Syst 5:3–13

Beer J (1988) Litter production and nutrient cycling in coffee (Coffea arabica) or cacao (Theobroma cacao) plantations with shade trees. Agrofor Syst 7:103–114

Beer MR, Kass D, Somarriba E (1998) Shade management in coffee and cacao plantations. Directions in tropical agroforestry research. Springer

Belsky A, Amundson R, Duxbury J, Riha S, Ali A, Mwonga S (1989) The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. J Appl Ecol 26:1005–1024

Bending GD, Turner MK, Jones JE (2002) Interactions between crop residue and soil organic matter quality and the functional diversity of soil microbial communities. Soil Biol Biochem 34:1073–1082

Blaser WJ, Oppong J, Yeboah E, Six J (2017) Shade trees have limited benefits for soil fertility in cocoa agroforests. Agric Ecosyst Environ 243:83–91

Blaser W, Oppong J, Hart S, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain 1:234

Bossuyt H, Denef K, Six J, Frey S, Merckx R, Paustian K (2001) Influence of microbial populations and residue quality on aggregate stability. Appl Soil Ecol 16:195–208

Chan K, Heenan D (1999) Lime-induced loss of soil organic carbon and effect on aggregate stability. Soil Sci Soc Am J 63:1841–1844

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WB, Duque A, Eid T, Fearnside PM, Goodman RC (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Chang Biol 20:3177–3190

Climate-Data.org (2016) Climate Data for Cities Worldwide

Clough Y, Putra DD, Pitopang R, Tscharntke T (2009) Local and landscape factors determine functional bird diversity in Indonesian cacao agroforestry. Biol Conserv 142:1032–1041

Clough Y, Barkmann J, Juhrbandt J, Kessler M, Wanger TC, Anshary A, Buchori D, Cicuzza D, Darras K, Putra DD (2011) Combining high biodiversity with high yields in tropical agroforests. Proc Natl Acad Sci 108:8311–8316

Elliott E (1986) Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci Soc Am J 50:627–633

FAOSTAT (2011) FAOSTAT database. In: FaAOotU Nations

FAO-UNESCO (1979) Soil map of the world - SE Asia. http://www.fao.org/. Accessed 2018

Fonte SJ, Quintero DC, Velásquez E, Lavelle P (2012) Interactive effects of plants and earthworms on the physical stabilization of soil organic matter in aggregates. Plant Soil 359:205–214

Giardina CP, Ryan MG, Hubbard RM, Binkley D (2001) Tree species and soil textural controls on carbon and nitrogen mineralization rates. Soil Sci Soc Am J 65:1272–1279

Graefe S, Meyer-Sand LF, Chauvette K, Abdulai I, Jassogne L, Vaast P, Asare R (2017) Evaluating farmers' knowledge of shade trees in different cocoa agro-ecological zones in Ghana. Hum Ecol 45:321–332

Hobbie SE, Reich PB, Oleksyn J, Ogdahl M, Zytkowiak R, Hale C, Karolewski P (2006) Tree species effects on decomposition and forest floor dynamics in a common garden. Ecology 87:2288–2297

Harja D, Rahayu S, Pambudi S (2018) Tree functional attributes and ecological database. World Agroforestry Centre (ICRAF), Nairobi

Hartemink AE (2005) Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. Adv Agron 86:227–253

Isaac M, Gordon A, Thevathasan N, Oppong S, Quashie-Sam J (2005) Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes. Agrofor Syst 65:23–31

Isaac M, Ulzen-Appiah F, Timmer VR, Quashie-Sam SJ (2007a) Early growth and nutritional response to resource competition in cocoa-shade intercropped systems. Plant Soil 298: 243–254. https://doi.org/10.1007/s11104-007-9362-x

Isaac ME, Timmer VR, Quashie-Sam S (2007b) Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of Theobroma cacao by vector analysis. Nutr Cycl Agroecosyst 78:155–165

Jagoret P, Michel-Dounias I, Snoeck D, Ngnogué HT, Malézieux E (2012) Afforestation of savannah with cocoa agroforestry systems: a small-farmer innovation in Central Cameroon. Agrofor Syst 86:493–504

Janudianto KN, Roshetko JM, Mahrizal (2014) Cacao agroforestry system (CAS) improving productivity and profitability of smallholder cacao in Sulawesi. World agroforestry congress. World agroforestry Centre - ICRAF, SEA regional office., India, Bogor

Koko LK, Snoeck D, Lekadou TT, Assiri AA (2013) Cacao-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. Agrofor Syst 87:1043–1052

Kong AY, Six J, Bryant DC, Denison RF, Van Kessel C (2005) The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Sci Soc Am J 69:1078–1085

Lehmann J, da Silva Cravo M, Zech W (2001) Organic matter stabilization in a Xanthic Ferralsol of the Central Amazon as affected by single trees: chemical characterization of density, aggregate, and particle size fractions. Geoderma 99:147–168

Miller R, Jastrow J (2000) Mycorrhizal fungi influence soil structure. Arbuscular mycorrhizas: physiology and function. Springer

Mithöfer D, Roshetko JM, Donovan JA, Nathalie E, Robiglio V, Wau D, Sonwa DJ, Blare T (2017) Unpacking 'sustainable'cocoa: do sustainability standards, development projects and policies address producer concerns in Indonesia, Cameroon and Peru? Int J Biodivers Sci Ecosyst Serv Manage 13:444–469

Muneer M, Oades J (1989) The role of ca-organic interactions in soil aggregate stability .III. Mechanisms and models. Soil Res 27:411–423. https://doi.org/10.1071/SR9890411

Naher UA, Othman R, Panhwar QA (2013) Beneficial effects of mycorrhizal Association for Crop Production in the tropics-a review. Int J Agric Biol 15

Pandey C, Singh A, Sharma D (2000) Soil properties under Acacia nilotica trees in a traditional agroforestry system in Central India. Agrofor Syst 49:53–61

Paul EA (2014) Soil microbiology, ecology and biochemistry. Academic press

Pinheiro J, Bates D, DebRoy S, Sarkar D, Heisterkamp S, Van Willigen B, Maintainer R (2016) Package 'nlme'

Radwanski S, Wickens G (1967) The ecology of Acacia albida on mantle soils in Zalingei, Jebel Marra, Sudan. J Appl Ecol 4: 569–579

Reich PB, Oleksyn J, Modrzynski J, Mrozinski P, Hobbie SE, Eissenstat DM, Chorover J, Chadwick OA, Hale CM, Tjoelker MG (2005) Linking litter calcium, earthworms and soil properties: a common garden test with 14 tree species. Ecol lett 8:811–818

Rhoades C (1996) Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. Agrofor Syst 35:71–94

Rousseeuw P, Croux C, Todorov V, Ruckstuhl A, Salibian-Barrera M, Verbeke T, Maechler M (2015) robustbase: Basic robust statistics [Software]

Ruhigwa B, Gichuru M, Mambani B, Tariah N (1992) Root distribution of Acioa barteri, Alchornea cordifolia, Cassia siamea and Gmelina arborea in an acid Ultisol. Agrofor Syst 19:67–78

Sanchez PA (1995) Science in agroforestry. Agroforestry: science, policy and practice. Springer

Sariyildiz T, Anderson J, Kucuk M (2005) Effects of tree species and topography on soil chemistry, litter quality, and decomposition in Northeast Turkey. Soil Biol Biochem 37:1695–1706

Schneidewind U, NIETHER W, ARMENGOT L, SCHNEIDER M, SAUER D, HEITKAMP F, GEROLD G (2018) Carbon stocks, Litterfall and pruning residues in monoculture and agroforestry cacao production systems. Exp Agric:1–19

Schroth G (1998) A review of belowground interactions in agroforestry, focussing on mechanisms and management options. Agrofor Syst 43:5–34

Schroth G, Bede LC, Paiva AO, Cassano CR, Amorim AM, Faria D, Mariano-Neto E, Martini AM, Sambuichi RH, Lôbo RN (2015) Contribution of agroforests to landscape carbon storage. Mitig Adapt Strateg Glob Chang 20:1175–1190

Six J, Paustian (2014) Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol Biochem 68: A4-A9

Six J, Elliott E, Paustian K, Doran J (1998) Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci Soc Am J 62:1367–1377

Six J, Paustian K, Elliott ET, Combrink C (2000) Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci Soc Am J 64:681–689

Six J, Carpentier A, van Kessel C, Merckx R, Harris D, Horwath WR, Lüscher A (2001) Impact of elevated CO2 on soil organic matter dynamics as related to changes in aggregate turnover and residue quality. Plant Soil 234: 27–36

Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res 79:7–31

Smiley G, Kroschel J (2010) Yield development and nutrient dynamics in cocoa-gliricidia agroforests of Central Sulawesi, Indonesia. Agrofor Syst 78:97–114

Smith HF, O'Connor PJ, Smith SE, Smith FA (1998) Vesicular-arbuscular mycorrhizas of durian and other plants of forest gardens in West Kalimantan, Indonesia. Soils of tropical Forest ecosystems. Springer

Somarriba E, Cerda R, Orozco L, Cifuentes M, Dávila H, Espin T, Mavisoy H, Ávila G, Alvarado E, Poveda V (2013) Carbon stocks and cocoa yields in agroforestry systems of Central America. Agric Ecosyst Environ 173:46–57

Steffan-Dewenter I, Kessler M, Barkmann J, Bos MM, Buchori D, Erasmi S, Faust H, Gerold G, Glenk K, Gradstein SR (2007) Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. Proc Natl Acad Sci 104:4973–4978

Swift MJ, Heal OW, Anderson JM (1979) Decomposition in terrestrial ecosystems. Univ of California Press

Tisdall J, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141–163

Tscharntke T, Clough Y, Bhagwat SA, Buchori D, Faust H, Hertel D, Hölscher D, Juhrbandt J, Kessler M, Perfecto I (2011) Multifunctional shade-tree management in tropical agroforestry landscapes–a review. J Appl Ecol 48:619–629

Vaast P, Somarriba E (2014) Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. Agrofor Syst 88:947–956

Van Bavel C (1950) Mean weight-diameter of soil aggregates as a statistical index of aggregation. Soil Sci Soc Am J 14:20–23

Van Noordwijk M, Purnomosidhi P (1995) Root architecture in relation to tree-soil-crop interactions and shoot pruning in agroforestry. In: Agroforestry: Science, Policy and Practice. Springer

van Noordwijk M, Cadisch G, Ong CK (2004) Below-ground interactions in tropical agroecosystems: concepts and models with multiple plant components. CABI

Vivanco L, Austin AT (2008) Tree species identity alters forest litter decomposition through long-term plant and soil interactions in Patagonia, Argentina. J Ecol 96:727–736

Wahid P, Valiathan M, Kamalam N, Eapen J, Vijayalakshmi S, Prabhu RK, Mahalingam T (2000) Effect of rare earth elements on growth and nutrition of coconut palm and root competition for these elements between the palm and Calotropis gigantea. J Plant Nutr 23:329–338

Waldron A, Justicia R, Smith L (2015) Making biodiversity-friendly cocoa pay: combining yield, certification, and REDD for shade management. Ecol Appl 25:361–372

Wartenberg AC, Blaser WJ, Gattinger A, Roshetko JM, Van Noordwijk M, Six J (2017) Does shade tree diversity increase soil fertility in cocoa plantations? Agric Ecosyst Environ 248: 190–199

Witjaksono J (2016) Asmin. Cocoa farming system in Indonesia and its sustainability under climate change. Agriculture, forestry. Fisheries 5:170–180

Zaman M, Chang S (2004) Substrate type, temperature, and moisture content affect gross and net N mineralization and nitrification rates in agroforestry systems. Biol Fertil Soils 39: 269–279

Zinke PJ (1962) The pattern of influence of individual forest trees on soil properties. Ecology 43:130–133