BIODIVERSITAS
Volume 23, Number 1, January 2022
Pages: 496-506

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d230153

Tree density impact on growth, roots length density, and yield in agroforestry based cocoa

ABDUL RAHIM SALEH[1,2], SIKSTUS GUSLI[3], AMBO ALA[4], RISMA NESWATI[3], SRI SUDEWI[5,♥]
[1]Program of Agriculture, Graduate School, Universitas Hasanuddin. Jl. Perintis Kemerdekaan Km. 10, Makassar 90245, South Sulawesi, Indonesia
[2]Department of Agrotechnology, Faculty of Agriculture, Universitas Sintuwu Maroso. Jl. Ir. P. Timor 01, Poso 94612, Central Sulawesi, Indonesia
[3]Department of Soil Science, Faculty of Agriculture, Universitas Hasanuddin. Jl. Perintis Kemerdekaan Km. 10, Makassar 90245, South Sulawesi, Indonesia
[4]Department of Agrotechnology, Faculty of Agriculture, Universitas Hasanuddin. Jl. Perintis Kemerdekaan Km. 10, Makassar 90245, South Sulawesi, Indonesia
[5]Department of Agrotechnology, Faculty of Agriculture, Universitas Alkhairaat. Jl. Diponegoro No. 39, Palu 94111, Central Sulawesi, Indonesia.
♥email: srisudewi@unisapalu.ac.id, arahim@unsimar.ac.id

Manuscript received: 20 November 2021. Revision accepted: 28 December 2021.

Abstract. *Saleh AR, Gusli S, Ala A, Neswati R, Sudewi S. 2022. Tree density impact on growth, roots length density, and yield in agroforestry based cocoa. Biodiversitas 23: 496-506.* Cocoa-based agroforestry systems using langsat trees as shade is aimed to maximize the absorptions of solar energy, water, and nutrients, and increase income sources for farmers. Limited information about interspecific interactions between cocoa and langsat which is needed to improve the performance of agroforestry systems is a challenging idea. We studied the relationship characteristics of cocoa trees as a present shaded effect in the agroforestry system. Compared agroforestry systems were based on ages, namely young and old cocoa agroforestry or YCAF and OCAF, and monoculture systems (Mono) regardless of plant age. On above stony soil, we observed root length density (RLD) of cocoa and langsat fine roots, from under cocoa canopy to three distance levels from the cocoa stem (i.e. at a distance 0.4 m, 1.2 m and, 1.7 m), and four distance depths for all systems (i.e. at a depth 0-10 cm, 10-20 cm, 20-30 cm and, 30-40 cm). Stem diameter, basal area, canopy cover, yield cocoa beans, and convertible products non-cocoa were equivalent to the price of cocoa beans by tree equivalent yield (TEY) formula. Cocoa RLD in the Mono system did not differ from RLD-cocoa in the OCAF system, but both significantly differed with RLD-cocoa in the YCAF system. Shade trees increased tree density in both agroforestry systems, triggering competition in the canopy for sunlight. Expansion of langsat roots that spread closer to the cocoa trunk increased competition for nutrients and water. Both cocoa and langsat roots overlapped, exploring the same area. The yield of cocoa beans harvested by farmers from the YCAF and OCAF systems decreased by 50%. However, the langsat tree and several other species were accounted for 50% of the TEY in the agroforestry system, thereby adding a source of income to farmers is equivalent to the yield of cocoa beans from a monoculture system.

Keywords: Agroforestry, cocoa tree, langsat tree, root length density, tree density, tree equivalent yield

Abbreviations: Mono: Monokulture; YCAF: Young cocoa agroforestry; OCAF: Old cocoa agroforestry; RLD: Root length density; TEY: Tree equivalent yield; LA: Leaf area; SLA: Specific leaf area; LNC: Leaf nitrogen content; LPC: Leaf phosphorus content; LKC: Leaf potassium content; IDR: Indonesia dalam rupiah; PCA: Principal component analysis; GV: Gliricidia value; FWG: Fresh weight gliricidia

INTRODUCTION

According to farmer information in the Indonesian District of Polewali Mandar, cocoa plantation (*Theobroma cacao*) was established in agroforestry systems on stony soil after the candlenut (*Aleurites moluccanus*) was lost to disease in the 90s. Although this soil type is not recommended for cultivation by agronomists (Ruf and Zadi 1998), stony soil has a high pore size (Meng et al. 2018), impact to store water at the low for plants, with moderate to fast infiltration rates, nutrient content low due to frequent nutrient leaching (Carrick et al. 2013; Hlaváčiková et al. 2018).

Experience shows that cocoa grown on rocky soil in Soubré, Ivory Coast fails to maintain its economic function. The cocoa tree is only productive for about ten years, and at the age of 15, the cocoa tree has shown growth much older than its biological age (Ruf and Schroth 2004). Many plants die before all the investment that has been spent, has not been fully returned (Ruf and Zadi 1998). On the contrary, we get reported that cocoa trees and fruit trees have grown side-by-side at the land with high rock content in Polewali Mandar District for more than three decades (Gusli et al. 2020). Langsat (*Lansium domesticum*) is a fruit plant native to Tropical Southeast Asia found in agroforestry landscapes, standing tall among rows of the cocoa tree, usually found with durian, coconut, avocado trees used as shade trees (Baka et al. 2019), rich in aromatics from the Meliaceae family, widely distributed in the tropical Asia-Pacific region up to 700 m above sea level (Alimuddin et al. 2018; Muellner et al. 2008).

Langsat has economic value for agroforestry systems in Southeast Asia by providing shade and carbon sequestration. Most importantly, the plant has fruit harvested as a substitute for cocoa beans lost from implementing agroforestry systems. Fruiting once a year, early flowers bloom at the beginning of the rainy season, after being induced by the dry season (Techavuthiporn 2018), and harvested when dormant at the end to the early year, considered a Sinterklaas in New Year celebrations by farmers, canopy cover is not too wide so that the penetration of light received by plants to the lower strata is still fulfilled, such characteristics are other things that the farmers like.

Even though farmers have been working on the cocoa-langsat agroforestry system for a long time, there is still an information gap among the interactions of the two trees in the use of shared resources, which must be filled immediately. Comprehensive research on the distribution of cocoa and langsat trees as a form of competition for underground nutrients and canopy density among species in increasing light is urgent to understand the interactions needed to develop recommendations towards improving productivity agroforestry systems.

How is the performance of cocoa-langsat in the agroforestry system and its prospects? To answer these and other implied questions, in this study, we compare young and old cocoa-langsat agroforestry systems to formulate future predictions before making recommendations to cocoa farmers. Our study is conducted to test the following hypotheses: First, root length density will be affected by underground competition, and the older the cocoa-langsat tree, the more significant the increase in RLD of cocoa under shade; second, tree density in agroforestry systems reduces yield and production of tree biomass; third, decreasing cocoa yield in agroforestry systems replaces shade tree products or fruit.

MATERIALS AND METHODS

Study area

Characteristics of the study site

The study was conducted on three cocoa land communities in Binuang sub-district, Polewali Mandar District, West Sulawesi Province, Indonesia. These locations are at the coordinates of 03° 25' 30" S and 119° 23' 09" W to 03° 25' 54" S and 119° 22' 59" W (Figure 1), and spread at altitude 100 to 350 m asl. The area has equatorial rainfall patterns, where the dry season is no more than three months (Wahid 2017). In 2020, rainfall reached 3074 mm, far exceeding the rainfall required for maximum cocoa growth with an annual rainfall of between 1,500 and 2,000 mm (Bertolde et al. 2012). The average weekly rainfall is shown in Figure 2. Rain intensity is high between weeks 1-23 and weeks 37-49. The lowest rainfall is in weeks 23-28 (Figure 2). Artificial treatments, where there is no rain for several weeks, are needed to stimulate flowering.

The soil type in the study site is categorized as stony soil with a rock fragment of 30% in topsoil (0-20 cm) to 50% in 20-40 cm based on depth (Saleh et al. 2021). Stony soil mixture refers to consecutive sandy clay, which is in the rough to moderate category, and clay is where the clay content increases as the depth increase (Gusli et al. 2020).

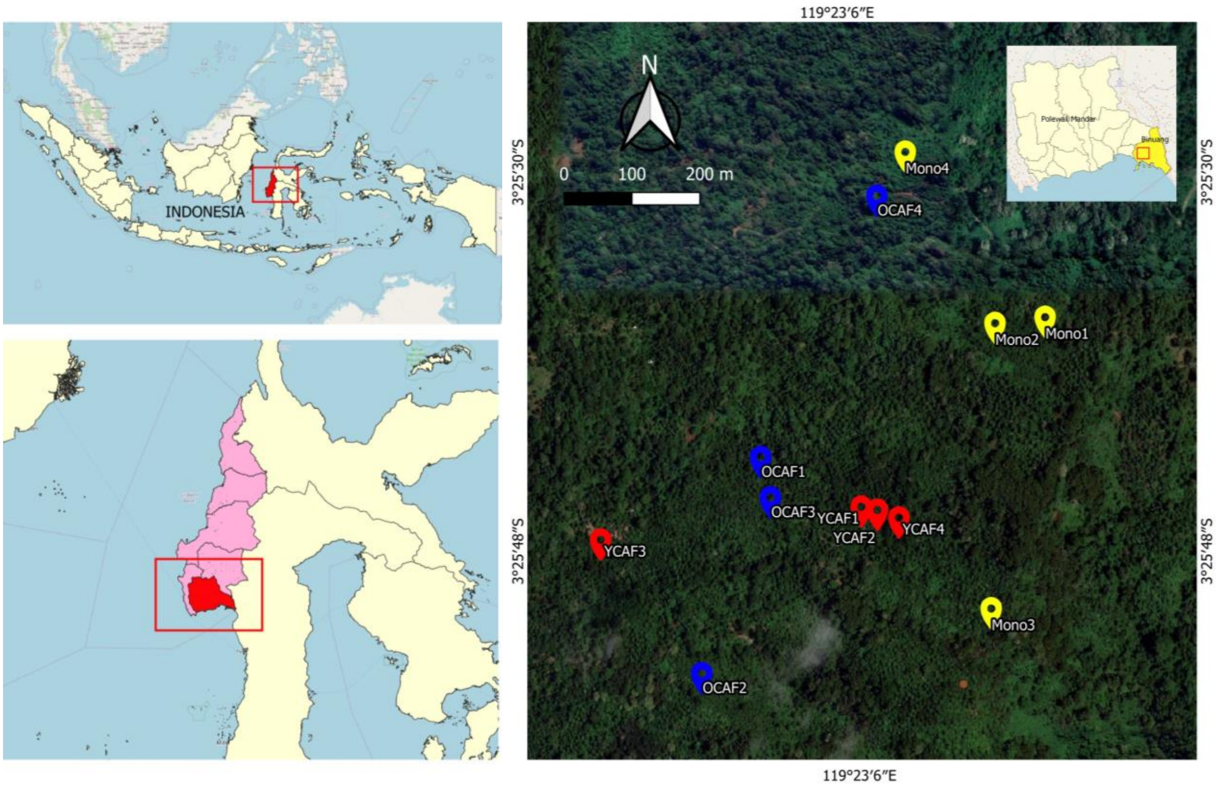

Figure 1. The map of Polewali Mandar District, West Sulawesi, Indonesia, showing Binuang Sub-district where the study was conducted (blue colored in red box) and the plot distribution on the site

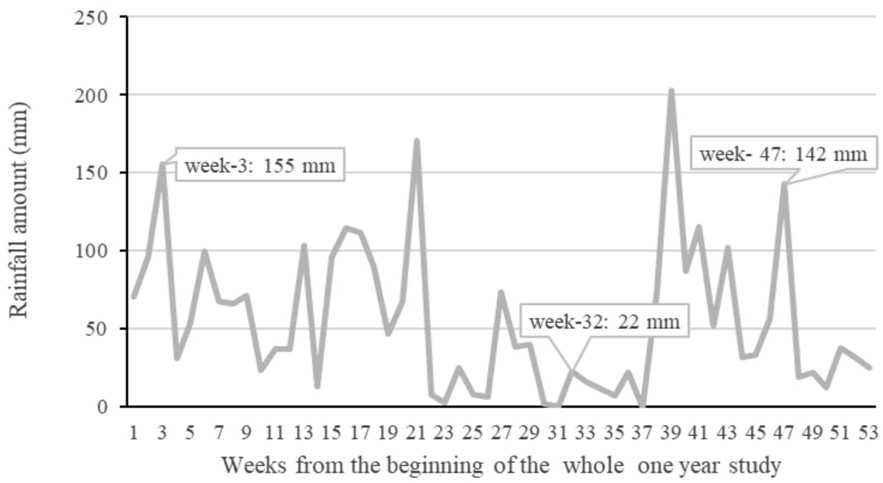

Figure 2. Measured weekly rainfall during the one-year study period in 2020

Procedures

The tree structure of the system

The plots were established on land managed by an "integrated farmer group." Three different cocoa production systems were allocated in a completely randomized design with four replications: Monoculture system (MONO 1-4), Young cocoa agroforestry (for age < 10 years) (YCAF 1-4); and, Old agroforestry cocoa (for age >18 years) (OCAF 1-4), In this study there was no monoculture langsat system. The plots were arranged in a length of 20 m x 20 m in width. All plots were managed using ZA (Zwavelzure Amonium) and SP36 (Super Phosphate) fertilization at 400 kg ha^{-1} y^{-1}, except for the addition 200 kg ha^{-1} y^{-1} ZA fertilizer in $Mono_1$ and $Mono_2$ plots, only $OCAF_4$ received ZA and SP36 each 200 kg ha^{-1} y^{-1}. Weeds control were twice a year with herbicides application. Treatments of fungicides and insecticides were every month starting when the fruit had formed until the end of harvest. The duration of spraying insecticides was carried out more often if the intensity of the rain increased. Spraying was still carried out even though there was no attack (personal communication with farmers).

Soil sampling

Soils were sampled in Juni 2020 at depth 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm for chemical analysis, disturbed soil sample, taken at three levels in a diagonal transect, two points at each level, that was one part in the terrace under the cocoa tree and the other in the oblique field, all samples were from the same layer on each plot evenly mixed to obtain a composite sample per depth. It was air-dried before being analyzed at the soil science laboratory at Hasanudin University. Analysis of soil C-organic (C_{org}) and N-total (N_{tot}) followed the Kjeldahl method, P_2O_5 with Olsen bray (P_{tot}).

Tree structure measurement

Canopy cover is the proportion of the hemisphere of the sky covered by vegetation. Canopy cover was calculated from 25 sample canopy cover photos per plot using image-J software. In addition, we measured the height of the stand (m), stem diameter at breast height of 130 cm (dbh in cm). If there are branches at that height, the diameter (d) is formulated as proposed by Schneidewind et al. (2019); $d = (d_1^2 + d_2^2 + \cdots + d_n^2)^{0,5}$, stem diameter data were used to calculate basal stem area (m^2 ha^{-1}), leaf area (LA, cm^2) was measured using five leaves per tree, representing the level of canopy and ten trees in the plot. The leaf area was estimated with the help of the Image-J software, and it was previously scanned with an Epson scan Type L-3150. Specific leaf area (SLA, cm^2 g^{-1}) is the area of fresh leaves divided by dry mass (Cornelissen et al. 2003). Leaf samples for nutrition leaf analysis were observed following the proposed procedure (INIAP, 2016). Sample preparation was sent to laboratory analysis, including leaf nitrogen content (LNC, %) performed according to the Kjeldahl procedure guidelines, leaf phosphorus content (LPC, %), and leaf potassium content (LKC, %).

Root length measurement

Fine roots of cocoa and langsat were sampled at three distances of 0.4 m, 1.2 m, and 1.7 m from the cocoa stem. The distance of 1.2 m refers to the limit of fertilization around the trunk, while the distance of 0.4 m represents the roots under the cocoa tree's canopy, and the distance of 1.7 m is half the distance between two cocoa trees. The cleaned topsoil was of litter and tree branches at the sampling site. The soil core was sampled with a ring size of 7 cm in diameter, and 10 cm in height or 385 cm^3 in volume. Soil samples for roots were taken at a 10 cm to 40 cm depth. The root separation method was carried out by immersion; the long roots were separated by hand, while the small root pieces were separated using a 0.1 mm sieve. They were separated before being evenly distributed on millimeter paper, for scanning with a Canon EOS camera, and root length was measured by software image-J (https://imagej.net/Fiji/Downloads).

Harvest production systems

Harvesting cocoa beans was done following farmers' way, with a two-week cycle from April to November 2020. All pod cocoa in the plot was harvested, fresh weight of fruit pods was weighed on the site. To determine the ratio of the dry weight of seeds to the importance of new pods, we used the 20 pods which represent all fruit size classes, from the cocoa tree in the monoculture system and both the cocoa agroforestry system, except the size of the fruit from cultivar has a size exceeding the average pods, we removed it from a measurement scale, that estimated to be less than 5%. Fruit components (skin, seeds, and placenta) were dried in the open space separately before being in the oven at 70°C for 48 hours. After that, the dry weight was measured in the soil science laboratory of Hasanuddin University, Indonesia.

The fruit counted was fruit sold to local collectors, and did not include fruit on-site because it does not meet the fruit qualifications required by the buyer. Fruit trees were harvested from January to March 2020. Non-cocoa crops in the agroforestry system are converted at a price equivalent to cocoa beans per kg. The price of cocoa beans used was 10% lower than the average world cocoa price in April - December 2020. The price was determined after communicating personally with the association of cocoa traders in Sulawesi. The 10% reduction was because farmers do not carry out fermentation related to post-harvest activities.

Fresh weight Gliricidia (FWG) were leaves harvested by farmers on bi-monthly or six yearly rotations (hd), sampled from ten trees (n) per plot in three YCAF plots. FWG per year was calculated by the formula:

$$FWG\ (kg\ ha^{-1}\ y^{-1}) = \frac{FWG\ (kg\ tree^{-1})\ x\ n}{Plot\ area\ \ (m^2)}\ x\ hd\ x\ 10000\ m^2$$

Gliricidia value (GV) is the production of goat equivalent feed for a year. It was used in calculating the average forage production of livestock in the year with a formula:

$$GV = \frac{FWG\ (kg\ ha^{-1})\ x\ 20\%}{365}$$

The number of goats obtained after dividing the dry weight (20% from FWG) of forage by the number of days in a year is reduced by 1 (mother goat). In addition to the parent that is not sold, farmers' habits of selling goats after one year, are done to reduce the cost burden related to feed and labor expenses. Although the results are not accepted by a garden owner, taking into account the social role of the agroforestry system, yield palm trees managed by those work as palm sugar tappers are still recorded as the production system, by converting the average amount of palm sugar production in IDR from plots YCAF 1 and 4. Total production equivalent cocoa bean was calculated with formula TEY by Ravi et al. (2021):

$$TEY = \frac{Non\ cocoa\ yield\ (kg\ ha^{-1})x\ Price\ non\ cocoa\ yield\ (IDR\ \ kg^{-1}\ ha^{-1})}{Price\ yield\ cocoa\ bean\ (IDR\ kg^{-1})}$$

Data analysis

Field observation data and laboratory data were tested Gaussian distribution using the Shapiro-Wilk test, previously transformed with the Box-Cox family (Atkinson et al. 2020) unless fine-root data was tested with the Shapiro-Wilk test, which was previously transformed with SQRT + 0.5. The result displayed is original data includes standard error. To analyze the relationship between tree species diversity, stand structure, and cocoa bean yield, we performed Principal Component Analysis (PCA) with the Minitab package.

RESULTS AND DISCUSSION

Effects of different systems on soil fertility

All soil parameters did not show any interaction between the system and depth. We found that C_{org} related to soil concentrations under the YCAF system was significantly higher than in the OCAF system, except that the C_{org} content in the MONO system did not differ from the two other systems. We noted that soil contents, N_{tot} and Pt_{ot}, in YCAF and Mono systems were significantly higher than in the OCAF system, while pH levels and C/N ratio did not show significant differences in the three systems (Table 1).

The soil pH level in the topsoil layer (0-10 cm depth) was 6.32. It was significantly higher than the pH recorded at the next depth except for 20-30 cm. The C concentration of 1.93% and soil N of 0.17% recorded in the topsoil was significantly higher than layers 30-40 but did not differ from the previous two layers (Table S1).

Shaded effect on cocoa tree growth

The density of cocoa trees in the all land-use system showed a significant difference, 800 trees ha^{-1} in YCAF, decreased after old age (OCAF) to 600 trees ha^{-1}, slightly lower and not significant in MONO (618 trees ha^{-1}). The langsat tree had a density of 106 trees ha^{-1} at YCAF to 137 trees ha^{-1} at OCAF. Total tree density in YCAF was 1431 ha^{-1} to 812 ha^{-1} in OCAF. The Shannon diversity index increased from 0 to 0.99 in YCAF, and reduced to 0.72 in OCAF (Table 2). In the OCAF system, the density of gliricidia decreased due to thinning by the farmers. After all, it interferes with the growth of cocoa trees or dies naturally due to age. The thinning of cocoa shade trees has been widely carried out in other places and times.

Table 1. Soil chemical properties in the three cocoa production systems: cocoa monoculture (Mono), young cocoa agroforestry (YCAF), and old cocoa agroforestry (OCAF)

Soil chemical properties	Mono	YCAF	OCAF
pH H_2O (1;2.5)	5.93^a	6.05^a	6.23^a
C_{org} (%)	1.72^{ab}	1.98^a	1.55^b
N_{Tot} (%)	0.15^a	0.16^a	0.13^b
C/N ratio	11.70^a	12.34^a	12.10^a
Olsen P (mg kg^{-1})	19.71^a	20.10^a	15.70^b

Note: a, b: Different letters along rows indicate significant differences ($p < 0.05$) according to Tukey's test

Table 2. Average tree density, basal area, stem diameter, tree height, crown cover, and Shannon index of cocoa monoculture (Mono), young cocoa agroforestry (YCAF), and old cocoa agroforestry (OCAF) systems

Systems/variable	MONO	YCAF	OCAF
Cocoa density (tree ha^{-1})	618 ± 54^b	800 ± 44^a	600 ± 27^b
Langsat density (tree ha^{-1})	0.0 ± 0.0^b	106 ± 27^a	137 ± 33^a
All tree density (tree ha^{-1})	618 ± 54^b	1431 ± 207^a	812 ± 44^b
Cocoa stem diameter (cm)	15.4 ± 0.2^a	10.1 ± 1.0^b	13.6 ± 1.7^{ab}
Langsat stem diameter (cm)	n/a	15.0 ± 1.4^a	17.9 ± 2.0^a
All stem diameter (cm)	15.4 ± 0.2^a	9.3 ± 0.6^b	15.9 ± 2.1^a
Stem BA cocoa tree (cm^2 ha^{-1})	12.5 ± 1.0^a	6.9 ± 1.2^a	9.5 ± 1.9^a
Stem BA langsat tree (cm^2 ha^{-1})	n/a	2.1 ± 0.7^a	4.4 ± 1.6^a
Stem BA All tree (cm^2 ha^{-1})	12.5 ± 1.0^a	12.2 ± 1.4^a	14.8 ± 1.3^a
Height cocoa tree (m)	4.1 ± 0.1^a	3.5 ± 0.1^a	4.3 ± 0.4^a
Height langsat tree (m)	n/a	9.6 ± 0.6^a	11.5 ± 2.3^a
Height All tree (m)	4.1 ± 0.1^b	4.5 ± 0.3^b	8.1 ± 0.7^a
Canopy cover (%)	81.5 ± 1.9^a	81.8 ± 2.6^a	84.8 ± 1.3^a
Shannon index	0 ± 0^b	0.99 ± 0.2^a	0.72 ± 0.03^a

Note: a, b: Different letters along rows indicate significant differences ($p < 0.05$) according to Tukey's test

Table 3. Average, standard error of the means, and statistical differences of leaf nitrogen (N), phosphorus (P), potassium (K)of cocoa monoculture (Mono), young cocoa agroforestry (YCAF), and old cocoa agroforestry (OCAF) systems

Parameter/Land use	MONO	YCAF	OCAF	*F value*
LNC (%)	1.11 ± 0.1 a	1.19 ± 0.2 a	1.03 ± 0.1 a	0.28^{ns}
LPC (%)	0.12 ± 0.0 a	0.13 ± 0.0 a	0.11 ± 0.0 a	1.15^{ns}
LKC (%)	1.49 ± 0.2 a	1.38 ± 0.1 a	1.29 ± 0.3 a	0.53^{ns}
SLA (cm^2 g^{-1})	152.35 ± 5.1 a	167.30 ± 1.9 a	159.55 ± 10.2 a	0.47^{ns}

Note: a, b: Different letters along rows indicate significant differences ($p < 0.05$) according to Tukey's test. LNC: Leaf Nitrogen content; LPC: Leaf Phosphorus Content; LKC: Leaf Potassium content; SLA: Specific Leaf Areavalue on the same columns followed by the same letter were not significantly different according to Tukey 5%, (ns) indicated that there was no interaction among each factor

The stem diameter in the MONO system was significantly higher than the YCAF systems, but they were not significant with OCAF. They were different in basal area observations in BA parameters, stem basal area in all land-use systems, case of same in canopy cover, and not significant for all (Table 2).

All chemical and physical parameters of the cocoa leaves were consistently insignificant differences in the three systems (Table 3). The cover crown seems to contribute to lower system productivity (Figure 3a), the gradient of decreasing TEY following an increase in canopy cover. Cocoa bean yields harvested from the MONO system of 1.2 ton ha^{-1} y^{-1} were significantly higher from YCAF dan OCAF weighing 0.6 and 0.5 ton ha^{-1} y^{-1}. Overall agroforestry system by TEY equivalent to results of cocoa monoculture was presented in Figure 3b. The presence of non-cocoa trees contributed about 40 - 50% yield equivalent cocoa bean. The harvested langsat and rambutan fruit were equivalent to 0.36 ton ha^{-1} y^{-1} cocoa beans in YCAF and increased to 0.45 ton ha^{-1} y^{-1} cocoa beans equivalent to OCAF. Gliricidia as animal feed was the next contributor to the YCAF. The price of goats after conversion was equal to the cost of cocoa beans of 0.22 ton ha^{-1} y^{-1} (Figure 3).

Relationships between yield, soil fertility and cover crown at the plot-scale

The Principal Component Analysis (PCA) results explained that the density of cocoa trees, Shannon index, and SLA were the first component, and explained 52.2% of the total variance in the cocoa plots studied. Although slightly apart from the other three, the canopy cover was included in the first component. The second component contained stem diameter, leaf N content, and cocoa bean yield explained 20.4% (Figure 4a). In another PCA analysis, the overall tree density, C-total, and N-total form the first component explained 56.6% of all variance. The second component of canopy cover, tree height, and trunk diameter explained 22.1% of the variance (Figure 4b).

Root length density

We observed RLD as a form of competition between cocoa and langsat trees underground. The highest RLD of cocoa trees was in the upper soil layer, where roots distributed on a contour of 100 cm/385 cm^3 starting from the closest distance to the cocoa trunk (0.4 m) to as far as 1.7 m. We found no difference in root distribution of cocoa roots both in the MONO and OCAF systems (Figures 5a and 5c), whereas in the YCAF system, RLD cocoa at the contour of 90 cm/385 cm^3 was distributed from the base to only 1.2 m in the distance. In other words, RLD decreased in YCAF system to 40 cm/385cm^3 contour at 1.7 m from cocoa trunk (Figure 5b). All systems had RLD decreased in soil layer deeper. RLD cocoa was lowest in OCAF system, and even lower than in the YCAF system after 20 cm depth (Figure 5).

We measured the langsat roots in the YCAF and OCAF systems, and noted that the lowest RLD of langsat in YCAF system was at a distance of 0.4 m from the trunk with a contour of 60 cm/385 cm^3 to 1.2 m in the distance with a contour of 80 cm/385 cm^{-3}, and reaching a distance of 1.7 m with a contour of 100 cm/385 cm^3 (Figure 6-a). In OCAF system, we did not find any significant difference in RLD langsat at three levels of distance from the cocoa tree (Figure 6-b). The RLD langsat decreased at a deeper level in the YCAF system, which was lower than the langsat RLD recorded in the OCAF system at the same depth (Figure 6).

Discussion

Effect of tree density on soil fertility and leaves ability

Our results noted an increase in C-soil in the YCAF system (Table 1), where this system had the highest tree density and Shannon index diversity values (Table 2). However, the age of the YCAF system was still < 10 years, so this increasing trend was not solely, this is due to the high tree density, but another possibility is the residual effect of tillage, and this finding is further strengthened by increasing the C-soil concentration at a depth of 20-30 cm (Table S1), carbon cycle stability can be achieved after the system reaches 15 years of age (Isaac et al. 2005). We were more interested in soil C concentration in the Mono system of 1.7% versus OCAF of 1.5%, neither of which showed a significant difference (Table 1), referring to the results reported by Rajab et al. (2016) in the Sulawesi region, which offers a similar trend to our results, the monoculture and agroforestry systems tend to retain equivalent soil C after the system reaches more than 15 years of age. The highest concentrations of N-total and P-available were recorded in the YCAF system. They did not differ significantly with the Mono system, and both Mono and YCAF systems were substantially higher than the OCAF system (Table 1). Other research showed no difference between monoculture and simple agroforestry in soil nutrition (Blaser et al. 2017; Rajab et al. 2016).

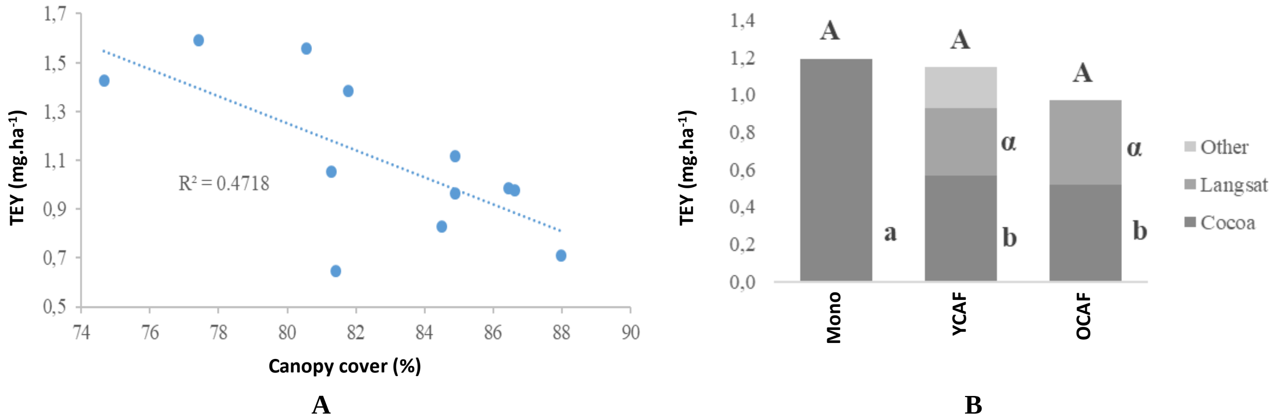

Figure 3. A. Correlation crown cover and tree equivalent yield (TEY is combining cocoa yields and shaded tree yields). The dotted lines indicate the predictions of the model; B. The production of cocoa and related trees in the TEY formulation. Different capital letters (A, B) indicate statistically significant differences among TEY in the system levels, while lower case letters (a, b) indicate significant differences among cocoa bean yield in the system levels, and lower case Greek letter (α, β) indicate significant differences among langsat yield in the YCAF and OCAF systems

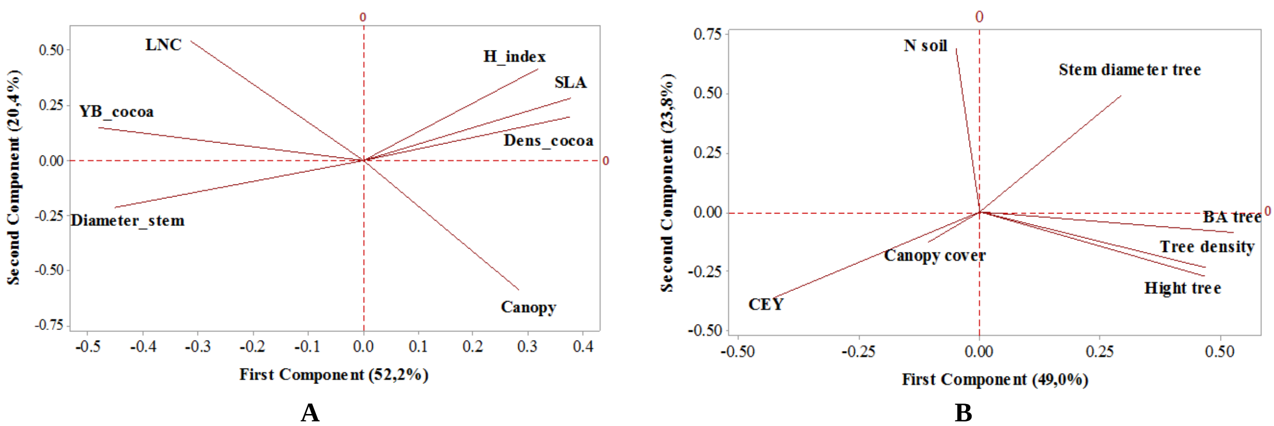

Figure 4. A. PCA of structure variables of the cocoa tree on Mono, YCAF, and OCAF systems; B. PCA of structure variables of all trees on Mono, YCAF, and OCAF systems

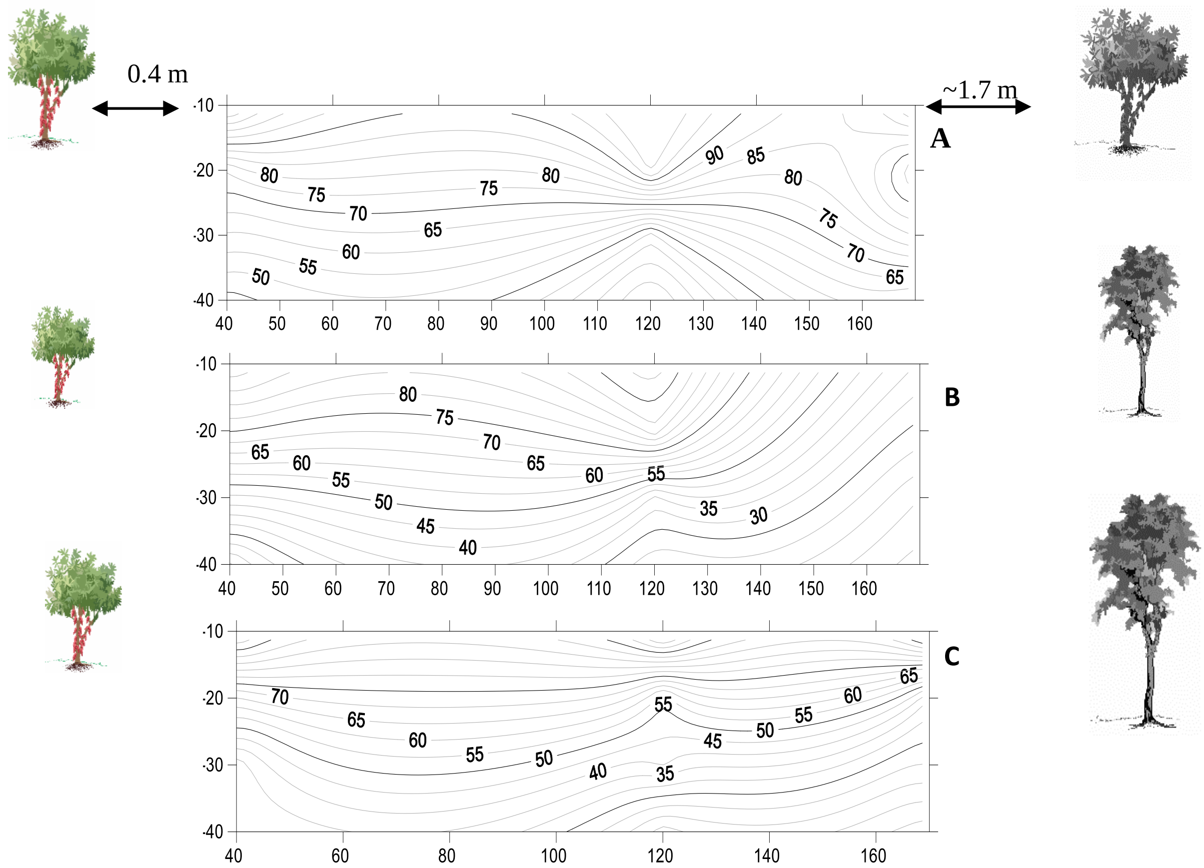

Figure 5. Cocoa root length distribution on systems: A. Mono; B. YCAF; C. OCAF

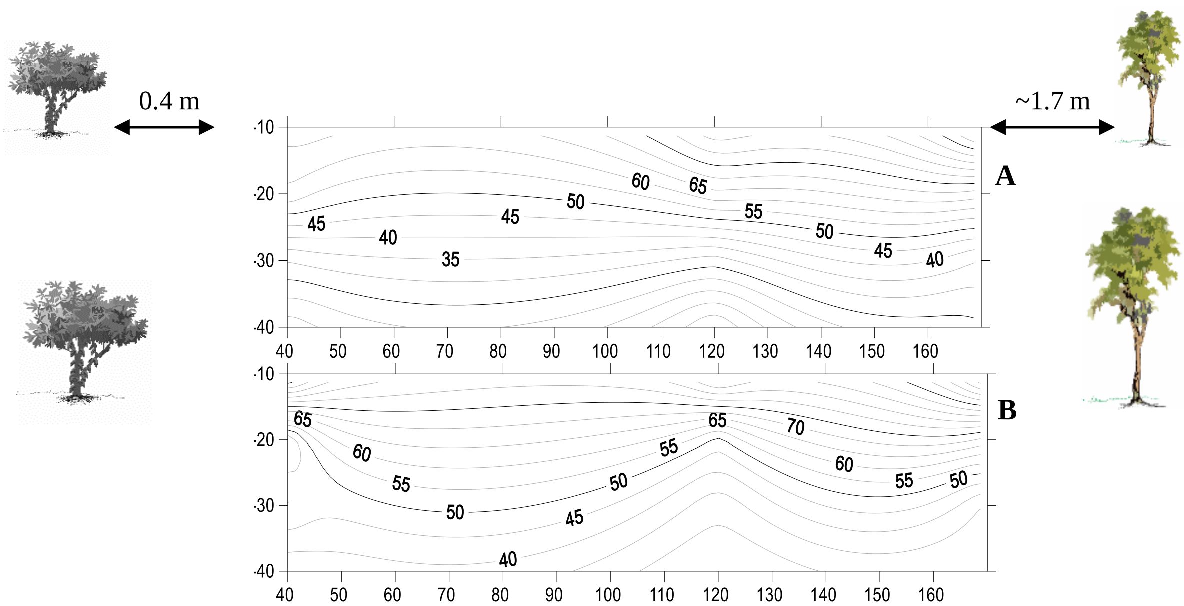

Figure 6. Root length density (RLD) of langsat tree under cocoa canopy: A. YCAF system, B. OCAF system

Soil fertility at the system level does not affect leaf nutrient uptake. Our data showed no significant differences in the parameters of LNC, LPC, and LKC. The nutrients available in the soil in all systems may be sufficient to meet the needs of the cocoa plant. Soil nutrient status in table 1 is higher than that reported by other researchers (Dewi et al. 2020). Meanwhile, referring to van Vliet and Giller's review (2017), the NLC status that we noted was at the deficiency level, the LPK status was low, and the LKC status was normal.

Cocoa growth and yield under shaded

The density of cocoa trees was in the range of 600-800 trees ha-1, the same density reported by Notaro et al. (2020), in the Dominican Republic. This density is relatively low compared to that reported in other areas of Sulawesi. In Kulawi, Central Sulawesi, cocoa tree density was between 900 to 1400 trees ha-1 (Rajab et al. 2016). Competition among species significantly affects tree biomass accumulation. The most visible impact was a decrease in stem diameter and cocoa bean yield recorded from YCAF and OCAF systems. Decreasing tree density in agroforestry systems is a determining factor for cocoa bean yield (Somarriba et al. 2018). Koko et al. (2013) noted that the amount of fruit harvested decreased by 50% in shaded orchards. A similar result also reported that a high tree density would significantly reduce tree productivity in coffee production (Tran et al. 2021). The decrease in production is associated with a reduction in photosynthesis that occurred in the rainy season, but moderate shade cover increases the rate of photosynthesis in the dry season (Acheampong et al. 2013).

We recorded tree trunk diameters in YCAF systems as 9.3 cm, and 15.9 cm in OCAF systems, basal area of 12.2 m^2 ha^{-1} in YCAF to 14.8 m^2 ha^{-1} in OCAF (Table 2). These results are relatively similar to those reported by Jagoret et al. (2017), which recorded basal area in the range of 11.5 - 52.9 m^2 ha^{-1}/ However, lower than written by other researchers, were 6.3 m^2 ha^{-1} in monoculture system, 4.3 m^2 ha^{-1} in agroforestry systems (Niether et al. 2018), and 2.7 m^2 ha^{-1} in young cocoa agroforestry systems (Gusli et al. 2020). These differences occur due to differences in the methodologies used and differences in the age of the trees observed. The cocoa tree height was between 3.5-4.3 m, and our results are lower, as reported by Rajab et al. (2016), in the range of 5.1 to 8.5 in the Sulawesi region. Farmers carry out regular pruning and maintain tree heights of no more than 4 m to facilitate activities related to maintenance and harvesting processes.

The increase in SLA accompanied by a decrease in the diameter of the cocoa tree trunk and yield of cocoa beans harvested by farmers in the YCAF and OCAF systems (Table 3, Figure 3A) is supposed by the effect of low light interception. Kotowska et al. (2015) also reported the same thing, where an increase in SLA in shaded trees is higher than in cocoa leaves that received full light. This reason is strengthened by Maghfiroh et al. (2020) with their notes that an increase in SLA causes a decrease in the rate of photosynthesis. In contrast, leaves tend to be thicker and have a higher photosynthetic capacity in sun leaves (Błasiak et al. 2021). Cocoa trees grown in monoculture systems have a great opportunity to capture more light to enhance photosynthesis, resulting in significantly more biomass accumulation than cocoa grown in shade agroforestry systems. Competition for nutrients and water is another plausible reason.

We found that there were no differences in the compartment between cocoa and langsat roots in agroforestry systems (Figures 5 and 6). Similar results are found in other studies in the cocoa-inga (*Inga edulis*) agroforestry systems. The fine roots of both plant species explored the same subsoil (Nygren et al. 2013). However, if the cocoa trees grow in the same field as gliricidia, the fine roots of cocoa more spread near the soil surface, while the roots of other species spread in deeper soil (Rajab et al. 2018). Both cocoa and langsat trees had fine roots, developed in the topsoil. These results are similar to the study conducted by Niether et al. (2019), where about 80% of the fine root distribution was found at a depth of 0-25 cm in agroforestry systems.

Langsat roots were horizontally distributed up to 3.5 m near the base of the cocoa tree, or about 3.0-3.5 m from the base of the langsat tree. This result is not much different than reported by Valmayor et al. (1984), who found that root distributed of 2.5 m horizontally from the base trunk. We also observed the vertical distribution of cocoa and langsat roots to a depth of 40 cm, where the density decreased with increasing depth, but both remained competitive. The maximum penetration depth of langsat roots can reach 1.2 m, taproots of langsat trees were not well developed, and fine root concentrations were found in the top 30 cm of soil (Medina et al. 1994; Valmayor et al. 1984), it results in increased competition among the two species, led to significantly lower cocoa biomass production in both agroforestry systems than monoculture systems, increased subsurface competition for nutrient uptake, and consequently widened the cocoa bean yield gap between monoculture and agroforestry systems. The roots of cocoa did not decrease with the presence of langsat roots. Whereas RLD of the wheat crop (Wang et al. 2014; Zhang et al. 2013), alfalfa (Yang et al. 2020) were reported to decrease when grown in the intercropping system and the effect of decreasing RLD is stronger as shade trees grow old, will form an extreme competition for water and nutrients, and become even more assertive on rocky soil because of high bulk density stony soil inhibits the development of plant roots growing on it (Cascaredo et al. 2021; Kormanek et al. 2015).

Plant density is not a problem for farmers when the cocoa plants are young until they are getting mature. The formation of cocoa tree branches is easy, not too tight, so there is still a little overlap among the tree crowns so that farmers have no reason to cut down some trees. However, when branch growth overlaps, such as cocoa tree branches in the OCAF system, farmers selectively cut down some trees considered unproductive, or self-defeating due to death. So what remains is a money tree with added economic value, which is why langsat is not eliminated in the agroforestry system.

By retaining some fruit trees as shade, farmers recover their lost cocoa beans through fruit picked from shade trees, juice converted to palm sugar, and gliricidia fodder which accounts for about half of the total production of both agroforestry systems. This claim may be premature because it is only used in 2020 production data. Tropical fruit is mainly determined by the rainy and dry seasons, and langsat trees only bear fruit after being induced by the dry season. However, yield production in a multi-species system can increase the total system gain compared to monoculture systems that have been reported by other researchers, the accumulated output of the main cocoa tree and companion tree resulted in 16% greater value than the monoculture system (Schneider et al. 2017), banana crop, and contributing higher system yields (Niether et al. 2019).

To conclude, tree density in agroforestry systems increases competition between cocoa, langsat, and other protective trees. The roots of cocoa and langsat roam the same soil layers in the YCAF and OCAF systems, causing increased competition among the two plant species for nutrients and water, which results in reduced growth and production of cocoa beans. However, on the other hand, this competition increases land exploration to become wider with increased resource uptake by some tree species to be converted into plant biomass, so that the production of agroforestry systems (YCAF and OCAF) increases to meet the productivity of the monoculture systems for agroforestry products that can be sold. Spacing is intended to maximize the absorption of sunlight and to meet an adequate supply of photosynthetic, which is essential to increase the productivity of the agroforestry system.

ACKNOWLEDGEMENTS

We would like to deliver our gratitude to the Kemenristekdikti - LPDP (Lembaga Pengelola Dana Pendidikan) for funding this study, we are also grateful to all farmers for fieldwork supports, especially Anas, Sahabuddin, AmboDalle, Abdullah, and their team for coordinating with the farmer group.

REFERENCES

Acheampong K, Hadley P, Daymond AJ. 2013. Photosynthetic activity and early growth of four cacao genotypes as influenced by different shade regimes under west African dry and wet season conditions. Exp Agric 49 (1): 31-42. DOI: 10.1017/S0014479712001007.

Alimuddin AH, Muharini R, Proksch P. 2018. New tetranortriterpenoids, langsatides A and B from the seeds of *Lansium domesticum* Corr. (Meliaceae). Phytochem Lett 23 (November 2017): 90-93. DOI: 10.1016/j.phytol.2017.11.019

Atkinson AC, Riani M, Corbellini A, Scienze D. 2020. The box-cox transformation: review and extensions. Statistical Sci 36 (2): 239-255.

Baka W, Rianse I, Rianse U, Abdullah W, Zulfikar. 2019. Pattern of palm-based agroforestry the Bugis etnic community in the District of Kolaka Indonesia. In The 1st International Conference on Environmental Sciences (ICES2018). IOP Publishing. DOI: 10.1088/1755-1315/314/1/012041.

Bertolde FZ, Almeida AAF, Pirovani CP, Gomes FP, Ahnert D, Baligar VC, Valle RR. 2012. Physiological and biochemical responses of *Theobroma cacao L.* genotypes to flooding. Photosynthetica 50 (3): 447-457. DOI: 10.1007/s11099-012-0052-4.

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. DOI: 10.1016/j.agee.2017.04.007.

Błasiak A, Andrzej W, Łukowski A, Sułkowski S, Turski M. 2021. The effects of tree and stand traits on the specific leaf area in managed scots pine forests of different ages. Forests 12 (4): 396.

Carrick S, Palmer D, Webb T, Scott J, Lilburne L. 2013. Stony soils are a major challenge for nutrient management under irrigation development. Accurate and efficient use of nutrients on farms.

Cascaredo C, Huerta L, Ortiz S. 2021. Fine root density across soil profiles in tropical. Trop Subtrop Agroecosys 24 (3).

Cornelissen JHC, Lavorel S, Garnier E, Díaz S, Buchmann N, Gurvich DE, Reich PB, Streege H, Morgan HD, Heijden V, Pausaa JG, Poorter H. 2003. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. Aust J Bot 51 (4): 335-380. DOI: 10.1071/BT02124.

Gusli S, Sumeni S, Sabodin R, Muqfi IH, Nur M, Hairiah K, Useng D, van Noordwijk M. 2020. Soil organic matter, mitigation of and adaptation to climate change in cocoa-based agroforestry systems. Land 9 (9): 1-19. DOI: 10.3390/LAND9090323.

Hlaváčiková H, Novák V, Kostka Z, Danko M, Hlavčo J. 2018. The influence of stony soil properties on water dynamics modeled by the HYDRUS model. J Hydrol Hydromechanics 66 (2): 181-188. DOI: 10.1515/johh-2017-0052.

INIAP. 2016. Estación Experimental Tropical Pichilingue. INIAP 1 (4): 13-16. www.iniap.gob.ec

Isaac ME, Gordon AM, Thevathasan N, Oppong SK, 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 (1): 23-31. DOI: 10.1007/s10457-004-4187-6.

Jagoret P, Michel I, Ngnogué HT, Lachenaud P, Snoeck D, Malézieux E. 2017. Structural characteristics determine productivity in complex cocoa agroforestry systems. Agron Sustain Dev 37 (6): 1-12. DOI: 10.1007/s13593-017-0468-0.

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 (5): 1043-1052. DOI: 10.1007/s10457-013-9619-8.

Kormanek M, Głąb T, Banach J, Szewczyk G. 2015. Effects of soil bulk density on sessile oak *Quercus petraea* Liebl. seedlings. Eur J For Res 134 (6): 969-979. DOI: 10.1007/s10342-015-0902-2.

Kotowska MM, Hertel D, Rajab YA, Barus H, Schuldt B. 2015. Patterns in hydraulic architecture from roots to branches in six tropical tree species from cacao agroforestry and their relation to wood density and stem growth. Front Plant Sci 6 (March): 1-16. DOI: 10.3389/fpls.2015.00191.

Maghfiroh CN, Tarwaca E, Putra, Dewi ES. 2020. Root detection by resistivity imaging and physiological activity with the dead-end trench on three clones of cocoa (*Theobroma cacao*) 21 (6): 2794-2803. DOI: 10.13057/biodiv/d210656.

Medina SM, Anase M, Narioka H. 1994. The use of agroforestry as a soil conservation strategy in the Philippines. Irrig Eng Rural Plann (27): 49-64. DOI: 10.11408/jierp1982.1994.27_49.

Meng C, Niu J. Zhi, Yin, Z. Luo Z. Lin X, Jia, JW. 2018. Characteristics of rock fragments in different forest stony soil and its relationship with macropore characteristics in mountain area, northern China. J Mount Sci 15 (3): 519-531. DOI: 10.1007/s11629-017-4638-y.

Muellner AN, Pannell CM, Coleman A, Chase MW. 2008. The origin and evolution of Indomalesian, Australasian and Pacific island biotas: insights from Aglaieae (Meliaceae, Sapindales), 1769-1789. DOI: 10.1111/j.1365-2699.2008.01935.x.

Niether W, Armengot L, Andres C, Schneider M, Gerold G. 2018. Shade trees and tree pruning alter throughfall and microclimate in cocoa (*Theobroma cacao* L.) production systems. Ann For Sci 75 (2): 1-16. DOI: 10.1007/s13595-018-0723-9.

Niether W, Schneidewind U, Fuchs M, Schneider M, Armengot L. 2019. Below-and aboveground production in cocoa monocultures and agroforestry systems. Sci Tot Environ 657: 558-567. DOI: 10.1016/j.scitotenv.2018.12.050.

Notaro M, Gary C, Deheuvels O. 2020. Plant diversity and density in cocoa-based agroforestry systems: how farmers' income is affected in the Dominican Republic. Agrofor Syst 94 (3): 1071-1084. DOI: 10.1007/s10457-019-00472-7.

Nygren P, Leblanc HA, Lu M, Gómez-Luciano CA. 2013. Distribution of coarse and fine roots of *Theobroma cacao* and shade tree *Inga edulis* in a cocoa plantation. Ann For Sci 70 (3): 229-239. DOI: 10.1007/s13595-012-0250-z.

Rajab YA, Hölscher D, Leuschner C, Barus H, Tjoa A, Hertel D. 2018. Effects of shade tree cover and diversity on root system structure and dynamics in cacao agroforests: The role of root competition and space partitioning. Plant and Soil, 422 (1-2): 349-369. DOI: 10.1007/s11104-017-3456-x.

Rajab Y. A, Leuschner C, Barus H, Tjoa A, Hertel D. 2016. Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. PLoS ONE 11 (2): 1-22. DOI: 10.1371/journal.pone.0149949.

Ravi V, Suja G, Saravanan R, More SJ. 2021. Advances in cassava-based - multiple-cropping systems. Hortic Rev 48: 153-232.

Rudiyansyah, Alimuddin, A. H., Masriani, Muharini, R., & Proksch, P. (2018). New tetranortriterpenoids, langsatides A and B from the seeds of Lansium domesticum Corr. (Meliaceae). Phytochemistry Letters, 23 (November 2017): 90–93. DOI: 10.1016/j.phytol.2017.11.019

Ruf FO, Schroth G. 2004. Chocolate forests and monocultures: A historical review of cocoa growing and its conflicting role in tropical deforestation and forest conservation. Agroforestry and biodiversity conservation in tropical landscapes 6: 107-134.

Ruf F. Zadi H. 1998. From Deforestation to Reforestation. In Paper presented at the First Sustainable Workshop on Sustainable Cocoa Growing, Panama City, Panama, March 30-April 2, 1998. DOI: 10.1057/9781137343819.0018.

Saleh AR, Gusli S, Ala A, Neswati R, Sudewi S. 2021. Morphological adaptation of cocoa fine roots to stony soil. International Conference on Climate Change, Agriculture, Biodiversity, and Environment Study (CABE 2021) (Under review).

Schneider M, Andres C, Trujillo G, Alcon F, Amurrio P, Perez E, Weibel F, Milz J. 2017. Cocoa and total system yields of organic and conventional agroforestry vs. monoculture systems in a long-term field trial in Bolivia. Exp Agric 53 (3): 351-374. DOI: 10.1017/S0014479716000417.

Schneidewind U, Niether W, Armengot L, Schneider M, Sauer D, Heitkamp F, Gerold G. 2019. Carbon stocks, litterfall and pruning residues in monoculture and agroforestry cacao production systems. Exp Agric 55 (3): 452-470. DOI: 10.1017/S001447971800011X.

Somarriba E, Orozco-Aguilar L, Cerda R, López-Sampson A. 2018. Analysis and design of the shade canopy of cocoa-based agroforestry systems. Achieving sustainable cultivation of cocoa. Burleigh Dodds Science Publishing. DOI: 10.19103/as.2017.0021.29.

Techavuthiporn C. 2018. Langsat - *Lansium domesticum*. Exotic fruits reference guide. Elsevier Inc. DOI: 10.1016/B978-0-12-803138-4.00036-8.

Tran HTM, Nathan S, Ilmma A, Burkiewicz M, Wisana IDGK. 2021. Identifying limiting factors for feasible productivity improvement for smallholder farmers in coffee sector in Indonesia. Asian J Agric 5 (2): 53-60. DOI: 10.13057/asianjagric/g050202.

Valmayor R, Tabora P, Ramirez M, Herrera W, Asencion A. 1984. The natural distribution of the root systems of citrus, lanzones and cacao. Phil Agriculturist, UP at Los Banos. http://scinet.science.ph/union/SearchHoldings/agency_view.php?agency=PCARRD

Van-Vliet JA, Giller KE. 2017. Mineral nutrition of cocoa: A review. Adv Agron 141: 185-270. DOI: 10.1016/bs.agron.2016.10.017.

Wahid H. 2017. Analisis karakteristik dan klasifikasi curah hujan di Kabupaten Polewali Mandar. Sains, Matematika dan Teknologi 6 (1): 15-27. [Indonesian]

Wang BJ, Zhang W, Ahanbieke P, Gan YW, Xu WL, Li LH, Christie P, Li L. 2014. Interspecific interactions alter root length density, root diameter and specific root length in jujube/wheat agroforestry systems. Agrofor Syst 88 (5): 835-850. DOI: 10.1007/s10457-014-9729-y.

Yang T, Zhu Y, Duan ZP, Lu WH, Zhang FF, Wan SM, Xu WX, Zhang W, Li LH. 2020. Root distribution and productivity in a poplar tree + alfalfa silvopastoral system in northwest China’s Xinjiang Province. Agrofor Syst 94 (3): 997-1010. DOI: 10.1007/s10457-019-00466-5.

Zhang W, Ahanbieke P, Wang BJ, Xu WL, Li LH, Christie P, Li L. 2013. Root distribution and interactions in jujube tree/wheat agroforestry system. Agrofor Syst 87 (4): 929-939. DOI: 10.1007/s10457-013-9609-x.

Table S1. Soil chemical properties in tree cocoa production systems: cocoa monoculture (Mono), young cocoa agroforestry (YCAF), and old cocoa agroforestry (OCAF) systems

Parameters	Depth (cm)	Mono	YCAF	OCAF	Mean depth
pH H_2O	0-10	6.26	6.31	6.40	6.32 a
(1;2,5)	10-20	5.86	5.97	5.84	5.89 b
	20-30	5.89	6.15	6.45	6.16 ab
	30-40	5.73	5.78	6.23	5.91 b
	Mean systems	5.93 a	6.05 a	6.23 a	
C organic	0-10	1.80	2.32	1.66	1.93 a
(%)	10-20	1.41	2.05	1.45	1.64 ab
	20-30	2.07	2.10	1.85	2.00 a
	30-40	1.60	1.45	1.26	1.44 b
	Mean systems	1.72 ab	1.98 a	1.55 b	
N Total	0-10	0.15	0.20	0.15	0.17 a
(%)	10-20	0.13	0.18	0.14	0.15 ab
	20-30	0.18	0.16	0.14	0.16 a
	30-40	0.13	0.12	0.10	0.12 b
	Mean systems	0.15 a	0.16 a	0.13 b	
C/N ratio	0-10	11.87	11.63	11.68	11.73 a
	10-20	10.67	12.59	10.87	11.38 a
	20-30	11.78	13.28	12.93	12.66 a
	30-40	12.47	11.85	12.91	12.41 a
	Mean systems	11.70 a	12.34 a	12.10 a	
Olsen P	0-10	21.29	22.40	15.74	19.81 a
(mg kg^{-1})	10-20	18.25	20.25	14.07	17.53 a
	20-30	18.67	19.30	16.95	18.30 a
	30-40	20.63	18.42	16.03	18.36 a
	Mean systems	19.71 a	20.10 a	15.70 b	

Note: a,b,c: Different letters along rows indicate significant differences ($p < 0.05$) according to Tukey's test