Agroforest Syst
https://doi.org/10.1007/s10457-023-00931-2

Shade canopy density variables in cocoa and coffee agroforestry systems

Eduardo Somarriba · Stéphane Saj · Luis Orozco-Aguilar · Aurelio Somarriba · Bruno Rapidel

Received: 2 March 2023 / Accepted: 20 November 2023

Abstract An estimated 3.4 million hectares of cocoa and 9.7 million hectares of coffee are cultivated, globally, under shade trees, i.e. in agroforestry systems. Shade canopies are characterized in terms of tree density (N, trees ha^{-1}), tree basal area (G, m^2 ha^{-1}) and percent canopy cover (%Cov). N, G and %Cov are named shade canopy density variables (SCDV). The use of these SCDV has two important limitations: (1) different combinations of values of the three SCDV variables generate very different shade tree stands (hence very different shading levels), and (2) Additional factors modify shading under shade canopies with constant SCDV values. This article uses the software ShadeMotion (www.shademotion.net) to show how 24 different, simple, even-sized, mono-layered, *Cordia alliodora* shade canopies with constant N, G and %Cov display significantly different shade levels and temporal patterns of shading depending on tree stem and crown diameter ratios, tree height, spatial planting configurations (square, random and alleys) and leaf fall patterns. A minimum set of variables capable of providing a more accurate description of the shading characteristics of a cocoa or coffee shade canopy is proposed. Our findings can shed light on the current debate on the pros and cons of the definitions of cocoa agroforestry used by chocolate and certification companies, governments, non-governmental organizations, and donors, especially in West and Central Africa. In this article, emphasis is given to cocoa, but the analysis, results and conclusions are equally applicable to coffee agroforestry systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-023-00931-2.

E. Somarriba (✉)
CATIE (Centro Agronómico Tropical de Investigación y Enseñanza), Turrialba, Costa Rica
e-mail: esomarri@catie.ac.cr

E. Somarriba
Montpellier Advanced Knowledge Institute for Transitions (MAK'IT), Montpellier, France

S. Saj
Department of International Cooperation, Research Institute of Organic Agriculture (FiBL), Frick, Switzerland
e-mail: stephane.saj@fibl.org

L. Orozco-Aguilar
Fundación NicaFrance, Finca La Cumplida, Matagalpa, Nicaragua
e-mail: lorozcoaguilar1980@gmail.com

A. Somarriba
IBM Business Transformation Center, San José, Costa Rica
e-mail: asomarri@ibm.com

B. Rapidel
CIRAD-UMR-ABSys, Montpellier, France
e-mail: bruno.rapidel@cirad.fr

Published online: 18 December 2023

Keywords ShadeMotion · *Cordia alliodora* · Basal area · Canopy cover · Shade tree density · Spatial planting patterns · Monthly leaf fall pattern

Introduction

Cocoa agroforestry is now widely recommended to increase and diversify farmers' income, cope with climate change (Ashiagbor et al. 2022; Julian 2016) and reduce tropical deforestation (Kroeger et al. 2017; Nepstad et al. 2018; Orozco-Aguilar et al. 2021).

Globally, cocoa cultivation covers some 11 million hectares (Fountain and Hutz-Adams 2022), while coffee is cultivated on 20.2 million hectares (Panhuysen and Pierrot 2020). It is estimated that 31% of cocoa (3.4 million hectares) and 48% of coffee (9.7 million hectares) is produced under shade trees, i.e. in agroforestry systems (AFS) (Somarriba and López-Sampson 2018). Shade trees influence (i) the photosynthesis, growth, and yield of cocoa/coffee plants and (ii) the dynamics of cocoa/coffee pests, pathogens and natural enemies impairing crop yields (Avelino et al. 2022; Blaser et al. 2018; Charbonnier et al. 2013; Koutouleas et al. 2022; Piato et al. 2020; Suarez-Salazar et al. 2018).

A cocoa/coffee AFS can be conceived as a 3-D volume containing the plants of the crop (e.g. 1000 plants ha^{-1} or 5000 plants ha^{-1} of cocoa or coffee, respectively) and all shade trees (Somarriba et al. 2018) in a variety of arrangements. Optimal "filling up" and management of such a volume remains a challenge for both farmers and agroforestry experts. Forestry experts have long debated over the most suitable variables to characterize the density, crowding and level of stocking of a tree stand (West 1983). Following developments in forestry, cocoa and coffee agroforestry systems are characterized in terms of shade tree density (N, trees ha^{-1}), shade tree basal area (G, m^2 ha^{-1}), and tree canopy cover (%Cov) (Asare and Anders 2015; Asare et al. 2019; Blaser et al. 2018; Ebratt-Matute 2022; Jagoret et al. 2017; Notaro et al. 2020; Saj et al. 2017; Sonwa et al. 2015; Suarez-Salazar et al. 2018). In this paper, N, G and %Cov are named shade canopy density variables (SCDV).

This article aims to: (1) document the extent of use of these SCDV in the scientific literature on cocoa agroforestry; (2) demonstrate two important limitations of these SCDV, namely: (a) radically different tree stands may have the same SCDV estimates, and (b) tree stands with similar SCDV display strongly different shading patterns depending on other factors (such as crown size, tree height, spatial planting and temporal leaf fall patterns); and (3) propose a minimum set of variables to properly describe the shading characteristics of a cocoa or coffee agroforestry system.

The findings of this study can shed light on the current, heated debate on the pros and cons of the definitions of cocoa agroforestry used by chocolate companies, governments, certification companies, NGOs, and donors, especially in West and Central Africa.

In this paper, emphasis is given to cocoa, but the analysis, results and conclusions are likely to be also applicable to coffee agroforestry systems.

Methods

Shade canopy density variables (SCDV) in the scientific literature on cocoa agroforestry

The extent of the use of N, G and %Cov in the scientific literature was explored using a natural language processing algorithm designed to "read-and-search" within the Smithsonian Institute´s specialized bibliographic database on cocoa agroforestry (https://www.zotero.org/groups/2785774/cocoa_library/library). The Smithsonian database combines information from several databases such as SCOPUS, Web of Science, etc. The following set of "keywords" was used: density, trees per hectare, trees/ha, trees ha^{-1}, individuals/ha, individuals ha^{-1}, stems ha^{-1}, stems/ha, plants per hectare, plants/ha, plants ha^{-1}, basal area, m^2 ha^{-1}, m^2/ha, canopy cover, shade percent, percentage of shade, tree cover, shade cover, percent cover, and percentage of cover. Sentences containing these keywords were tagged and checked manually to discard off topics (e.g., the keyword density could be used to describe soil bulk density and not the density of shade trees in the canopy). Then, as various keywords refer to the same SCDV, we renamed synonyms according to the following rules: (1) density = trees per hectare = trees/ha = trees ha^{-1} = individuals/ha = individuals ha^{-1} = stems ha^{-1} = stems/ha = plants per hectare = plants/ha = plants ha^{-1}, (2) canopy cover = shade percent = percentage of shade = tree cover = shade cover = percent cover = percentage of cover, and (3) basal area on its own (no synonyms). We then created a clean database for statistical analysis.

The frequency and relevance of the use of each keyword in the database (corpus) was evaluated with four indexes used in natural language processing (Robertson 2004), modified to suit the needs of this study:

(1) Term frequency [TF(t)] in a document is the number of times a keyword (t) is mentioned in a document [F(t)] expressed as a fraction of the total number of words in the document. However, since our interest is to compare keywords in this study, TF(t) is expressed as a fraction of the total number of times all search terms appear in the corpus [Q = F(density) + F(canopy cover) + F(basal area)]. With this definition, TF(t) = F(t)/Q.
(2) Document Frequency (DF) is the number of documents [N(t)] in which a keyword (t) is present in the corpus (N). With this definition, DF(t) = N(t)/N.
(3) The inverse document frequency of keyword (t) is the ratio between the number of documents in the corpus and the document frequency of a keyword (t) and is calculated as [IDF(t) = N/N(t)]. IDF(t) is usually expressed in logarithmic form to reduce the scale of the ratio when analyzing very large databases. In this study, the corpus is small, and consequently, we expressed IDF(t) on its natural scale.
(4) The term 'Frequency–Inverse Document Frequency' (TF–IDH) integrates the number of times a search term (t) appears in a document and the number of documents the search term appears in. This index is calculated as TF–IDH (t) = TF(t)*IDF(t).

The algorithm was coded in Python (Version 3.8). The 'SciPDF Parser' library was used to parse PDF files (https://github.com/titipata/scipdf_parser). This library utilizes: (1) GROBID, a machine-learning library for extracting, parsing, and restructuring raw documents such as PDF into structured XML/TEI encoded documents, with a particular focus on technical and scientific publications, and (2) Pandas, a fast, powerful, flexible, and easy-to-use open-source data analysis and manipulation tool (https://pandas.pydata.org/). The classification, tokenization, stemming, tagging, parsing, semantic reasoning, and wrappers for industrial-strength natural language processing libraries used to process text information were implemented with the NLTK (Natural Language Toolkit) library (https://www.nltk.org/).

Limitation #1: different shade tree stands may have similar SDCV

To demonstrate the limitations of shade canopy density variables (SCDV, shade tree density (N, trees ha^{-1}), shade tree basal area (G, m^2 ha^{-1}), and tree canopy cover (%Cov)) to describe shading levels in cacao agroforestry system we firstly tested different combinations of values of any two SCDV, holding the third SCDV constant, to generate very different shade tree stands (and likely very different shading levels and patterns). We used equations (Appendix) and nomograms to explore the relationships between combinations of stem diameters (d, in cm, 10, 20, 30, 40 and 50), tree crown diameter to stem diameter ratios (R = k/d = 0.20, 0.25, 0.30 and 0.35, for crown diameter, k = 5 and 10, in meters and tree stem diameter above) and various G stocking targets (5, 10, 15, 20, 25 and 30 m^2 ha^{-1}). All tree stands were simple, mono-specific, even-sized, mono-layered shade canopies of *Cordia alliodora*, a widely used, well-known shade tree in cocoa and coffee in Latin America. In this analysis, crown opacity (*p*) was set to 0.5 based on Andrade and Segura (2016), personal observations and un-published measurements.

Limitation #2: shade tree stands with similar SCDV display different shading patterns

The software ShadeMotion version 5.1.47 (www.shademotion.net) (Somarriba et al. 2022) was used to show how different, simple, even-sized, mono-layered, *Cordia alliodora* shade canopies with the same G and %Cov values display different shading regimes depending on other factors such as different stem-to-crown diameter allometries, tree heights, spatial planting configurations (square, random and alleys) and leaf fall patterns. The software calculated the azimuth and solar elevation angle for one full year (365 days), every day from 9 am until 3 pm, every hour (i.e. a total of 365*7 = 2555 simulation instants per year).

At every simulation instant, the software used the two solar angles, the cartesian coordinate position (x,y) of each tree in the plot, and crown characteristics (diameter, opacity, position aboveground, leaf fall pattern) to "project" the shadow of every tree at ground level. In this article, trees are assumed not to grow nor change in population size during one simulation year.

Each shadow is described by a set of mathematical inequalities; a contour-tracing algorithm (Moore's neighborhood) is used to determine both the contour of the shadow and the set of grid cells (pairs of cartesian coordinates) inside the shadow. A random number generator allocates the condition of shade (1) or no shade (0) to each grid cell inside the shadow according to crown opacity and monthly leaf fall patterns. The number of simulation instants that every grid cell is under shade is recorded. More than one tree may cast shade on the same grid cell at one simulation instant (shade overlap). At the end of the simulation period (one year in this case), a file is generated containing all plot coordinate pairs (grid cells) and their cumulative number of simulation instants with shade. In this article, shading is defined as the number of shade-hours per grid cell per unit of time (year or month).

All simulations were run for a plot of 120×120 m (1.44 ha), but to avoid edge effects, only the grid cells contained in a central sampling area of 57 m×56 m (i.e. 3192 grid cells, 1 m^2 each) were used for statistical analysis. The sample area was representative of the spatial shade pattern observed in shade contour maps generated by the software. The plot was located at the equator (latitude = 0) on a flat, horizontal terrain.

(1) Twenty-four simple, even-sized, mono-layered shade canopies of *Cordia alliodora* were constructed by combining different tree stem diameters (two levels: d = 20 and 40 cm, equivalent to crown diameters, k = 5 m, and 10 m, respectively), leaf fall (two levels: yes/no), tree height (two levels, normal/taller) and tree planting spatial patterns [three levels: square, alleys (two orientations of tree lines: east–west, north–south), random]. All 24 canopy typologies had the same basal area (G = 10 m^2 ha^{-1}), crown diameter to stem diameter ratio (R = k/d = 0.25), percent cover (%Cov = 31%), and crown opacity (p = 0.5). See Fig. 1 and S1_Supplementary Material.

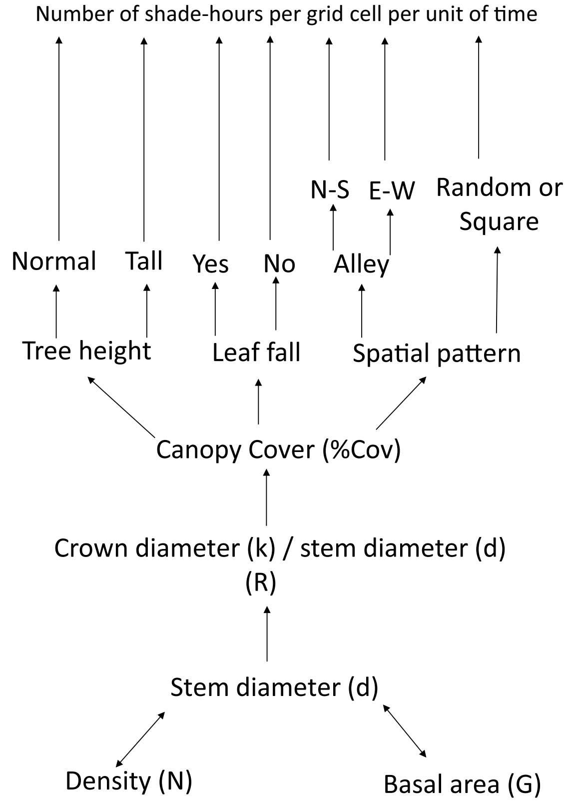

Fig. 1 Relationships between shade canopy density variables and other factors affecting the shading conditions in the understory of cocoa and coffee agroforestry systems

(2) Normal total tree heights for d = 20 (16 m) and d = 40 cm (27 m) were estimated using an allometric equation for *C. alliodora* (Somarriba and Beer 1987); the height of taller trees was set as 1.5 times normal tree height (changing only trunk height, but neither crown height nor crown diameter). Crown heights were set at 6 and 8 m for d = 20 and d = 40 cm, respectively.

(3) *C. alliodora* trees lose their leaves during the dry season in Central America according to the following pattern: trees have full foliage between June and January but lose foliage between February and May at the following monthly rates: 25% loss in February, 50% loss in March, 80% loss in April, 50% in May and 25% in June.

(4) Density (318 and 79 trees ha^{-1} for d = 20 and d = 40 cm, respectively) and square spacing

(5.6×5.6 m and 11.25×11.25 m for d = 20 and d = 40 cm, respectively) were estimated for each stem diameter using G, R, and p. The width of the alley was set at twice the spacing of the square planting. To maintain the same N and G used in square and random planting, in alleys, the spacing between trees within the line was set at half the spacing in square planting.

(5) The effect of the north–south (N–S) and east–west (E–W) orientations of the alleys on shading was evaluated only for trees with d = 40 cm, normal height and considering monthly leaf fall using a one-way ANOVA; cumulative frequency distributions of shade levels per grid cell were compared using a Kolmogorov–Smirnov test (NPAR1WAY procedure in SAS version 9.4).

(6) Shading between the 24 canopy typologies was compared using a balanced factorial analysis with heterogeneous variances (ANOVA). In this analysis, we (1) first assessed homogeneity of variance in a scatter diagram of residuals versus predicted and with a q–q plot; (2) since variances were found to be non-homogeneous [$p < 0.0001$; the model of heterogeneous variance performed better as indicated by its lower Akaike Information Criterion (AIC) and Bayesian Information Criteria (BIC)], a cluster analysis was used (using variances as clustering variable and Euclidean distances as measure of dissimilarity) to identify groups of grid cells with similar variances; (3) a linear mixed model (main effects plus their double, triple and quadruple interactions) was fitted using groups with similar variance as blocks (random effects); (4) estimated marginal means (also known as least-squares means) for factor combinations were computed with the R-emmeans package (version 1.8.3, https://cran.r-project.org/web/packages/emmeans/emmeans.pdf); and (5) pair wise comparisons between means are represented with letters following the algorithm proposed by Piepho (2004).

The fitted model has the following form:

$$S = \mu + d + t + l + h + d*t + d*l + d*h + t*l + t*h + l*h + d*t*l + d*t*h + d*l*h + t*l*h + d*t*l*h + \xi$$

where S = shade, μ = overall mean, d = tree stem diameter, t = spatial planting arrangement, l = leaf fall, h = tree height, and ξ = error

Published research supports the selection of the ranges used in the construction of the typologies (see S1_Supplementary Material).

Results

Use of SCVD in a sample of the scientific literature on cocoa agroforestry

Out of the 397 articles in the database, 313 could be used for analysis (corpus, N = 313). The three keywords were mentioned a total of 3267 times (Q), but with large differences between keywords. Density was mentioned 2.5 times more frequently than canopy cover and 4.9 times more frequently than basal area; canopy cover was mentioned 1.97 times more frequently than basal area (Table 1). The document frequency was nearly 80% for density, 69% for canopy cover, and 17% for basal area. The inverse document frequency [IDF(t)] indicates

Table 1 Frequency analysis of the use of three shade canopy density variables as search terms in a clean version of a bibliographic database on cocoa agroforestry (adapted from https://www.zotero.org/groups/2785774/cocoa_library/library)

Variables		Search term		
		Tree density	Canopy cover	Basal area
Search term frequency (TF)	Count	2041	813	413
	TF	0.6247	0.2489	0.1264
Document frequency (DF)	Count	250	215	53
	DF	0.7987	0.6869	0.1693
Inverse document frequency (IDF)	IDF	1.252	1.456	5.9056
Term frequency inverse document frequency (TF–IDF)	TF–IDF	0.7821	0.3624	0.7465

that 5.9 documents must be inspected to find one mention of basal area, but only between 1.3 and 1.5 documents for density or canopy cover (Table 1). Combining term frequency with inverse document frequency shows that the inspection of 1.26 documents for the keyword density, yielding a TF–IDF_density index of 0.7821, is similar to the inspection of 5.91 pages searching for the keyword basal area [TF–IDF_basal area = 0.7465]. However, inspecting 1.46 pages searching for canopy cover will yield a TF–IDF_canopy cover index of only 0.3624 (Table 1).

In summary, these results show that (1) most cocoa agroforestry systems are characterized in terms of tree density, followed by canopy cover, and to a lesser extent in terms of basal area, and (2) when mentioned in a document, canopy cover is used less intensively than either density or basal area.

Limitation #1: very different shade tree stands can have similar SCDV

Different combinations of tree density (N) and crown diameter (k) can generate tree stands with equal %Cov. For example, tree stands with G = 10 m^2 ha^{-1} and %Cov = 31% can be constructed by combining N between 50 and 1273 trees ha^{-1} with k between 2.5 and 12.6 m (Table 2). Low-stocking shade tree stands (e.g. G = 5 m^2 ha^{-1}) can achieve %Cov ≤ 30% for any combination of N (ranging from 25 to 636 tree ha^{-1}) and k (ranging from 2 to 17.5 m). Shade tree stands with G = 25 m^2 ha^{-1} can only be achieved by using small-crowned trees (Table 2). The relationships between N, k and %Cov was explored using the nomogram in Fig. 2. For example, a well recommended target of %Cov = 30% can be achieved by a tree stand with N = 40 trees ha^{-1}, each with k = 10 m; N must be reduced to 20 trees ha^{-1} if k = 14 m (Fig. 2).

Table 2 Density (N, trees ha^{-1}) and percent canopy cover (%Cov) for *Cordia alliodora* shade canopies as functions of shade tree basal area (G, m^2 ha^{-1}), stem diameter (d, cm), crown diameter (k, m), and the ratio between crown diameter and stem diameter (R, m/cm)

R	k	d	G (m^2 ha^{-1})									
			5		10		15		20		25	
			N	%Cov	N	%Cov	N	%Cov	N	%Cov	N	%Cov
0,20	2	10	636	**10**	1273	**20**	1909	**30**	2546	**40**	3183	**50**
0,20	4	20	159	**10**	318	**20**	477	**30**	636	**40**	795	**50**
0,20	6	30	70	**10**	141	**20**	212	**30**	282	**40**	353	**50**
0,20	8	40	39	**10**	79	**20**	119	**30**	159	**40**	198	**50**
0,20	10	50	25	**10**	50	**20**	76	**30**	101	**40**	127	**50**
0,25	2.5	10	636	**15**	1273	**31**	1909	**46**	2546	62	3183	78
0,25	5	20	159	**15**	318	**31**	477	**46**	636	62	795	78
0,25	7.5	30	70	**15**	141	**31**	212	**46**	282	62	353	78
0,25	10	40	39	**15**	79	**31**	119	**46**	159	62	198	78
0,25	12.5	50	25	**15**	50	**31**	76	**46**	101	62	127	78
0,30	3	10	636	**22**	1273	**45**	1909	67	2546	90	3183	112
0,30	6	20	159	**22**	318	**45**	477	67	636	90	795	112
0,30	9	30	70	**22**	141	**45**	212	67	282	90	353	112
0,30	12	40	39	**22**	79	**45**	119	67	159	90	198	112
0,30	15	50	25	**22**	50	**45**	76	67	101	90	127	112
0,35	3.5	10	636	**30**	1273	61	1909	91	2546	122	3183	153
0,35	7	20	159	**30**	318	61	477	91	636	122	795	153
0,35	10.5	30	70	**30**	141	61	212	91	282	122	353	153
0,35	14	40	39	**30**	79	61	119	91	159	122	198	153
0,35	17.5	50	25	**30**	50	61	76	91	101	122	127	153

In bold %Cov ≤ 50%, an upper limit commonly recommended for both cocoa and coffee shade canopies

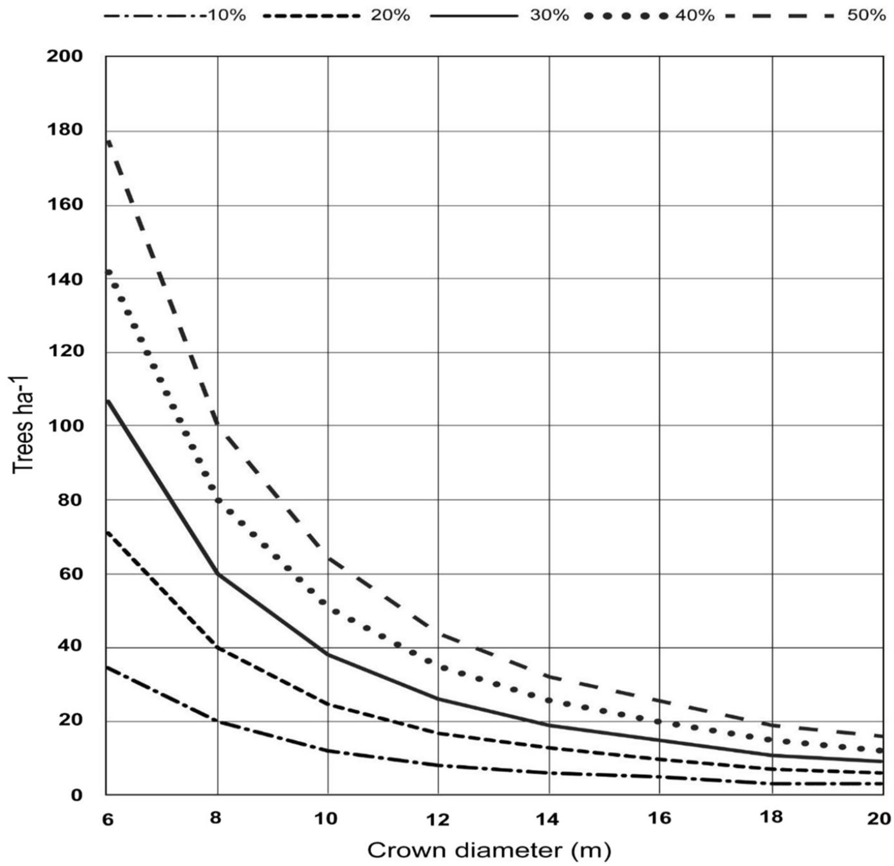

Fig. 2 Break-even lines between crown diameter (k) and density (Trees ha-1) for different target levels of shade canopy cover (%Cov)

Table 3 Average number of shade-hours per grid cell (1 m^2) per year under different shade canopies of *Cordia alliodora* grown at the equator

Spatial pattern	Leaf fall	Number of shade-hours per grid cell per year			
		Stem diameter 20 cm		Stem diameter 40 cm	
		Normal height	Taller	Normal height	Taller
Alley	Yes	783 (30)^{j}	785 (31)^{j}	659 (26)^{o}	695 (27)^{m}
	No	959 (38)^{c}	963 (38)^{c}	809 (32)^{g}	853 (33)^{e}
Random	Yes	848 (33)^{k}	848 (33)^{k}	688 (27)^{p}	688 (27)^{p}
	No	1059 (41)^{d}	1059 (41)^{d}	864 (34)^{l}	864 (34)^{kl}
Square	Yes	901 (35)^{i}	904 (35)^{h}	787 (31)^{f}	784 (31)^{o}
	No	1124 (44)^{b}	1128 (44)^{a}	987 (39)^{n}	985 (39)^{g}

The methodology proposed by Piepho 2004 to showsimilarities and differences between means use the entire alphabet, including p

Shade canopies constructed by combining different tree stem diameters, leaf fall patterns, tree height, and tree planting spatial patterns. All 24 canopy typologies had the same basal area ($G=10\ m^2\ ha^{-1}$), crown diameter to stem diameter ratio ($R=k/d=0.25$), percent cover (%Cov = 31%), and crown opacity ($p=0.5$). Taller trees are 1.5 times taller than normal height trees. Alleys with north–south orientation. Total number of simulation instants = 2555. Percent shading (shade averages divided by 2555, multiplied by 100, and rounded-off to the nearest integer) in parentheses. Average number of shade-hours per year with different letters are significantly different

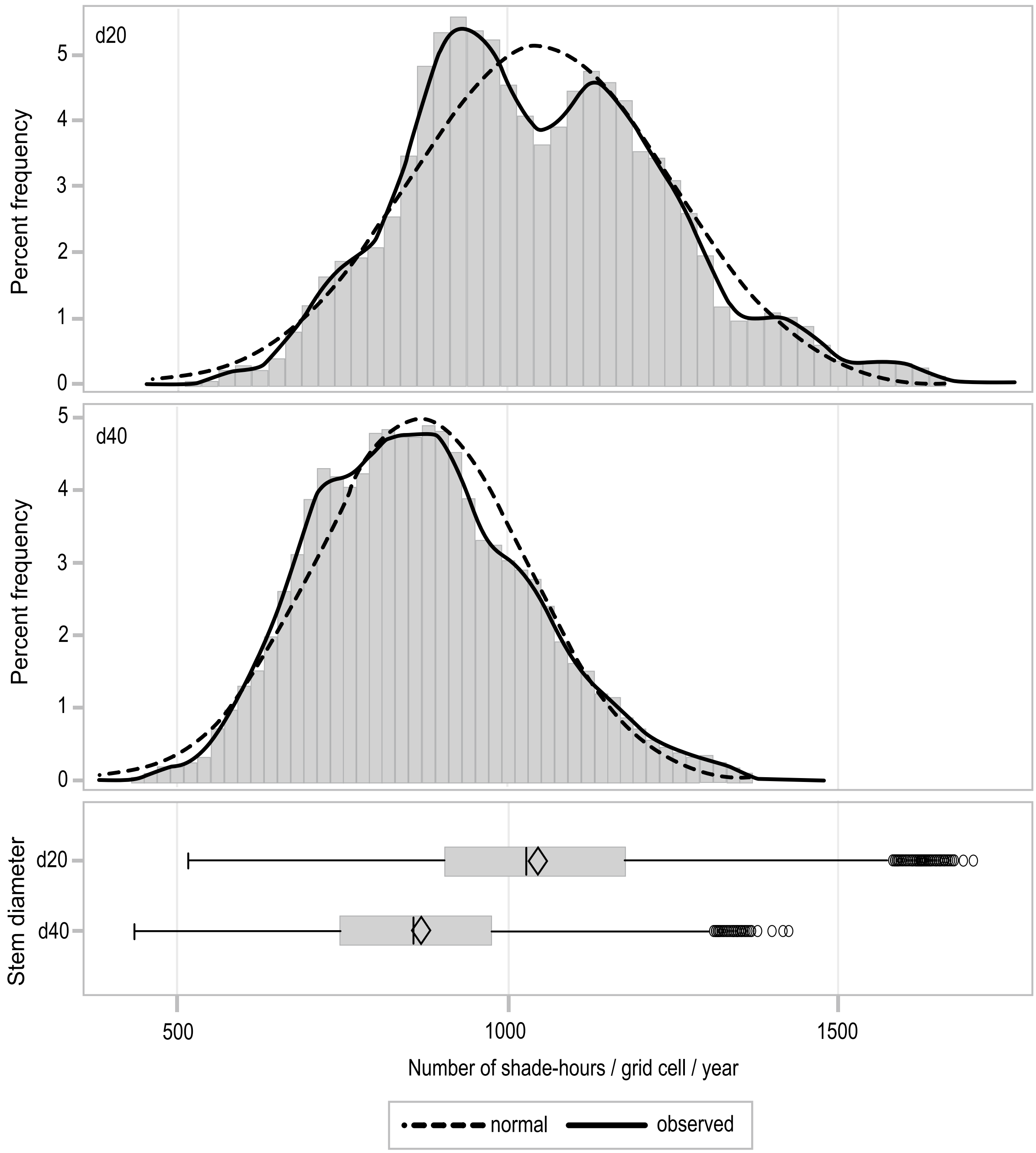

Fig. 3 Averages and frequency distributions (normal and observed) of the number of shade-hours per grid cell per year cast by shade canopies with small (stem diameter 20 cm (d20), crown diameter 5 m) or large (stem diameter 40 cm (d40), crown diameter 10 m) trees grown at the equator

Limitation #2: Other factors determine the shading regimes of canopies with similar SDCV

The annual shade averages for all 24 shade canopy typologies ranged between 26 and 44% (Table 3). The ANOVA indicated that, except tree height, all other main effects (stem diameter, planting spatial pattern, and leaf fall) and their interactions were significantly different. The results in Table 3 show: (1) highest shade-hours averages occurred when trees are planted in square planting configurations, intermediate with randomly planted trees, and lowest when trees are planted in alleys; (2) for constant %Cov (31%), more shade is obtained with many small trees (d = 20 cm) than with fewer larger trees (d = 40 cm); and (3) leaf fall reduces the amount of shade. As an example, differences in the average and frequency distributions of shade hours per grid cell per year between shade canopies with small-crowned (k = 5 m) or large-crowned (k = 10 m) trees are presented in Fig. 3. Pairwise comparisons of the levels and frequency distributions of shade between tall and short trees, with or without leaf fall, square, random or alley spatial planting patterns are presented in the supplementary material (S1_Supplementary Material).

The lack of differences in simulated shade averages between short and tall canopies was at odds with both farmers' traditional knowledge (Graefe et al. 2017) and geometric reasoning (Somarriba et al. 2018): higher shade averages are expected for short trees. A closer examination of this unexpected result showed that it was an artifact of the density (79 and 318 trees ha^{-1}), tree heights (27–40 m) and daily hour range (9 am–3 pm) used in the simulations. When the shade cast by only one short (trunk height 5 m) or tall (trunk height 10 m) tree (spherical crown, no leaf fall, crown opacity = 1, crown diameter = 5 m) was simulated (Fig. 4), the number of shade hours per grid cell was significantly higher (one-way ANOVA, F test, $p < 0.0001$) for short trees (163 ± 117) than for tall trees (83 ± 45); their frequency distributions were also significantly different (Kolmogorov–Smirnov distance, $p < 0.0001$).

Annual averages mask the wide variations in monthly shade levels. For example, shade levels reached 100 h per month (48% shade) when trees are in full foliage but dropped to only 15 h per month (7% shade) when 80% of tree foliage has been lost (Fig. 5). Figure 5 also shows that planting trees in alleys always resulted in the lowest shade averages, whereas square planting always produced the highest shade averages. The geographical orientation of the alleys significantly affected both average shade hours per grid cell per year (one-way ANOVA F test, $p < 0.0001$) and their frequency distribution (Kolmogorov–Smirnov, KSa test, $p < 0.0001$). More shade was observed in north–south (950 average hours-shade per grid cell per year) than in east–west orientated alleys (849 shade-hours per grid cell per year) (Fig. 6).

Discussion

Assumptions and limitations

Our analysis shows that: (1) tree density (N), the simplest, most frequently used SCDV, if taken alone, is clearly inappropriate to describe a shade tree stand because tree size (e.g., crown diameter) is not taken into consideration (Zeide 2005); (2) basal area (G), the most popular forestry measure for determining the level of "stocking" of a tree stand (West 1983; Zeide 2005), has also important limitations as SCDV because: (a) an allometric relationship between tree stem diameter and crown diameter must be specified to determine canopy cover, and (b) the same G can be obtained by radically different combinations of tree stem diameter and N; and (3) percent canopy cover is the only SCDV directly related to shading. The availability of smartphone applications, drone-based high-resolution photography (Blaser et al. 2018) and LIDAR technology can now be used to assess percent canopy cover accurately, quickly, and cheaply (in the case of smartphone applications). Adding information on tree leaf fall monthly or weekly can provide a meaningful description of the shading regime.

Tree density and basal area will continue to be useful surrogate variables for aboveground tree biomass and should also be recorded (and reported) to inform about the capacity of the shade tree stand to compete with crop plants for nutrients and water while providing valuable products (e.g., firewood and timber) and other ecosystem services (habitat, carbon sequestration, water regulation, etc.). Adding information on the tree stem diameter frequency distribution will greatly increase the suitability of density and basal area data to describe both shading conditions and tree stock yields.

The results from this study are particularly relevant for open, discontinuous shade canopies. In fully closed canopies, the discriminant power of percent canopy cover, density, basal area, aboveground biomass, or carbon tends to be the same. In full canopy cover, it will not matter whether trees are planted at random, in alleys or square spatial arrangement, whether trees are big-crowned or small-crowned, or

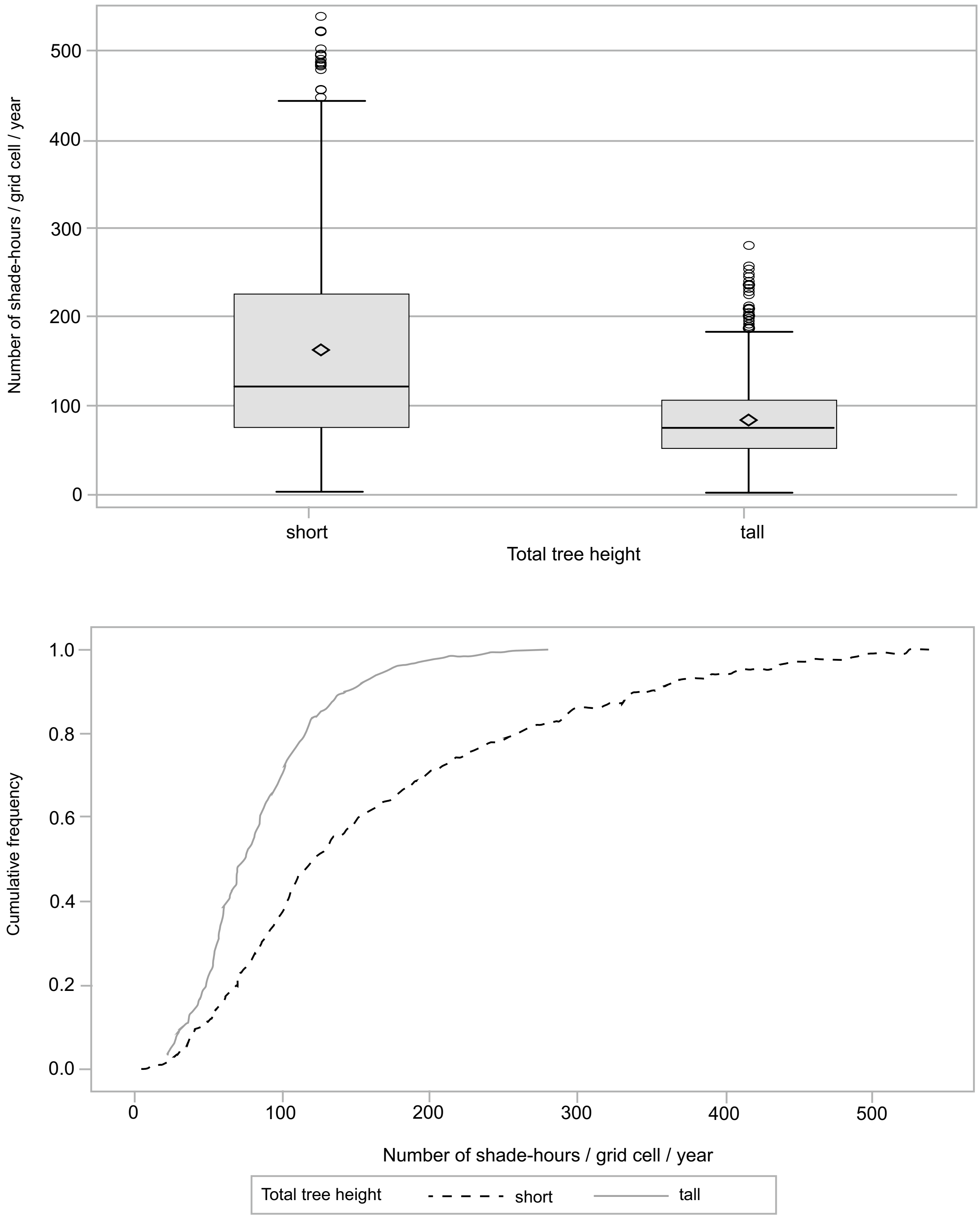

Fig. 4 The effect of the position of the crown above the ground (trunk height) on the average and cumulative frequency distribution of the number of shade-hours per grid cell per year. Simulation of shade cast by one, single short (trunk height 5 m) or tall (trunk height 10 m) tree (spherical crown, no leaf fall, crown opacity = 1, crown diameter = 5 m) grown at the equator

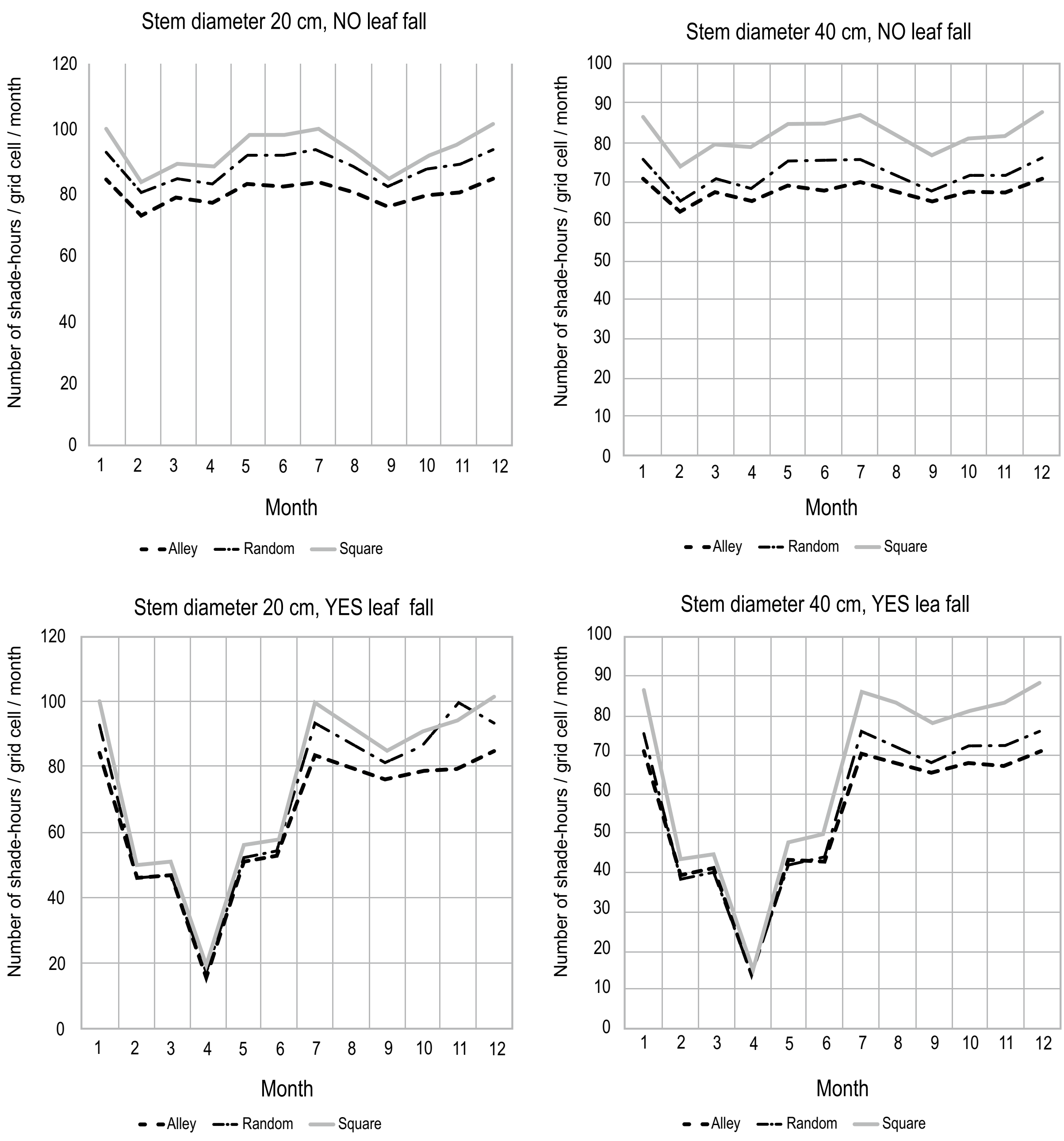

Fig. 5 Average number of shade-hours per grid cell per month cast by *Cordia alliodora* canopies grown at the equator with trees of different sizes (stem diameters of 20 and 40 cm corresponding to crown diameters of 5 and 10, respectively) planted in three different spatial patterns (alleys, random or square), with or without considering the monthly leaf fall pattern. Percentages can be calculated by dividing monthly values by 210, the number of simulation instants in 1 month

whether they are 10 m or 40 m tall. In fully closed canopies, tree leaf fall patterns will be the only element of relevance in determining changes in shading conditions in the understory. In discontinuous shade canopies, shade tree height influences cocoa yields (Asante et al. 2021; Blaser et al. 2018; Notaro et al. 2020).

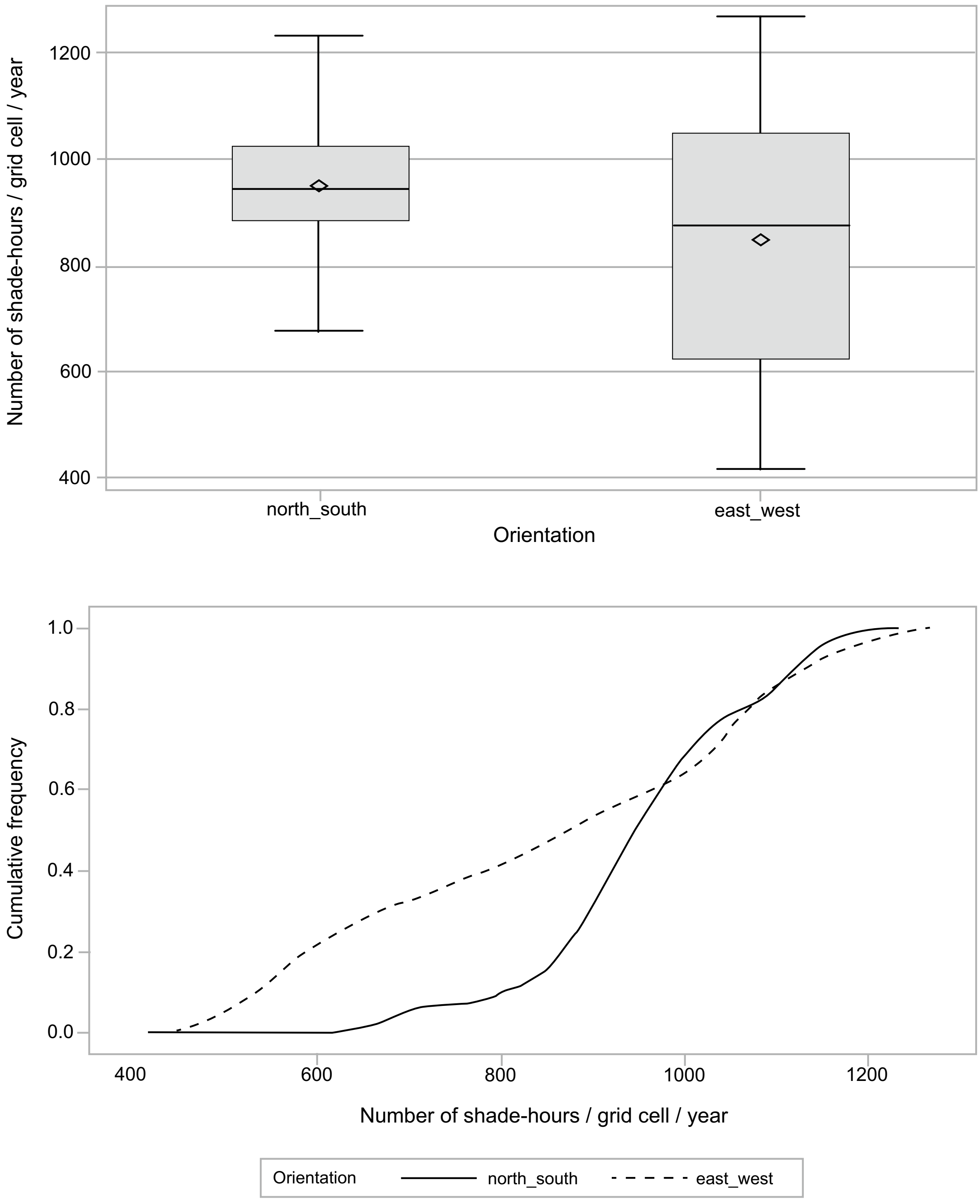

Fig. 6 Average and cumulative frequency distributions of the number of shade-hours per grid cell per year cast by *Cordia alliodora* trees, 40 cm stem diameter, normal trunk tree height 19 m, crown height 8 m, 10 m crown diameter, with monthly leaf fall, and planted in alleys (22.5 m×5.6 m) with orientation north–south or east–west. Plot at the earth's equator

Our work is theoretical and as such we made several simplifications and assumptions to highlight the limitations of tree density, basal area, and percent tree canopy cover as SCDV. First, the formulas relating tree size (trunk diameter and crown diameter) to canopy cover and tree density (number of trees or basal area per hectare) assume that the vertical projection of tree crowns on the ground are perfect circles whose area can be calculated exactly based on crown diameter. If the vertical projection of the crown is not a circle, but its area can be correlated with the diameter (or circumference) of the crown, it will always be possible to develop an equation describing this allometric relationship. The final formula will be different, but the same compensatory effects between density and percent cover discussed in this paper will be observed.

Second, we used simple, mono-layered, single-species shade canopies, planted at the earth's equator to demonstrate the limitations of N, G and %Cov as SCDV. We argue that relaxing these restrictions (e.g. use trees of multiple species, each with different crown diameter, crown density, leaf fall pattern, tree height, different latitudes, etc.) will change the average shade-hours or the spatial distribution of the shadows on the ground but it will continue to be affected by the compensatory interactions between N, G and %Cov demonstrated for simple shade canopies. Our overall results, conclusions and recommendations are valid for mixed-species, shade canopies.

Third, all our simulations were static and with adult trees i.e. simulations were run for only one full year (and not over the entire life span of the trees) and did not considered within-year changes in tree size or in population density. Farmers regularly prune or thin shade trees (Jagoret et al. 2018) and this strongly modifies the density and percent canopy cover of the trees in the cocoa plantation.

Which shade canopy density variables? A proposition

This study shows that to properly describe the level and spatiotemporal patterns of shade in the understory, the following elements should be included in the characterization of the shade tree stand: (1) the number of trees per unit area (i.e. density, N, trees ha^{-1}), (2) the spatial and temporal arrangements of the trees on the ground, (3) tree height, (4) crown diameter, (5) leaf fall temporal patterns, and (6) crown opacity. All SCDV used to date fall short in considering all six elements. Other elements not related to the shade tree stand must also be considered. For instance, latitude, topography, cloudiness and wind, soil fertility, water availability, crowding and self-shading in the cocoa stand itself (Asare and Anders 2015; Asante et al. 2021; Blaser-Hart et al. 2021; Notaro et al. 2020; Somarriba et al. 2018). A summary of the elements that researchers and farmers could assess when describing cocoa and coffee agroforestry systems is presented in Table 4.

Defining cocoa agroforestry

Agroforestry is now widely promoted in cocoa cultivation around the world, particularly in West and Central Africa. However, alignment on an adequate definition of cocoa agroforestry is missing, causing a lot of confusion, and driving cocoa companies, governments, and certification agencies to use different definitions when formulating policies and implementing agroforestry programs. Current definitions are typically framed in terms of shade canopy tree density, canopy cover, tree species richness (sometimes disaggregated into exotic or native, or successional guild) and, in a few cases, of the vertical stratification of the shade canopy (https://stories.mightyearth.org/voice-network-agroforestry-in-cocoa/index.html).

This study demonstrated that tree density alone is clearly inappropriate as an SCDV because the many combinations between density, tree size and stem diameter—crown diameter allometries may render current recommendations useless or even detrimental in terms of shading. For example, recommending tree density alone may lead to over-shading if farmers choose to plant many small instead of few large-crowned trees. Shading may conflict with recommendations to increase the use of fertilizer to achieve higher cocoa yields (van Vliet and Giller 2017). Basal area and percent shade canopy cover also have important limitations in properly describing the shading conditions in the understory of a cocoa agroforestry system. Evidently, a more nuanced analysis of the cocoa agroforestry definitions is warranted. The use of nomograms relating density, basal area, crown diameter and canopy cover is highly recommended.

Table 4 Descriptive elements that may be used to characterize cocoa and coffee agroforestry systems

Element	Mandatory	Recommended
Soil	Soil order/type, fertility level. Example: https://soilgrids.org/	pH, acidity, organic matter, soil texture and structure
Site	Geographic coordinates, climate typology (Kotteck et al. 2006), cloudiness weekly or monthly pattern, prevalent wind direction, velocity, and monthly pattern	Mean air temperature, rainfall (total annual, number of dry months), relative humidity (%), daily/monthly hours of sunshine
Location	Altitude, slope (degree, geographic orientation)	Height of neighbor vegetation that could provide lateral shading to the cocoa/coffee plantation
Agroforestry typology	Example: Somarriba and Lachenaud (2013)	Other typologies may be used. Toledo and Moguel 2012
Crop	Crop density (plants ha^{-1}), spacing, age (years after planting)	Pruning practices (frequency, intensity), planting genetic material (clonal, seedling), self-shading level and crop canopy closure
Canopy vertical structure	Number of strata, density of tree crowns by strata	Total tree height (m), trunk height (m), crown height (m)
Canopy horizontal structure	Density (trees ha^{-1}) by functional group (fruit, timber, firewood, shade, soil fertility improvement, etc.)	Basal area (m^2 ha^{-1}), tree spatial planting pattern (i.e. square, triangular, alleys, clustered, random), tree diameter frequency distribution
Species richness	Total number of tree species, species by ecological and functional group, natives and exotics, origins	Diversity index, rarefaction curves
Tree canopy cover	Weekly or monthly leaf fall pattern, and percent canopy cover pattern	Crown shape (e.g. see Asante et al. 2021 or Somarriba et al. 2022), Crown diameter frequency distribution

Conclusions

This study demonstrates the limitations of N, G and %Cov as SDCV to describe a shade tree stand in a cocoa or coffee agroforestry system. The two major limitations include: (1) Different combinations of values of any two SCDV variables holding constant the value of the third variable generate very different shade tree stands (hence very different shading levels and patterns), and (2) shade canopies with constant SCDV display significantly different shade levels due to other factors such as different tree stem and crown diameter ratios, tree height, spatial planting configurations (square, random and alleys) and leaf fall pattern.

This study demonstrated that neither shade tree density nor basal area provide direct evidence of the shading conditions in a cocoa plantation. Allometric relationships between tree stem diameter and crown diameters must be specified to estimate percent canopy cover, the SCDV directly linked to shading. If complemented with information on leaf fall patterns, percent canopy cover is a powerful SCDV.

Our simulations showed that more shade is cast when trees are planted in square or random spatial planting patterns than when planted in alleys, and that the geographical orientation of the alley (north–south or east–west) has significant effects on shading. For tree alleys planted at the equator, more shade was recorded with north–south than east–west orientations. Leaf-fall reduced shade levels in all spatial planting patterns. For a constant percent canopy cover, fewer, larger (large-crowned, taller) trees cast less shade than many small (narrow-crowned, short) trees.

A more comprehensive description of the shade cast by a tree stand in a cocoa or coffee agroforestry system should include at least six elements: (1) the number of trees per unit area (i.e. density, N, trees ha^{-1}), (2) the spatial and temporal arrangements disposition of the trees on the ground, (3) tree height, (4) crown diameter, (5) leaf fall temporal patterns, and (6) crown opacity.

Acknowledgements This research was funded by the University of Montpellier's MAK'IT (Montpellier Advanced Knowledge Institute on Transitions) visiting scientist program, CATIE (Centro Agronómico Tropical de Investigación y Enseñanza), and CIRAD. Sergio Vílchez provided valuable orientation and help in the statistical analysis of the data. Two anonymous reviewers provided suggestions and comments that helped the authors to improve the quality of the manuscript.

Author contributions ES designed the study, ran the simulations with the software ShadeMotion, and wrote the various drafts of the manuscript. AS analyzed the bibliographic database and wrote the natural language processing algorithm. All authors carefully reviewed and commented on various versions of the manuscript and contributed to the interpretation of the results. All authors read and approved the final manuscript.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose, no competing interests, and no proprietary interests in any material discussed in this article.

Appendix 1: The mathematical relationships between N, G, %Cov, R, d, and k

With trees of same stem diameter (d), basal area per hectare (G) is obtained by multiplying the sectional stem area of one tree (g, m^2 $tree^{-1}$) by the population density represented in number of trees per hectare (N). Symbolically:

$G = g * N$

Assuming tree stems are cylindrical, the sectional area can be estimated by the area of a circle of diameter d (in meters i.e. d in cm divided by 100),

$$g = (d/100)^2 * (\pi/4) = \left(\pi * d^2\right)/40000$$

Hence

$$G = \left(N * \pi * d^2\right)/40000 \tag{1}$$

Re-arranging Eq. 1

$$N = (G * 40000)/\left(\pi * d^2\right) \tag{2}$$

And

$$d = \left[(G * 40000)/N * \pi)\right]^{1/2} \tag{3}$$

Considering that

$$R = k/d$$
$$K = R * d$$
$$d = k/R$$

For a given R

$$G = \left(N * k^2 * \pi\right)/\left(40000 * R^2\right) \tag{4}$$

$$N = \left(40000 * G * R^2\right)/\left(\pi * k^2\right) \tag{5}$$

$$K = \left[\left(40000 * G * R^2\right)/(N * \pi)\right]^{1/2} \tag{6}$$

Percent canopy cover (%Cov) is obtained by multiplying the opacity-adjusted crown projection area per tree (z) by the number of trees per hectare, divided by 10,000 m^2 in one hectare and later multiply it by 100 to express the ratio in percent. Assuming that vertical crown projection is circular,

$$z = k^2 * (\pi/4) * p = (R * d)^2 * (\pi/4) * p = R^2 * d^2 * (\pi/4) * p$$

Hence

$$\%Cov = 100 * (N * z * p)/10000 = \left(N * R^2 * d^2 * p * \pi\right)/400 \tag{7}$$

Substituting N by Eq. (1) and rearranging terms,

$$\%Cov = 100 * G * p * R^2 \tag{8}$$

Also

$$\%Cov = (N * p * \pi * k^2)/400 \tag{9}$$

References

Andrade HJ, Segura MA (2016) Dinámica de la sombra de *Cordia alliodora* en sistemas agroforestales con café en Tolima, Colombia. Agronomía Costarricense 40(2):77–86

Asante WA, Ahoma G, Gyampoh BA, Kyereh B, Asare R (2021) Upper canopy tree crown architecture and its implications for shade in cocoa agroforestry systems in the Western Region of Ghana. Trees for People 5:100100. https://doi.org/10.1016/j.tfp.2021.100100

Asare R, Anders R (2015) Tree diversity and canopy cover in cocoa systems in Ghana. New for. https://doi.org/10.1007/s11056-015-9515-3

Asare R, Markussen B, Asare RA, Anim-Kwapong G, Ræbild A (2019) On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana. Climate Dev 11(5):435–445. https://doi.org/10.1080/17565529.2018.1442805

Ashiagbor G, Asante WA, Forkuo EK, Acheampong E, Foli E (2022) Monitoring cocoa-driven deforestation: the contexts of encroachment and land use policy implications for deforestation free cocoa supply chains in Ghana. Appl Geogr 147:102788. https://doi.org/10.1016/j.apgeog.2022.102788

Avelino J, Gagliardi S, Perfecto I, Isaac ME, Liebig T, Vandermeer J, Merle I, Hajian-Forooshani Z, Motisi N (2022) Tree effects on coffee leaf rust at field and landscape scales. Plant Dis. https://doi.org/10.1094/PDIS-08-21-1804-FE

Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to intermediate shade agroforests. Nat Sustain 1:234–239. https://doi.org/10.1038/s41893-018-0062-8

Blaser-Hart WJ, Hart SP, Oppong J, Kyereh D, Yeboah E, Six J (2021) The effectiveness of cocoa agroforests depends on shade-tree canopy height. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2021.107676

Charbonnier F, le Maire G, Dreyer E, Casanoves F, Christina M, Dauzat J, Eitel JUH, Vaast P, Vierling LA, Roupsard O (2013) Competition for light in heterogeneous canopies: application of MAESTRA to a coffee (*Coffea arabica* L.) agroforestry system. Agric for Meteorol 181:152–169

Ebratt-Matute DJ (2022) Composición florística y estructura de las especies de sombrío en los sistemas agroforestales de cacao (*Theobroma cacao* L.) en la subregión de los Montes de María, Bolívar-Colombia. Intropica 17(1):47–60. https://doi.org/10.21676/23897864.4495

Fountain A, Hütz-Adams F (2022) Cocoa Barometer. Prins Bernhardlaan: Public Eye. https://voicenetwork.cc/cocoa-barometer/

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. https://doi.org/10.1007/s10745-017-9899-0

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 37:60. https://doi.org/10.1007/s13593-017-0468-0

Jagoret P, Snoeck D, Bouambi E, Ngnogue HT, Nyasse S, Saj S (2018) Rehabilitation practices that shape cocoa agroforestry systems in Central Cameroon: key management strategies for long-term exploitation. Agrofor Syst 92:1185–1199. https://doi.org/10.1007/s10457-016-0055-4

Julian WA (2016) Cocoa farming system in Indonesia and its sustainability under climate change. Agric for Fish 5(5):170–180. https://doi.org/10.11648/j.aff.20160505.15

Kotteck M, Grieser J, Beck CH, Dudolg B, Ranz R (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130

Koutouleas A, Sarzynsk T, Bertrand B, Bordeaux M, Bosselmann AS, Campa C, Etienne H, Turreira-García N, Léran S, Markussen B, Marraccini P, Cochicho Ramalho J, Vaast P, Ræbild A (2022) Shade effects on yield across different *Coffea arabica* cultivars—How much is too much? A meta-analysis. Agron Sustain Dev 42:55. https://doi.org/10.1007/s13593-022-00788-2

Kroeger A, Koenig S, Thomson A, Streck C, Weiner P-H, Bakhtary H (2017) Forest- and climate-smart cocoa in Côte d'Ivoire and Ghana, aligning stakeholders to support smallholders in deforestation-free cocoa. World Bank: Washington, DC, USA. Available online: https://openknowledge.worldbank.org/bitstream/handle/10986/29014/122086.pdf

Nepstad D, Lovett P, Irawan S, Watts J, Pezo D, Somarriba E, Shimada J, Cudjoe DN, Fernandez ECM (2018) Leveraging agricultural value chains to enhance tropical tree cover and slow deforestation (LEAVES). Synthesis report. The World Bank, Washington, DC, USA, p 28

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. Agroforest Syst 2020(94):1071–1084. https://doi.org/10.1007/s10457-019-00472-7

Orozco-Aguilar L, López-Sampson A, Leandro ME, Robiglio V, Reyes M, Bordeaux M, Sepulveda N, Somarriba E (2021) Elucidating pathways and discourses linking cocoa cultivation to deforestation, reforestation and tree cover change in Nicaragua and Peru. Front Sustain Food Syst. https://doi.org/10.3389/fsufs.2021.635779

Panhuysen S, Pierrot J (2020) Coffee Barometer 2020. The Coffee Collective 2020: Conservation International, Hivos, Oxfam Wereldwinkels, Solidaridad (CB2020@ethosagriculture.com), Belgium, p 56

Piato K, Lefort F, Subía C, Caicedo C, Calderón D, Pico J, Norgrove L (2020) Effects of shade trees on robusta coffee growth, yield and quality. A meta-analysis. Agron Sustain Dev 40:38. https://doi.org/10.1007/s13593-020-00642-3

Piepho HP (2004) An algorithm for a letter-based representation of all-pairwise comparisons. J Comput Graph Stat 13(2):456–466. https://doi.org/10.1198/1061860043515

Robertson S (2004) Understanding inverse document frequency: on theoretical arguments for IDF. J Doc 60(5):503–520. https://doi.org/10.1108/00220410410560582

Saj S, Jagoret P, Etoa LE, Fonkeng EE, Tarla JN, Nieboukaho JDE, Sakouma KM (2017) Lessons learned from the long-term analysis of cacao yield and stand structure in central Cameroonian agroforestry systems. Agric Syst 156(2017):95–104. https://doi.org/10.1016/j.agsy.2017.06.002

Somarriba EJ, Beer J (1987) Dimensions, volumes, and growth of *Cordia alliodora* in agroforestry systems. For Ecol Manag 18:113–126

Somarriba E, Lachenaud P (2013) Successional cocoa agroforests of the Amazon–Orinoco–Guiana shield. For Trees Livelihoods 22(1):51–59. https://doi.org/10.1080/14728028.2013.770316

Somarriba E, López Sampson A (2018) Coffee and cocoa agroforestry systems: pathways to deforestation, reforestation, and tree cover change. Background paper, leveraging agricultural value chains to enhance Tropical tree cover and slow deforestation, LEAVES, program on forests (PROFOR), The World Bank, Washington, DC, USA, p 51

Somarriba E, Orozco-Aguilar L, Cerda R, López-Sampson A (2018) Analysis and design of the shade canopy of cocoa-based agroforestry system. In: Umaharan P (ed) Achieving sustainable cultivation of cocoa. Burleigh Dodds Science Publishing, Cambridge, UK, pp 469–499. https://doi.org/10.19103/AS.2017.0021.29

Somarriba E, Zamora R, Barrantes J, Sinclair F, Quesada F (2022) ShadeMotion: modeling tree shade patterns in agroforestry systems. Agrofor Syst. https://doi.org/10.1007/s10457-022-00784-1

Sonwa D, Weise SF, Nkongmeneck BA, Tchatat M, Janssens MJJ (2015) Structure and composition of cocoa agroforests in the humid forest zone of Southern Cameroon. Agrofor Syst 2017(91):451–470. https://doi.org/10.1007/s10457-016-9942-y

Suarez Salazar JC, Ngo Bieng MA, Melgarejo LM, Di Rienzo JA, Casanoves F (2018) First typology of cacao (*Theobroma cacao* L.) systems in Colombian Amazonia, based on tree species richness, canopy structure and light availability. PLoS ONE 13(2):e0191003. https://doi.org/10.1371/journal.pone.0191003

Toledo VM, Moguel P (2012) Coffee and sustainability: the multiple values of traditional shaded coffee. J Sustain Agric 36(3):353–377. https://doi.org/10.1080/10440046.2011.583719

van Vliet JA, Giller KE (2017) Mineral nutrition of cocoa: a review. Adv Agron 141:185–270. https://doi.org/10.1016/bs.agron.2016.10.017

West PW (1983) Comparison of stand density measures in even-aged regrowth eucalypt forest of southern Tasmania. Can J for Res 13:22–31

Zeide B (2005) How to measure stand density. Trees 19:1–14. https://doi.org/10.1007/s00468-004-0343-x