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Brahima K. Silue[1,2,3] , Armand W. Koné[1] , Alain J.A. Kotaix[2], Klotioloma Coulibaly[2],
Sékou Aïdara[2], Lydie Chapuis-Lardy[3,4] and Dominique Masse[1,3,4]

[1]UR Gestion Durable des Sols, Pôle de Recherche Environnement et Développement Durable, UFR Sciences de la Nature, Université Nangui Abrogoua, 02 BP 801, Abidjan 02, Cote d'Ivoire, [2]Programme Cacao, Centre National de Recherche Agronomique (CNRA), BP 808 Divo, Côte d'Ivoire, [3]Eco&Sols, Université de Montpellier, CIRAD, INRAE, IRD, Institut Agro, Montpellier, France and [4]LMI Intensification Ecologique des Sols Cultivés en Afrique de l'Ouest (LMI IESOL), Dakar, Sénégal
Corresponding author: Brahima K. Silue; Email: siluekb@gmail.com

Summary

The choice of tree species planted with cacao trees is essential for ensuring the efficiency and sustainability of cacao farming systems. This raises the question of the long-term impact of associated tree legumes (ATLs) on cacao bean yields and biomass accumulation. This study was carried out in accordance with four-block randomised experimental design in Divo (Ivory Coast, West Africa). The study involved cacao-*Albizia lebbeck* (Cacao-Alb) and cacao-*Acacia mangium* (Cacao-Aca) intercrops and unshaded cacao plots (Control). After 20 years of intercropping, we assessed cacao dendrometry (height, circumference, biomass, and biomass C-stock) and production (number of pods per tree and bean yield at the plot level) as well as soil fertility (soil organic matter (SOM) concentration) at various distances from ATLs (D1:0–1.75 m; D2:3.25–5 m; D3:7–9 m). The distance from the ATLs had no significant effect on the measured cacao dendrometric parameters, except for cacao height. In contrast, the Cacao-Aca association had a negative impact on the SOM concentration (−22%), cacao tree height (−6.15%), and productivity parameters (biomass: −12.4%; bean yield: −43%). However, Cacao-Alb and the Control had no significant differences in terms of SOM, tree biomass, or bean production. Intercropping cacao with the tested tree legumes did not enhance cacao productivity and, in some cases, hindered it, depending on the ATL species. This study highlighted the importance of identifying appropriate shade tree legume species that could be promoted in cacao-based agroforestry systems.

Keywords: cacao agroforestry systems; *Albizia lebbeck*; *Acacia mangium*; cacao biomass C-stock; cacao yield

Introduction

Cacao (*Theobroma cacao* L.) is an undergrowth tree that is mostly grown by small-scale farmers in the main producing countries such as Cote d'Ivoire and Ghana (Koko *et al.,* 2013; Jagoret *et al.,* 2017; Mattalia *et al.,* 2022; Sanial *et al.,* 2022). Initially, it was grown under tree canopies (Jagoret *et al.,* 2018; Sanial *et al.,* 2022). Between 1961 and 2020, worldwide increasing cacao demand and economic interest resulted in an increase in cultivated area from 4 to 12 million hectares (FAO, 2022). This is particularly the case in Ivory Coast, the world's largest cacao bean producer, where more than 70% of the cacao orchards were established following forest clearing with no overhead shade trees, except during the early years of plantation establishment (Assiri *et al.,* 2009). The monoculture cropping system, known to produce high cacao bean yields, called the 'full sun' system, was the main advocated

system during this period (Koko *et al.,* 2013; Jagoret *et al.,* 2018; Mattalia *et al.,* 2022). The monoculture cropping system relies also on improved varieties of cacao and increased chemical soil fertilisation. As a result, almost 80% of the country's forest area was lost in the second half of the last century, partly due to cacao culture expansion. This heavy deforestation in favour of monoculture cropping systems combined with a lack of sustainable soil management practices has led to biodiversity loss, soil degradation, plant disease outbreaks (such as swollen shoot virus), and decreased production capacity. Also, it has contributed to increased carbon emissions in the atmosphere (Somarriba *et al.,* 2013; Abou Rajab *et al.,* 2016; Panja, 2021). Cacao agroforestry, which involves the temporal and/or spatial association of one or more woody species with cacao, has been proposed as a solution for tackling biodiversity loss, reducing human pressure on remaining forests, and mitigating climate change effects (Sanial *et al.,* 2022). Trees in cacao plantations provide shade for cacao plants, contribute to carbon sequestration in tree biomass, recycle nutrients to maintain soil fertility, accumulate soil organic matter (SOM), and conserve soil biodiversity (Beer *et al.,* 1997; Somarriba *et al.,* 2013; Batsi *et al.,* 2021). Several studies of traditional cacao-growing systems in Cameroon and Ghana have shown that shade trees favour cacao tree establishment and survival and reduce physiological stress by protecting cacao trees from increased temperatures (Beer *et al.,* 1997; Abou Rajab *et al.,* 2016; Blaser *et al.,* 2018). Furthermore, companion trees in cacao plantations generate additional income through the production of wood products (e.g., timber, firewood, fruit, resins, and medicines), and cultural and aesthetic services (Beer *et al.,* 1997; Somarriba *et al.,* 2013; Batsi *et al.,* 2021). Many studies have shown that intercropping shade trees with cacao improves cacao growth and bean yield (Koko *et al.,* 2013; Asitoakor *et al.,* 2022). However, others have reported a neutral or even negative effect on cacao beans in terms of yield (Abou Rajab *et al.,* 2016; Abdulai *et al.,* 2018; Sauvadet *et al.,* 2020; Blaser-Hart *et al.,* 2021). The interactions between two layers of trees in a plantation may involve competition for light, water, or nutrient resources. However, facilitation processes such as a favourable microclimate and the supply of nutrients from litter to the soil could also occur (Beer *et al.,* 1997; Abdulai *et al.,* 2018). Trebissou *et al.* (2021) reported several factors affecting cacao growth and productivity, such as the characteristics of neighbouring trees, resource limitations (nutrients and water), and physiological conditions (photoinhibition, radiation load, and low leaf water potential) inducing a competitive effect and/or affecting production mechanisms. These interactive effects are mainly related to the associated tree species, notably the quantity and quality of their leaf litter (Sauvadet *et al.,* 2020). These authors also reported that shade trees could be expected to improve soil parameters even if cacao yields remain unchanged.

It should be stressed that most of these results were not obtained via an experimental design. These studies were mostly based on the comparisons between farmers' orchards where the species and number of companion trees varied (Abou Rajab *et al.,* 2016; Abdulai *et al.,* 2018; Sauvadet *et al.,* 2020; Blaser-Hart *et al.,* 2021; Asitoakor *et al.,* 2022). Other factors, such as soil or farmer practices, were not always under control. The shade trees in these studies involved mainly forest and fruit tree species maintained after forest clearing (Asitoakor *et al.,* 2022).

Fast-growing tree legumes, due to their ability to fix atmospheric nitrogen in symbiotic association with microorganisms, provide benefits and have been tested in agroforestry systems over the last few decades. Several authors have reported improved productivity when tree legumes are combined with other tree plantations, such as coconut or cacao plantations (N'guessan *et al.,* 2006; Somarriba *et al.,* 2013; Abou Rajab *et al.,* 2016; Koutika and Richardson, 2019; Sauvadet *et al.,* 2020). However, very few of these studies have assessed the long-term influence of specific shade tree species in cacao-based agroforestry systems (Asitoakor *et al.,* 2022), especially regarding cacao productivity and the achievement of broader carbon sequestration objectives.

Tree characteristics, such as the quality and quantity of litter produced, influence soil fertility and net primary production. Indeed, there is a close relationship between foliage and litter characteristics and soil nutrient availability (Hobbie, 2015). According to the agroecological performance evaluation tool promoted by the Food and Agriculture Organization of the United Nations (FAO), the SOM content is the most relevant indicator of soil health (Mottet *et al.,* 2020).

Indeed, SOM is widely recognised for its significance in nutrient exchange within the soil environment, as a carbon sink, and for its influence on soil fertility. Consequently, it is closely related to plant productivity, particularly that of cacao (Oldfield *et al.,* 2019; Minasny *et al.,* 2020; Rangel-Mendoza and Silva-Parra, 2020).

In 1998, the Centre National de Recherche Agronomique (CNRA) launched an experiment at the Divo Research Station to test the growth and production of cacao plants planted with two types of tree legumes, *Albizia lebbeck* (L.) Benth. (Fabaceae) and *Acacia mangium* Willd. (Fabaceae), against a control [cacao without associated tree legume (ATL)]. After 20 months of intercropping, Konan and Koffi (2003) reported positive effects of *A. lebbeck* and negative effects of *A. mangium* on the growth and productivity parameters of young cacao trees. After 20 years, the trial was still ongoing, enabling the positive or negative impact of the two legumes on cacao productivity to be evaluated experimentally over a longer period. Consequently, this study evaluated the biomass of 20-year-old cacao plants and their bean yield in the presence or absence of tree legumes using observed and measured data.

Materials and methods

Study area

This study was carried out in the centre-west of Ivory Coast at the CNRA experimental station in Divo (5° 47.528280' N/-5° 15.041462' W). The natural vegetation of this region is the Guinean semideciduous forest. The climate is subequatorial, with an annual average temperature of 26 °C and an average relative humidity of 85%. The rainfall regime is bimodal, with two dry seasons and two wet seasons. The annual average precipitation is more than 1200 mm (Ehounou *et al.,* 2019). Soils are highly weathered, as in most intertropical regions of the world. These soils have diffuse horizon boundaries, a clay assemblage dominated by low-activity clays (mainly kaolinite), and a high sesquioxide content. They have great soil depth (> 100 cm), good permeability, and stable microstructure. However, these soils are chemically poor and characterised by extremely low native fertility resulting from very low nutrient reserves (WRB, 2015).

The soil at the experimental site (pedo-horizon A: 0 to 15 cm depth) had the following characteristics: (i) clay content of 224–447 g kg^{-1}; (ii) soil organic carbon (SOC) of 6.4–9.7 g kg^{-1}; (iii) total nitrogen (N) of 0.8 to 1.0 g kg^{-1}; (iv) total phosphorus (P) of 94.5–138.8 mg kg^{-1}; (v) available P of 0.8–2.4 mg kg^{-1}; (vi) exchangeable potassium (K$^+$) 0.1–0.2 cmol kg^{-1}; (vii) magnesium (Mg^{2+}) of 0.4–1.1 cmol kg^{-1}; (viii) calcium (Ca^{2+}) of 2.1–3.3 cmol kg^{-1}; and (ix) pH$_{water}$ ranging from 5.1 to 5.9 (CNRA, unpublished technical report). These soils are generally considered suitable for cacao cultivation (Ehounou *et al.,* 2019).

Experimental design

An experimental cacao agroforestry system (cAFS) was set up in 1998 on a former experimental cacao plantation site that was left fallow and colonised by *Chromolaena odorata* for more than 10 years. The tree legumes *A. mangium* and *A. lebbeck* were planted after clearing, and two years later, the cacao seedlings were planted underneath. The trial was thus considered to be 20 years old at the time of data collection in 2020. Although the plants were maintained for 20 years, the whole experiment was supposedly conducted according to the same protocols. Indeed, the site has been managed more akin to many cacao plantations in Côte d'Ivoire, especially those operated by farmers, despite being on an experimental station. However, the trial plots exhibited no signs of infestation or disease.

The experiment involved four blocks arranged perpendicular to the slope ($< 1\%$) over a 2-ha area. Initially, each block was subdivided into five plots of 726 m^2 (33 m × 22 m) with five ATL factor levels: one unshaded cacao monoculture plot (Control), two plots with *A. lebbeck*

(Cacao-Alb), and two plots with *A. mangium* (Cacao-Aca). Four-metre-wide alleys separated blocks and plots. The cacao trees were planted at a spacing of 2.5 m between trees in a row and 3 m between rows, i.e., a density of 1333 plants ha^{-1}. ATLs were planted at a density of four trees per plot, i.e., 55 trees ha^{-1}. For 20 years, the trial was maintained using small farmers' traditional cacao plantation management practices. Few data were collected in the early years, but all parameters were unfortunately no longer evaluated due to difficulties during and after the internal armed conflict that ended in 2011. In 2020, considering the mortality of ATLs and cacao trees over time, three plots per block were selected, corresponding to Cacao-Alb, Cacao-Aca, and the Control group, for the purpose of the present study. In subplots delineated around the ATLs within these plots, the ATLs were assessed for biomass, while the cacao trees were assessed for biomass and bean yield along two 10 m transect diagonals.

Three distance classes delineated between the trunks of the cacao trees and ATL were defined according to the rows of planted cacao trees: D1 was defined as the first row of cacao trees closest to the ATL (1.75 m), D2 was defined as those between 3.25 and 5 m from the ATL, and D3 was defined as those between 7 and 9 m from the ATL.

Data collection

Cacao tree biomass production

Cacao trees and ATLs were counted, and the number of missing trees was assessed by the difference from the initial planting layout. The circumference of the trunk at a height of 50 cm was measured on the current cacao trees, from which the diameter at 50 cm (D50) was determined. The diameter at breast height (DBH) of the ATLs was also determined from the circumference at 1.30 m. The cacao and ATL heights at their tops were measured using a clinometer (Suunto, type PM-5/360PC). The extent of canopy cover of the ATLs was estimated from crown diameter measurements using a decametre. To test the effect of the distance between the ATL and the cacao, tree measurements at three distance classes (D1, D2, and D3) were considered. The cacao count was used to calculate the current density per unit area and compare it to the initial planting density. Cacao density under the ATL canopy was also specifically recorded.

The total biomass of each cacao plant, including both aboveground (AGB) and belowground (BGB) biomass, was estimated using the allometric equation developed by Somarriba *et al.* (2013) for AGB (Eq 1) and that of Cairns *et al.* (1997) for BGB (Eq 2), assuming a 50 cm diameter. The ATL total biomass was estimated using the allometric equations of Chave *et al.* (2014) for AGB (AGBi; Eq 3) and that of Cairns *et al.* (1997) for BGB (BGBi; Eq 4). For ATL wood density, we referred to the International Centre for Agroforestry African wood density database produced by (Carsan *et al.*, 2012).

$$AG = 10^{(-1{,}684 + 2{,}158 \times \log(D50) + 0{,}892 \times \log(H))} \tag{1}$$

$$BGB = e^{[-1{,}0587 + 0{,}8836 \times \ln(AGB)]} \tag{2}$$

$$AGBi = 0.0509 \times (Wi \times (DBHi^2) \times Hi \tag{3}$$

$$BGBi = e^{[-1{,}0587 + 0{,}8836 \times \ln(AGBi)]} \tag{4}$$

where AGB = cacao aboveground biomass (kg tree^{-1}); BGB = cacao belowground biomass (kg tree^{-1}); H = cacao tree height (m); D50 = cacao diameter at 50 cm height (cm); AGBi = ATL aboveground biomass (kg ha^{-1}); BGBi = ATL belowground biomass (kg ha^{-1}); Hi = ATL tree height (m); DBHi = ATL diameter at breast height (cm); and Wi = ATL wood density (g cm^{-3}).

Cacao bean yield

Cacao bean yields were determined using the counting methodology proposed by Jagoret *et al.* (2017). The pods were counted four times at regular intervals from May to November 2020, considering the gradual appearance and maturation of pods. The survey included all the pods and cherelles at least 10 cm long. These were assumed to reach maturity (Jagoret *et al.,* 2017). At each round of counting, immature pods were counted but not removed. However, they were marked to avoid double counting. All ripe pods were collected, classified, and counted as healthy, damaged, or rotten for each cacao tree. Each healthy pod was weighed. According to Tahi *et al.* (2017), the bean yield per tree was calculated from the number of pods and the average pod weight per tree. The potential bean yield (PBY) was estimated using the total number of pods (healthy or not), and the estimated marketable bean yield (MBY) was determined using only the number of healthy pods (Eq 5 and Eq 6). The difference between PBY and MBY was considered the estimated bean yield loss (BYL) due to unmarketable pods (Eq 7), and its relative proportion to the estimated PBY (BYLR) was also calculated for each treatment (Eq 8).

$$PBY = NP \times HPW \times CC \tag{5}$$

$$MBY = NHP \times HPW \times CC \tag{6}$$

$$BYL = PBY - MBY \tag{7}$$

$$BYLR = 100 \times (PBY - MBY)/PBY \tag{8}$$

where PBY is the estimated potential bean yield (kg tree^{-1}); MBY is the estimated marketable bean yield (kg tree^{-1}); NP is the total pod number (pod tree^{-1}); NHP is the healthy pod number (pod tree^{-1}); HPW is healthy ripe pod weight average (kg tree^{-1}); BYL is the estimated loss of bean yield from unhealthy pods (kg tree^{-1}); BYLR is the estimated bean yield loss proportion relative to PBY; and CC is the pod weight-to-marketable cacao bean conversion coefficient for healthy ripe pods (0.0875).

Soil organic matter assessment

Soil was sampled in November 2019 in the subplot using a 6-cm diameter cylindrical auger every 10 cm to a depth of 30 cm. In the ATL subplots, sampling points were located 1.75 m, 3.25 m, 5 m, 7 m, and 9 m from the tree legume trunk within two diametrically opposed transects. Soil samples were then pooled from both transects for each distance from the ATL to obtain one composite sample per tree distance and soil depth. In the control plots, the same sampling protocol was applied considering a randomly chosen point on each subplot from which the sampling distances were defined. Sampling was performed after carefully removing the topsoil litter layer. The soil samples were air-dried and stored at ambient temperature. The soil samples were sieved at 2 mm. To assess the SOC content, infrared spectrometry and chemical analysis of soil C were performed according to the procedure of Malou *et al.* (2021). Visible and near-infrared reflectance spectra of each sample (n = 1320 sieved at 2 mm) were acquired at 2-nm intervals between 350 and 2500 nm with a LabSpec 4 spectrophotometer (Analytical Spectral Devices, Boulder, CO, USA). The soil C content of the subset samples was determined by the Dumas method on 100 mg aliquots of soil (ground to < 0.2 mm) using a CHN elemental analyser (Thermo Finnigan Flash EA1112, Milan, Italy) (NF ISO 10694 1995). The numerical processing of spectral data was carried out using TheUnscrambler® X 10.4 software (Camo Software, Oslo, Norway). The SOM content was estimated from the SOC content (Eq 9). For this study, only the SOM data from 0 to 30 cm were considered to test the relationships between soil fertility and the cacao tree biomass and bean yield.

$$SOM = SOC \times 1.724 \tag{9}$$

Table 2. Means (± standard deviation) of cacao cropping systems characteristics when associated with the tree legumes *Albizia lebbeck (*in *Cacao-Alb)* or *Acacia mangium (*in *Cacao-Aca),* or without (Control) in a 20-year-old experiment in Divo (Ivory Coast). Cacao tree variables: Circumference: the circumference of the trunk was measured at 50 cm above ground

	Treatments			
Variables	Cacao-Aca	Cacao-Alb	Control	Probability levels of ATL effect
Circumference (cm)	53.7 ± 14.6a*	56.4 ± 13.2a	56.3 ± 16.9a	0.3
Height (m)	6.1 ± 1.6b	6.7 ± 1.3a	6.5 ± 1.6ab	0.003
AGB (kg tree^{-1})	55.3 ± 44.5a	63.0 ± 37.8a	63.4 ± 46.2a	0.3
BGB (kg tree^{-1})	11.7 ± 8.1a	13.3 ± 6.9a	13.2 ± 8.5a	0.2
AGB + BGB (kg tree^{-1})	67.1 ± 52.6a	76.3 ± 44.8a	76.6 ± 54.7a	0.2
NP (pods tree^{-1})	23.0 ± 22.3b	35.7 ± 26.8a	34.6 ± 26.3a	<0.001
NHP (pods tree^{-1})	12.7 ± 14.2b	20.4 ± 17.9a	18.7 ± 14.1a	0.001
HPW (kg pod^{-1})	0.40 ± 0.08b	0.41 ± 0.05b	0.44 ± 0.06a	<0.001
PBY (kg tree^{-1})	0.8 ± 0.8b	1.3 ± 1.1a	1.4 ± 1.1a	<0.001
MBY (kg tree^{-1})	0.4 ± 0.5b	0.7 ± 0.7a	0.7 ± 0.6a	<0.001
BYL (kg tree^{-1})	0.3 ± 0.5b	0.6 ± 0.5a	0.6 ± 0.8a	0.003
BYLR (%)	40.7 ± 28.5a	40.3 ± 20.6a	41.5 ± 23.0a	0.8

AGB = Aboveground biomass; BGB = Belowground biomass; NP = total pods number; NHP = healthy pods number; HPW = healthy pods weight; PBY = potential bean yield; MBY = marketable bean yield; BYL = bean yield loss due to unhealthy pods; BYLR = proportion of bean yield lost relative to PBY.
*Values followed by the same letter in a row are not significantly different ($p < 0.05$).

Table 3. Means (± standard deviation) of cacao tree biomass and bean yields at the plot level in 20-year-old cacao plantations associated with the tree legumes *Acacia mangium* (in Cacao-Aca) or *Albizia lebbeck* (in Cacao-Alb) compared with a conventional 20-year-old cacao monoculture (Control)

Variables	Cacao-Aca	Cacao-Alb	Control	*P* value
AGB + BGB (Mg ha^{-1})	42.3 ± 34.4b*	61.4 ± 36.9a	70.7 ± 59.5a	<0.001
PBY (kg ha^{-1})	535 ± 596.5b	1104 ± 982.9a	1163 ± 883.7a	<0.001
MBY (kg ha^{-1})	275 ± 303.2b	617 ± 618.4a	634 ± 494.4a	<0.001

AGB = Aboveground biomass; BGB = Belowground biomass; PBY = potential bean yield; MBY = marketable bean yield.
*Values followed by the same letter in a row are not significantly different ($p < 0.05$).

significant ($p > 0.05$; Table 2). Cacao–Alb association also had no significant effect on cacao biomass compared to that in the Control group. Generally, the cacao stand biomass was not significantly different between the Cacao-Alb group and the Control group after 20 years of intercrop (Table 2, Table 3). In contrast, the presence of *A. mangium* significantly reduced the cacao biomass compared to the Control (Table 3; −40%).

There were as many as 36 pods tree^{-1} in Cacao-Alb. The number of pod tree^{-1} was significantly lower ($p < 0.001$) in the Cacao-Aca plot than in the Cacao-Alb or Control plots (Table 2). The introduction of ATL resulted in a significant ($p < 0.001$) decrease in pod weight in both the Cacao-Aca and Cacao-Alb plots (Table 2). Cacao PBY was estimated to vary between 535 and 1163 kg ha^{-1} among the treatments. Furthermore, the yield was lower in Cacao-Aca plot (−43%; $p < 0.001$) than in the Control and Cacao-Alb plots, which showed similar values. The proportion of unmarketable beans (BYLR) resulting from unhealthy pods ranged from 40.7% to 41.5%, and the proportion did not differ among the treatments (Table 2). Finally, cacao stand bean production was not significantly different between the Cacao-Alb group and the Control group after 20 years of intercrop (Table 3). In contrast, the presence of *A. mangium* significantly reduced cacao PBY (−54%) and MBY (−57%) compared to those observed in the other treatments.

Effect of the distance between cacao trees and the associated tree legumes

The mean cacao height measured close to the ATL (at distance D1) in Cacao-Aca was significantly lower ($p < 0.01$) than that measured at distances D2 and beyond (Table 4). Trunk circumference

Table 4. Means (±standard deviation) of growth characteristics and bean production of cacao trees at three distances to the associated tree legumes *Albizia lebbeck* (in Cacao-Alb) or *Acacia mangium* (in Cacao-Aca), in a 20-year-old experiment in Divo (Ivory Coast). Distance between cocoa trunk and ATL trunks D1:0 to 1.75 m, D2:3.25 to 5 m, D3:7 to 9 m. The circumference of the trunk was measured at 50 cm above ground

Variables	Cacao-Aca			Cacao-Alb			Lmer test		
	D1	D2	D3	D1	D2	D3	ATL effect	Distance effect probability	Interaction probability
Circumference (cm)	48.7 ± 12.1a*	54.2 ± 15.8a	55.7 ± 14.4a	56.2 ± 14.7a	54.8 ± 12.7a	58.0 ± 13.1a	0.1	0.2	0.3
Height (m)	5.2 ± 1.3b	6.3 ± 1.5a	6.3 ± 1.7a	6.4 ± 1.4a	6.7 ± 1.3a	6.8 ± 1.3a	<0.001	0.01	0.2
AGB (kg tree^{-1})	38.3 ± 26.6a	59.5 ± 52.2a	60.4 ± 42.9a	62.6 ± 42.0a	58.9 ± 34.5a	67.3 ± 39.4a	0.09	0.2	0.2
BGB (kg tree^{-1})	8.5 ± 5.2a	12.4 ± 9.4a	12.7 ± 7.9a	13.1 ± 7.8a	12.5 ± 6.4a	14.1 ± 7.2a	0.06	0.2	0.2
AGB + BGB (kg tree^{-1})	46.8 ± 31.8a	71.9 ± 61.5a	73.2 ± 50.9a	75.8 ± 49.8a	71.4 ± 40.9a	81.3 ± 46.6a	0.08	0.2	0.2
NP (pods tree^{-1})	15.5 ± 13.0a	23.4 ± 21.4	26.4 ± 26.1a	35.6 ± 29.4a	33.2 ± 25.5a	38.2 ± 27.4a	<0.001	0.3	0.5
NHP (pods tree^{-1})	10.4 ± 11.3a	11.3 ± 10.0a	15.2 ± 18.1a	22.4 ± 22.8a	19.4 ± 14.0a	20.5 ± 19.4a	<0.001	0.6	0.5
HPW (kg pod^{-1})	0.35 ± 0.1b	0.38 ± 0.1b	0.42 ± 0.1a	0.44 ± 0.05a	0.40 ± 0.05a	0.41 ± 0.06a	<0.001	0.06	<0.001
PBY (kg tree^{-1})	0.5 ± 0.4a	0.8 ± 0.7a	0.9 ± 0.9a	1.4 ± 1.3a	1.2 ± 0.9a	1.4 ± 1.1a	<0.001	0.3	0.2
MBY (kg tree^{-1})	0.3 ± 0.4a	0.4 ± 0.4a	0.5 ± 0.7a	0.9 ± 1.0a	0.7 ± 0.5a	0.7 ± 0.8a	<0.001	0.5	0.2
BYL (kg tree^{-1})	0.1 ± 0.1a	0.4 ± 0.5a	0.4 ± 0.5a	0.5 ± 0.4a	0.5 ± 0.5a	0.6 ± 0.5a	<0.001	0.06	0.2
BYLR (%)	38.9 ± 36.5a	42.7 ± 28.6a	39.8 ± 23.8a	41 ± 22.2a	35.4 ± 19.2a	44.8 ± 20.7a	0.6	0.5	0.2

AGB = Aboveground biomass; BGB = Belowground biomass; NP = total pods number; NHP = healthy pods number; HPW = healthy pods weight; PBY = potential bean yield; MBY = marketable bean yield; BYL = bean yield loss due to unhealthy pods; BYLR = proportion of bean yield lost relative to PBY; Lmer = linear mixed models.
*For each variable and within the same agroforest, values followed by the same letter are not significantly different ($p < 0.05$).

did not differ significantly with distance to the ATL regardless of the species. Likewise, the distance to the ATL did not significantly impact the calculated cacao biomasses.

The healthy pod weight (HPW) and PBY decreased when the cacao plants were growing close to the *A. mangium* plants (at D1 and D2). Conversely, these variables were significantly greater in cacao trees close to *A. lebbeck* ($p < 0.001$; Table 4).

Tree legume effects on the soil organic matter pool

The SOM content in the 0–10 and 0–30 cm soil layers significantly differed among the treatments ($p < 0.001$; Table 5). In both soil layers, Cacao-Alb and Control groups showed similar SOM values. However, in comparison to those in the control group, the SOM of the Cacao–Aca group exhibited a significant decrease (−22%) in both soil layers. Overall, in terms of absolute values, the Cacao-Alb treatment had the highest SOM content compared to the other two treatments. Specifically, there was a 12% and 9% increase in SOM at 0–10 cm and 0–30 cm soil depths, respectively, compared to those in the Control. Additionally, there was 44% and 40% more SOM at 0–10 cm and 0–30 cm soil depths, respectively, in the Cacao-Alb group than in the Cacao-Aca group.

The distance to the ATL did not significantly impact the estimated SOM content in any of the Cacao-Aca and Cacao-Alb plots ($p > 0.05$; Table 5).

Discussion

In this study, the estimated potential cacao bean yields of the studied systems fall within the production range typically observed in Ivory Coast (250–1251 kg ha^{-1}), as reported by Assiri *et al.* (2009, 2012). Cacao circumferences and heights measured at the Divo experimental station were within the range of values reported by Borden *et al.* (2019) in Ghana and Jagoret *et al.* (2017, 2018) in Cameroon. The experimental cacao plantations in this study could be considered representative of non-intensive cacao plantations, as are most smallholder plantations on Ivory Coast. However, it is important to note that the yield evaluation covered only an 8-month period rather than the generally recommended 2-year period.

Intercropping *A. mangium* and *A. lebbeck* in a cacao stand induced no significant variation in the biomass of individual cacao trees compared to that in the cacao monoculture, regardless of the ATL species. However, Cacao-Aca negatively affected the productivity parameters calculated at the stand level ($p < 0.05$). In contrast, when used as a companion tree, *A. lebbeck* did not result in a reduction in cacao biomass or bean production compared to the unshaded cacao trees (Control). This difference may be due to litter quality and SOM content in addition to differences in cacao stand density per plot compared with those of the Control, which were lower in the Cacao-Aca plots than in the Cacao-Alb plots. Therefore, the density of cacao trees appeared to be the main determinant of biomass production per unit of surface area. SOM is widely known to be important for nutrient exchange in the soil environment, as a carbon sink, and for soil fertility and is therefore related to the productivity of plants, notably cacao (Oldfield *et al.*, 2019; Rangel-Mendoza and Silva-Parra, 2020). Furthermore, it is widely known that in a tree and a shrub plantation such as a cAFS, soil fertility is restored over time by the transformation of the litter produced by cacao and/or ATL into SOM. Litter decomposition and mineralisation in the soil are determined by the activities of decomposers and soil microorganisms. The chemical and physical qualities of the litter also play major roles in litter transformation and nutrient availability. *A. mangium* phyllodes (10–15 cm in length and 8 cm in width) are known to be rich in tannins, lignin, and polyphenols, making their leaf litter difficult to decompose; their annual decomposition rate was found to be slow at 40–60%, (Ngoran *et al.*, 2006; Castellanos-Barliza and Peláez, 2011; Gnahoua *et al.*, 2014). In contrast, *A. lebbeck* leaves have very small leaflets (< 2 cm in diameter) with a lower C/N ratio (12) than do the leaves of *A. mangium* (18) according

Table 5. Mean (± standard deviation) of soil organic matter (SOM) in 20-year-old cacao agroforests at the plot level and at three distances to the associated tree legumes (ATL) *Acacia mangium* (in Cacao-Aca) or *Albizia lebbeck* (in Cacao-Alb) compared to a conventional 20-year-old cacao monoculture (Control). Distance between cocoa trunk and ATL trunks D1:0 to 1.75 m, D2:3.25 to 5 m, D3:7 to 9 m. Probability levels derived from the linear mixed models (Lmer) test on SOM for comparison of effects considering [A] presence or absence of ATL, [B] distance from the ATL, and [A × B] interaction of ATL presence with distance to the cacao tree

	Cacao-Aca				Cacao-Alb				Control	Lmer test		
Variables	Plot level	D1	D2	D3	Plot level	D1	D2	D3	Plot level	A	B	A × B
SOM 0–10 (g kg^{-1})	20.4 ± 7.8B*	21.6 ± 11.5a†	20.6 ± 6.9a	19.7 ± 6.5a	29.4 ± 16.3A	34.9 ± 21.6a	26.2 ± 14.2a	29.8 ± 14.8a	26.2 ± 11.6A	<0.001	0.1	0.3
SOM 0–30 (g kg^{-1})	15.7 ± 6.5B	17.7 ± 7.7a	15.6 ± 6.9a	14.7 ± 5.1a	21.9 ± 12.9A	24.6 ± 15.1a	20.9 ± 12.7a	21.4 ± 12.04a	20.0 ± 11.6A	<0.001	0.3	0.9

*For each variable, plot-level values followed by the same capital letter across treatments are not significantly different ($p < 0.05$).
†For each variable and within the same agroforest, values at the distances to the ATL followed by the same lowercase letter are not significantly different ($p < 0.05$).

to Gnahoua *et al.* (2014). The litter produced by *A. lebbeck* was thus assumed to decompose faster than that produced by the other species, resulting in mass losses of 60–70% annually (Singh *et al.,* 2004; Ochire-Boadu *et al.,* 2020). Cacao leaves, which have lower annual decomposition rates, lose 30–40% of their mass (Yao *et al.,* 2021; Bai *et al.,* 2022). Soil nutrient improvement through litter decomposition would therefore be limited by *A. mangium* compared to *A. lebbeck*.

In the studied system, the cacao trees were relatively small (7 m), covering the whole ground, shedding, and producing new leaves and pods that were harvested for approximately five months in a year. These small trees were overhead by higher tree legumes, which induced shade, produced new leaves annually, and potentially fixed atmospheric N_2. Thus, the growth and production of the two tree layers resulted in interactions between the cacao trees and the ATLs. These interactions imply competition for water or nutrient resources. However, facilitation processes such as a favourable microclimate and continuous nutrient supply from the litter to the soil could also occur. These interaction effects are mainly related to the associated tree species, notably the quantity and the quality of their leaf litter (Sauvadet *et al.,* 2020). Shaded trees can therefore be expected to improve soil parameters even if cacao yields remain unchanged as reported by Sauvadet *et al.* (2020). Trebissou *et al.* (2021) reported several factors affecting cacao growth and productivity, such as the characteristics of neighbouring trees, resource limitations (soil nutrients and water), and physiological stress conditions (photoinhibition and shading effect), which can induce a competitive effect and/or affect production mechanisms. Wibaux *et al.* (2017) indicated that the average cacao production is proportional to the resources available to each tree. Thus, the drivers of cacao production included the area used by each cacao in the plot, i.e., the density of cacao, the resources available in this area (water, nutrients, and radiation), and ultimately, the technical management applied, which could have an impact on the above factors. In the present study, the management methods used were the same for all plots and can therefore be excluded as an explanation for the differences between treatments.

Cacao trees close to *A. mangium* had smaller trunk diameters and shorter heights, which could also reflect a greater competition between the two tree species. This difference between the cacao trees in the Cacao-Aca plots and those in the Cacao-Alb plots and the Control was reflected more in the cacao tree height than in the trunk diameter. Blaser-Hart *et al.* (2021) showed in the same environmental context in Ghana that shade trees with low crowns caused larger reductions in incoming light than shade trees with more elevated crowns, which was associated with lower yield. However, in the present study, we observed that a negative impact occurred under *A mangium*, which had the most elevated crown. This suggested that the difference in light incidence between the two tree legumes could explain the difference in tree cacao growth and density, which was less relevant in this cacao tree plantation experiment. Trebissou *et al.* (2021) reported that greater density of cacao trees increased the inter-tree competition (cacao vs. cacao; cacao vs. ATL): the closer the trees were to each other, the more they would try to grow taller to obtain more light. This competition between cacao trees occurred gradually, intensifying over time as resources were depleted (Trebissou *et al.,* 2021). For Rijkers *et al.* (2000), increased tree size (height) under conditions of shade and high density is a mechanism for ensuring plant photosynthetic efficiency. Therefore, the difference in tree density under the different treatments could also explain the difference in cacao tree size and consequently in biomass and bean production. However, the greater cacao density under *A. lebbeck* after 20 years of intercropping favoured cacao height growth in contrast to that under *A. mangium* where the cacao density was lower. Therefore, tree legumes would have limited available resources, especially nutrients, to a degree in the context of this study, resulting in competition between and with cacao, as noted by Nygren *et al.* (2013).

The roots of the trees determined competition or facilitation processes for nutrients and water uptake between ATL and cacao. *A. mangium* and *A. lebbeck* are reported to have a very extensive lateral root system with approximately 80% of the length concentrated in the first 60 cm of soil (Orwa *et al.,* 2009; Saifuddin *et al.,* 2022). Cacao plants also have a surface-concentrated root system that can cause significant competition for nutrients (Nygren *et al.,* 2013). Therefore, ATL

and cacao could draw the water and nutrients they need from the same soil pool. *A. mangium* presented greater dendrometric parameters and consequently greater biomass. This indicated higher nutrient and water requirements for this tree legume than for Cacao-Alb and could explain the negative impacts on cacao stands. The negative impact of *A. mangium* on cacao trees, particularly those closer to their trunk, suggests the occurrence of a possible allelopathic process limiting the survival and productivity of cacao trees (Notaro *et al.*, 2021; Asitoakor *et al.*, 2022). The same explanation could hypothetically apply to the greater mortality of cacao trees in the Cacao-Aca plots, given that, as reported by Konan and Koffi (2003), the same trend was observed 20 months after planting the cacao trees at the start of the experiment. This tree legume may have limitations in improving soil fertility and agrosystem productivity as reported by Koutika and Richardson (2019). These authors reported the negative impacts of *A. mangium* on nutrient concentrations in the soil and in neighbouring trees. ATLs produce considerable quantities of litter annually and are thus able to rapidly return a substantial amount of mineral matter, particularly nitrogen, to the soil (Gnahoua *et al.*, 2014). However, the phosphorus and potassium contents of litter can be quite low in this type of system, and external fertiliser inputs are required to compensate for these deficiencies if the soils are cultivated.

The decreased cacao PBY in response to *A. mangium* may also be related to the relatively small size of the plants. Trebissou *et al.* (2021) reported greater pod production for taller hybrid cacao plants, such as those under *A. lebbeck* and those in Control plots (Table 2). For Niklas (2005), this could be explained by a more developed cacao root system in correlation with the AGB of the cacao plants. This would lead to a greater nutrient acquisition capacity relative to a greater soil volume exploration capacity. Furthermore, small trees would have lower carbohydrate reserves, thus limiting their ability to regulate their growth and pod production as rainfall variability between years and competition effects increase (Tosto *et al.*, 2022).

Blaser *et al.* (2017) showed that shade trees reduced cacao biomass and pod production in farmer plots in Ghana. These authors mainly argued for a tree-shading effect instead of a soil fertility effect. In contrast, Mensah *et al.* (2023), in the same country, reported a beneficial effect of shading on cacao tree physiology, growth, and yield. In this study, the benefits of shade trees were related to the tree legume species. *A. mangium* showed reduction but *A. lebbeck* did not. However, distinguishing the shading effect on the soil fertility effect of tree companions was difficult in these long-term cacao experiments because we did not evaluate the shading ratio of the two ATLs.

Conclusion

This study showed that, 20 years after planting, the cacao biomass and bean production were significantly lower under *A. mangium* shading than under full-sun cacao cropping systems. The presence of *A. lebbeck* maintained similar cacao tree biomasses and PBYs. These results showed the importance of tree species even within the same plant family. If plant traits such as leaf and litter characteristics explain this divergent effect, the density of cacao trees under shade conditions seems to be the main determinant of cacao tree productivity. Therefore, planting cacao trees under a shade tree does not necessarily impede biomass or bean production relative to a full-sun cacao tree system. *A. lebbeck* could be a beneficial species for cacao agroforest establishment.

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