

Shade canopy density variables in cocoa and coffee agroforestry systems

Eduardo Somarriba (✉ esomarri@catie.ac.cr)

Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)

Stéphane Saj

CIRAD-UMR-ABSys

Luis Orozco-Aguilar

Fundación NicaFrance, Finca La Cumplida

Aurelio Somarriba

AKAMAI Technologies

Bruno Rapidel

CIRAD-UMR-ABSys

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Abstract

An estimated 3.41 million hectares of cocoa and 8.08 million hectares of coffee are cultivated under shade trees i.e. in agroforestry systems. Shade canopies are usually characterized in terms of tree density (N, trees ha⁻¹), tree basal area (G, m² ha⁻¹) and percent canopy cover (%C). This article shows that these variables have cross-compensation effects that reduce their capacity to inform on the shading conditions in the understory. Density and basal area are not directly related to canopy cover (and hence to shading) and need additional assumptions about both tree size and species-specific allometric relationships between stem diameter and crown diameter. This article explores the compensatory effects between these variables and uses simulations with 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 %C display significantly different shade levels and temporal patterns of shading depending on tree stem and crown diameters, tree height, spatial planting configurations (square, random and alleys) and leaf fall patterns. A minimum set of variables capable of providing a more informative description of the shading characteristics of a cocoa or coffee shade canopy is proposed. Findings in this study can shed light on the current, heated debate on the pros and cons of definitions of cocoa agroforestry used by chocolate companies, governments, certification companies, NGOs, 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.

Introduction

Cocoa agroforestry is widely recommended to cope with climate change (Ashiagbor et al 2022; Julian Witjaksono 2016) and reduce tropical deforestation (Kroeger et al 2017; Nepstad et al 2018; Orozco-Aguilar et al 2021) while increasing and diversifying the livelihoods of some 5 million smallholder farmers worldwide. Globally, cocoa cultivation covers some 11 million hectares (Fountain and Hutz-Adams 2018). Coffee is cultivated in 20.2 million hectares by 12.5 million smallholder farmers (Panhuysen and Pierrot 2020). It is estimated that 31% of the cocoa (3.41 million hectares) and 40 % of the coffee (8.08 million hectares) are produced under shade trees i.e. in agroforestry systems (AFS) (Somarriba and López-Sampson 2018).

A cocoa/coffee AFS can be conceived as a 3-D volume (Somarriba et al 2018). Optimal “filling up” and management of such a volume remains a challenge both for farmers and agroforestry experts. Along with the competition between shade trees and crop plants for soil resources (water and nutrients – not addressed in this paper), the taller nature of shade trees reduces the availability of sunlight and modifies the microclimate in the understory. A rich literature documents the approaches and level of detail needed to describe the microclimate determining the physiological and productive response of the crops in the understory (Charbonnier et al 2013; Suarez-Salazar et al 2018; Somarriba et al 2022). In cocoa/coffee AFS, shade trees influence (i) the photosynthesis, growth, and yield of the 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; Koutouleas et al 2022; Piato et al 2020).

Foresters 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 are characterized in terms of shade tree density (N, trees ha⁻¹), shade tree basal area (G, m² ha⁻¹), and tree canopy cover (%C) (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). Yet, the capacity of these variables to inform on the shading conditions in a cocoa/coffee AFS has never been explored.). In this paper, N, G and %C are named Shade Canopy Density Variables (SCDV).

This article makes the very first attempt of such an exploration. It aims at: 1) documenting the use of these SCDV in the scientific literature on cocoa agroforestry, 2) demonstrating how the cross-compensatory effect of N, G and %C can generate radically different shade canopies, and 3) using simulations with the software ShadeMotion version 5.1.47 (www.shademotion.net) to show how 24 different, simple, even-sized, mono-layered, *Cordia alliodora* shade canopies with same N, G and %C but different stem-to-crown diameter allometries, tree heights, spatial planting configurations (square, random and alleys) and leaf fall patterns display significantly different levels and temporal patterns of shading. The use of a simple shade canopy was necessary to provide convincing arguments and evidence on the limitations of N, G and %C to inform on the shading characteristics of a shade canopy without the confounding effects of both the mixtures of tree species (each with specific crown opacity, allometries, leaf fall patterns, tree size, etc.) and the vertical stratification of the shade canopy. *C. alliodora* is a well-known and widely used shade canopy tree species in Latin America. A minimum set of variables capable of providing a good description of the shading characteristics of a cocoa or coffee shade canopy is proposed. Findings in this study can shed light on the current, heated debate on the pros and cons of 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 equally 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 %C in the scientific literature on cocoa agroforestry was explored using a natural language processing algorithm to “read-and-search” within the Smithsonian Institute’s specialized bibliographic data base (https://www.zotero.org/groups/2785774/cocoa_library/library). 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, m² ha⁻¹, m²/ha, canopy cover, shade percent, percentage of shade, tree cover, shade cover, percent cover, 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 between keywords in this study TF(t) is expressed as a fraction of the total number of times all search terms appear in the corpus [$Q = F(\text{density}) + F(\text{canopy cover}) + F(\text{basal area})$]. 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. 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) in its natural scale.
4. Term Frequency Inverse Document Frequency integrates the number of times a search term appears in a document and the number of documents the search term appears in. This index is calculated as $TF-IDF(t) = TF(t) * IDF(t)$.

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 GROBID, a machine-learning library for extracting, parsing, and re-structuring raw documents such as PDF into structured XML/TEI encoded documents, with a particular focus on technical and scientific publications. 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, and semantic reasoning, and wrappers for industrial-strength NLP libraries used to process text information were implemented with the NLTK (Natural Language Toolkit) library (<https://www.nltk.org/>).

Cross-compensation effects between N, G, R and %C

To explore the cross-compensation effects between N, G and %C, and hence their limitations as good SCDV for describing the shading conditions in the understory, we calculated shade tree density and percent canopy cover for simple, mono-specific, even-sized, mono-layered shade canopies of *Cordia alliodora* for various stem diameters (d, in cm, 10, 20, 30, 40 and 50), various ratios ($R = k/d$) between crown diameter ($k = 5$ and 10, in meters) and tree stem diameter ($d = 0.20, 0.25, 0.30$ and 0.35) and G

stocking targets (5, 10, 15, 20, 25 and 30 m² ha⁻¹). Low values of R represent small-crowned trees and high values represent big-crowned trees; the value of G represents “stocking” level of the shade tree stand.

The relationships between N, G, R, and %C were explored using equations 1 and 2:

$$N = (40000 \cdot G) / (\pi \cdot d^2) \text{ Equation 1}$$

$$\%C = 100 \cdot G \cdot R^2 \text{ Equation 2}$$

In this analysis crown opacity was set a 0.5.

Shading under canopy typologies with same N, G, R, p and %C

The software ShadeMotion (Somarriba et al 2022) was used to quantify the effects of tree height, leaf fall patterns and spatial planting configurations of trees of different stem diameter on the level and spatiotemporal pattern of shading of 24 shade canopies with same N, G and %C. The software calculates 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 uses the two solar angles, the coordinate position (x,y) as well as the dimensions and the crown characteristics of every tree in the plot to “project” the shadow of every tree at ground level. Trees don't grow nor change in numbers during the simulation year. Light passage through the crown is modeled by the product between crown opacity (p) and the percent of foliage retained monthly by the trees (f). The product p*f is used to estimate the fraction of shaded area in the shadow cast by every tree on any day of each month. Each shadow is described by a set of mathematical inequalities and a contour-tracing algorithm (Moore's neighborhood) used to determine both the contour of the shadow and the set of coordinate pairs (grid cells) 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 p*f. The number of simulation events that every grid cell is under shade is recorded. More than one tree may cast shade on a grid cell at a 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. To avoid edge effects, a central sampling area of 57 m x 56 m (i.e. 3192 grid cells, 1 m² each) was used for statistical analysis. In this article, shading is defined as the cumulative number of shade-hours per grid cell, per year.

The construction of the 24 shade canopies followed the protocol described below (Fig. 1 and in S1_SupplementaryMaterial):

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 planting spatial patterns (three levels: square, alley, random). All 24 canopy typologies had the same basal area (G = 10 m² ha⁻¹), same crown diameter to stem diameter ratio (R

- = $k/d = 0.25$), same percent cover (%C = 31%), and same crown opacity ($p = 0.5$). Trees were planted in a hypothetical plot 1.44 ha plot (120 m x 120 m, 14400 coordinate pairs or grid cells, 1 m² each), located at the equator (latitude = 0) on a flat, horizontal terrain.
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 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 x 5.6 m and 11.25 x 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) orientation 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 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 model fitted has the form:

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

With 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_SupplementaryMaterial)

Results And Discussion

Use of SCVD in the scientific literature on cocoa agroforestry

Out of the 397 PDFs 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 notorious 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). Document Frequency was nearly 80% for density, 69% for canopy cover, and 17% for basal area. The inverse document frequency [IDF(t)] indicates that 5.9 documents must be inspected to find one mention of basal area, but only between 1.3–1.5 documents for density or canopy cover (Table 1). Combining term frequency with inverse document frequency shows that the inspection of 1.26 documents searching for the keyword density yields a TF-IDF_density index (0.7821) 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 less so in terms of basal area, and 2) when mentioned in a document, canopy cover is used less intensively than either density or basal area. These findings are unfortunate because, as shown in the following section, density and basal area are poor surrogates to describe the shading conditions in the understory of a cocoa agroforestry system.

The goodness of N, G and %C as SCDC

Due to cross-compensation effects between N, k, G and %C; different tree densities are needed to achieve the same tree cover and basal area (Fig. 2 and Table 2). For instance, to achieve both $G = 10 \text{ m}^2 \text{ ha}^{-1}$ and $\%C = 31\%$ canopy cover requires 318 trees ha^{-1} with small-crowned trees (crown diameter 5 m), but only 79 trees ha^{-1} with medium-crowned trees (crown diameter 10 m). Tree density (N), the simplest, most frequently used SCDC, is clearly inappropriate because tree size (e.g. crown diameter) is not taken into consideration (Zeide 2005).

Basal area, the most popular measure for determining the level of “stocking” of a tree stand (West 1983; Zeide 2005) is also inappropriate as a SCDC because: 1) an allometric relationship between tree stem diameter and crown diameter to determine canopy cover, hence shading, and 2) the same basal area can be obtained by combining tree stem diameter and density, and as shown by simulations presented in the following section, tree size significantly changes the levels and patterns of shading in the understory.

Canopy cover is the only SCDV directly linked to shading. Tree density and basal area can only be related to canopy cover and hence to shading through allometric relationships between tree stem diameter and crown diameter. The availability of smartphones applications, drone-based high-resolution photography (Blaser et al 2018) and LIDAR technology can now be used to assess accurately, quickly, and cheaply (in the case of smartphone applications) the percent canopy cover. Adding information on tree leaf fall monthly or weekly patterns to snap-shot assessments of canopy cover can provide a meaningful description of the radiation regime in the understory.

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, provide valuable tree products (e.g. firewood and timber) and other ecosystem services (habitat, carbon sequestration, water regulation, etc.). Adding information on tree size (e.g. stem diameter frequency distribution) will greatly increase the goodness of density and basal area data to describe both shading conditions and tree stock yields.

The effects of crown diameter, tree height, spatial plating patterns, leaf fall patterns and alley orientation on shading

Annual shade averages for all 24 shade canopy typologies ranged between 28–44% (Table 3). The ANOVA indicated that with the exception of tree height, all other main effects (stem diameter, planting spatial pattern, and leaf fall) and their interactions were statistically different (Chi-square probabilities extremely low, in the order of 2.3×10^{-16} i.e. virtually zero). Results in Table 3 showed: 1) highest shade level averages in square, intermediate in random, and lowest in alleys, 2) more shade with many small-crowned trees than with fewer, bigger-crowned trees, and 3) less shade with than without leaf fall. As an example, differences in average and frequency distributions of shade-hours per grid cell per year between shade canopies with small-crowned or big-crowned trees is presented in Fig. 3. Pairwise comparisons of the levels and frequency distributions of shade between tall and short trees, yes or no leaf fall, square, random or alley spatial planting patterns are presented in supplementary material (S1_SupplementaryMaterial).

The lack of differences in shade levels between short and tall tree canopies is 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) is simulated (Fig. 4), the number of shade-hours per grid cell is significantly higher (one-way ANOVA, F test, $p < 0.0001$) for short trees (163 ± 117) than for tall trees (83 ± 45); their frequency distribution were also significantly different (Kolmogorov-Smirnov distance, $p < 0.0001$). This analysis suggests that the height of the canopy should be recorded when describing a canopy, but especially so when tree density is low, and the

canopy is largely discontinuous. Empirical evidence has shown that shade tree height influences the yield of cocoa plants in the understory (Asante et al 2021; Blaser et al 2018; Notaro et al 2020).

Annual shade averages mask the wide variations in monthly shade levels. For example, shade levels reach 100 hours per month (48% shade) when trees are in full foliage but drop to only 15 hours per month (7% shade) when 80% of tree foliage has been lost (Fig. 5). This Figure also shows that planting trees in alleys always resulted in the lowest shade levels whereas square planting always produced the highest shade levels. 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 (708 ± 104 hours-shade per year) than in East-West orientated alleys (681 ± 164) (Fig. 6).

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 disposition of the trees on the ground, 3) tree height, 4) crown diameter, 5) leaf morphological (e.g. leaf size and type) and physiological (e.g. leaf fall temporal patterns) traits, 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 be considered as well. 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 could assess when describing cocoa and coffee agroforestry systems is presented in S1-SupplementaryMaterial.

Defining cocoa agroforestry

Agroforestry is now widely promoted in cocoa cultivation around the world, particularly in West and Central Africa. But 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 programs to mainstream cocoa agroforestry. 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 few cases, of the vertical stratification of the shade canopy (<https://stories.mightyearth.org/voice-network-agroforestry-in-cocoa/index.html>). The frequency analysis of the use of shade tree density, canopy cover and basal area in the 373 scientific articles contained in the Smithsonian Institution bibliographic data base on cocoa agroforestry systems (https://www.zotero.org/groups/2785774/cocoa_library/library) showed that shade tree density is by far the most commonly used shade canopy density variable. This study demonstrated that tree density is clearly inappropriate as a SCDV because it has cross-compensation effects with tree size and stem diameter – crown diameter allometries that render current recommendations useless or even detrimental in terms of shading. For example, scoring agroforestry farming in terms of tree density

alone may lead to over shading if farmers choose to plant big-crowned trees to achieve certain percent canopy cover target. This is relevant because may it conflict with recommendations to increase the use of fertilizer to achieve higher cocoa yields (Asare et al 2017; van Vliet and Giller 2017). Basal area and percent shade canopy cover too have important limitations to properly describe the shading conditions in the understory of a cocoa agroforestry system. Evidently, a more nuanced analysis of the recommendations implicit in each cocoa agroforestry definition in use is warranted.

Conclusions

This study demonstrated that neither shade tree density (the most widely used shade canopy density variable) nor basal area provide direct evidence of the shading conditions in a cocoa plantation. Allometric relationships between tree stem diameter and crown diameters are necessary to link density and basal area with canopy cover, and hence with shading. Canopy cover is the only shade canopy density variable directly linked to shading. However, on its own, it provides a limited perspective of the shading conditions in cocoa and coffee agroforestry systems. Shade canopy cover, when complemented with information on leaf fall patterns can significantly increase its power to describe the shading conditions in the understory of the cocoa agroforestry system.

The results from this study are particularly relevant for open, discontinuous shade canopies. In fully closed canopies (100% canopy cover) the discriminant power of percent canopy cover, density, basal area, aboveground biomass, or carbon tend to be the same. In full canopy cover it will not matter whether trees are planted at random, in alleys or any other spatial arrangement, whether the canopy is at 10 m or 40 m above ground, or whether trees are big-crowned or small-crowned. In fully closed canopies, tree leaf fall patterns will be the only element of relevance in determining changes in shading conditions in the understory.

Simulations using a simple, mono-layered, single-species, even-sized canopy with constant basal area and canopy cover displayed significantly different level and spatiotemporal patterns of shading in the understory depending on tree planting spatial arrangements, leaf fall patterns, and tree size (crown diameter and tree height). Our results show that more shade is cast in square and random planting patterns than in alley planting, and if planted in alleys, 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. Fewer, bigger (large-crowned, taller) trees casted less shade than many small (narrow-crowned, short) ones.

Declarations

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Authors contributions

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

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Tables

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		
		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

Table 2. Density (N, trees ha⁻¹) and percent canopy cover (%C) for *Cordia alliodora* shade canopies as functions of shade tree basal area (G, m² ha⁻¹), stem diameter (d, cm), crown diameter (k, m), and the ratio between crown diameter and stem diameter (R, m/cm). In bold %C ≤ 50 %, a commonly reported range for both cocoa and coffee shade canopies.

R	k	G (m ² ha ⁻¹)										
		d	5		10		15		20		25	
			N	%C	N	%C	N	%C	N	%C	N	%C
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

Table 3. Average number of shade-hours per grid cell (1 m²) per year under different shade canopies of *Cordia alliodora*. Total number of simulation instants = 2555. Overlap of shadows from more than one tree are considered. Percent shading (shade averages divided by 2555, multiplied by 100, and rounded-off to the nearest integer) in parenthesis. Averages with different letters are statistically different.

Spatial pattern	Leaf fall	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

Figures

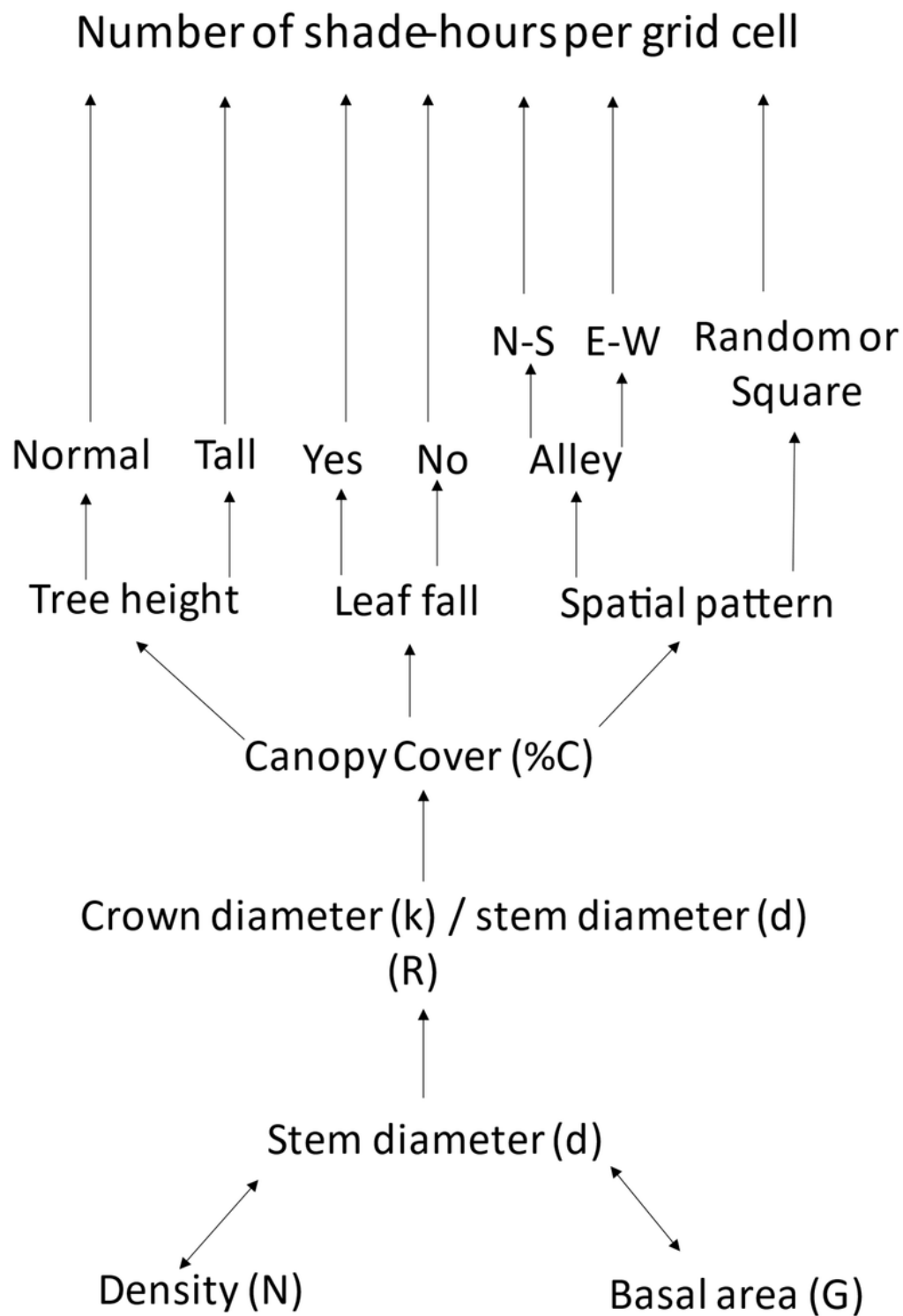


Figure 1

Relationships between shade canopy variables affecting the shading condition in the understory of cocoa and coffee agroforestry systems.

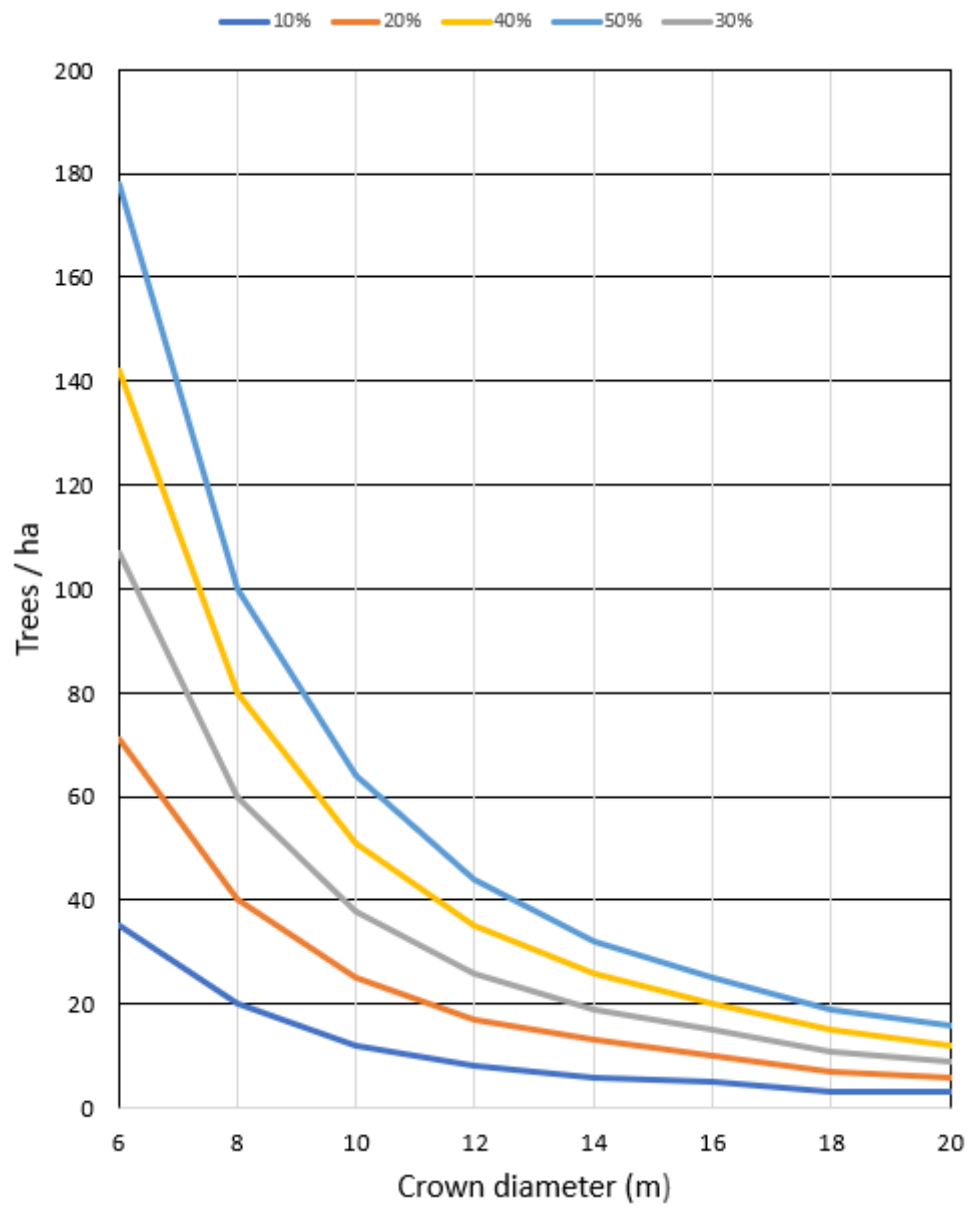


Figure 2

Break even lines between crown diameter and density (trees per hectare) for different target levels of shade canopy cover.

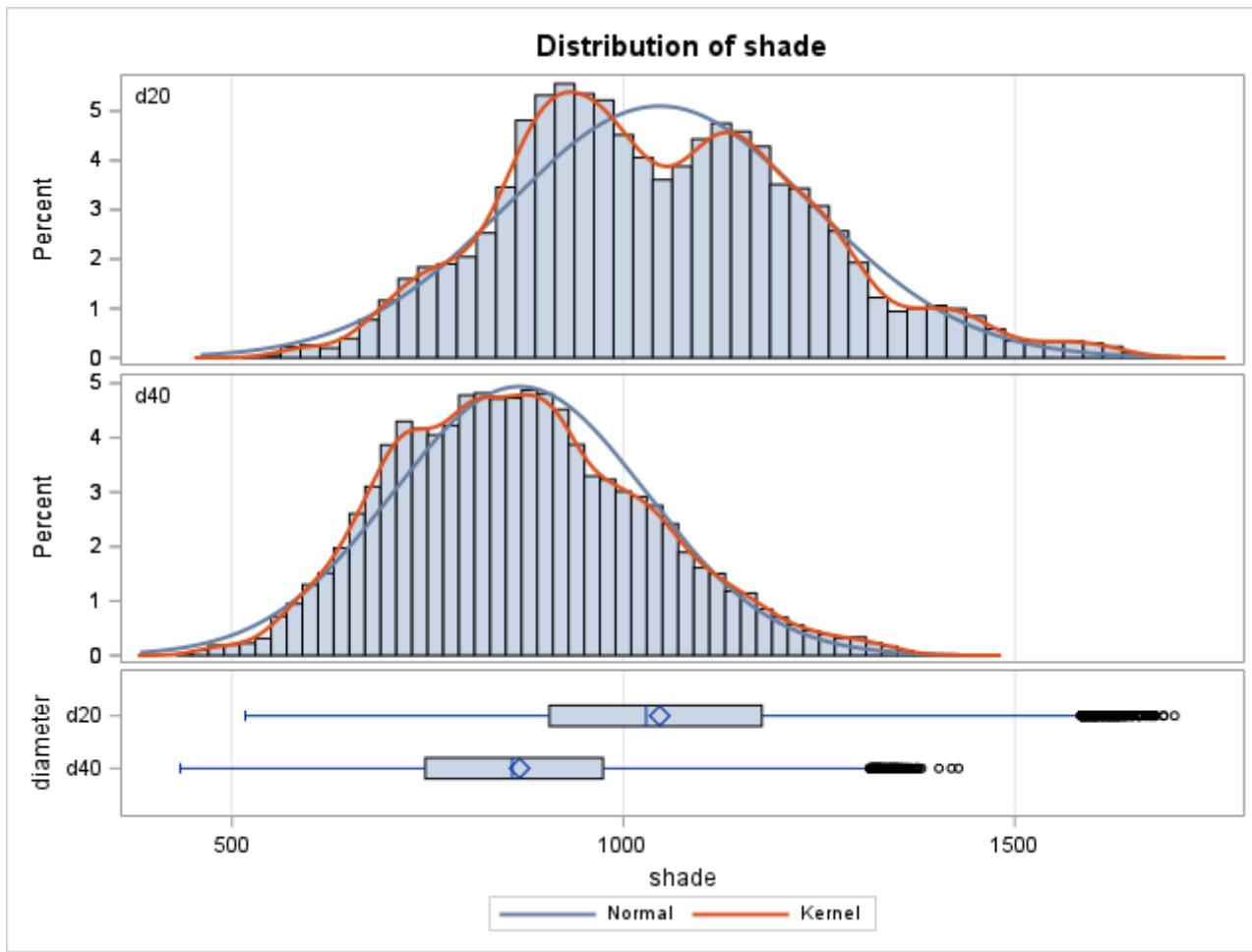


Figure 3

Level and frequency distribution of shade (number of shade-hours per grid cell per year) cast by shade canopies with small (stem diameter 20 cm, crown diameter 5 m) or big (stem diameter 40 cm, crown diameter 10 m) trees. Simple, even-sized, mono-layered, *Cordia alliodora* shade canopies with basal area, $G = 10 \text{ m}^2 \text{ ha}^{-1}$, percent canopy cover, $\%C = 31\%$, crown diameter (m) to stem diameter (cm) ratio, $R = 0.25$, and crown opacity, $p = 0.50$.

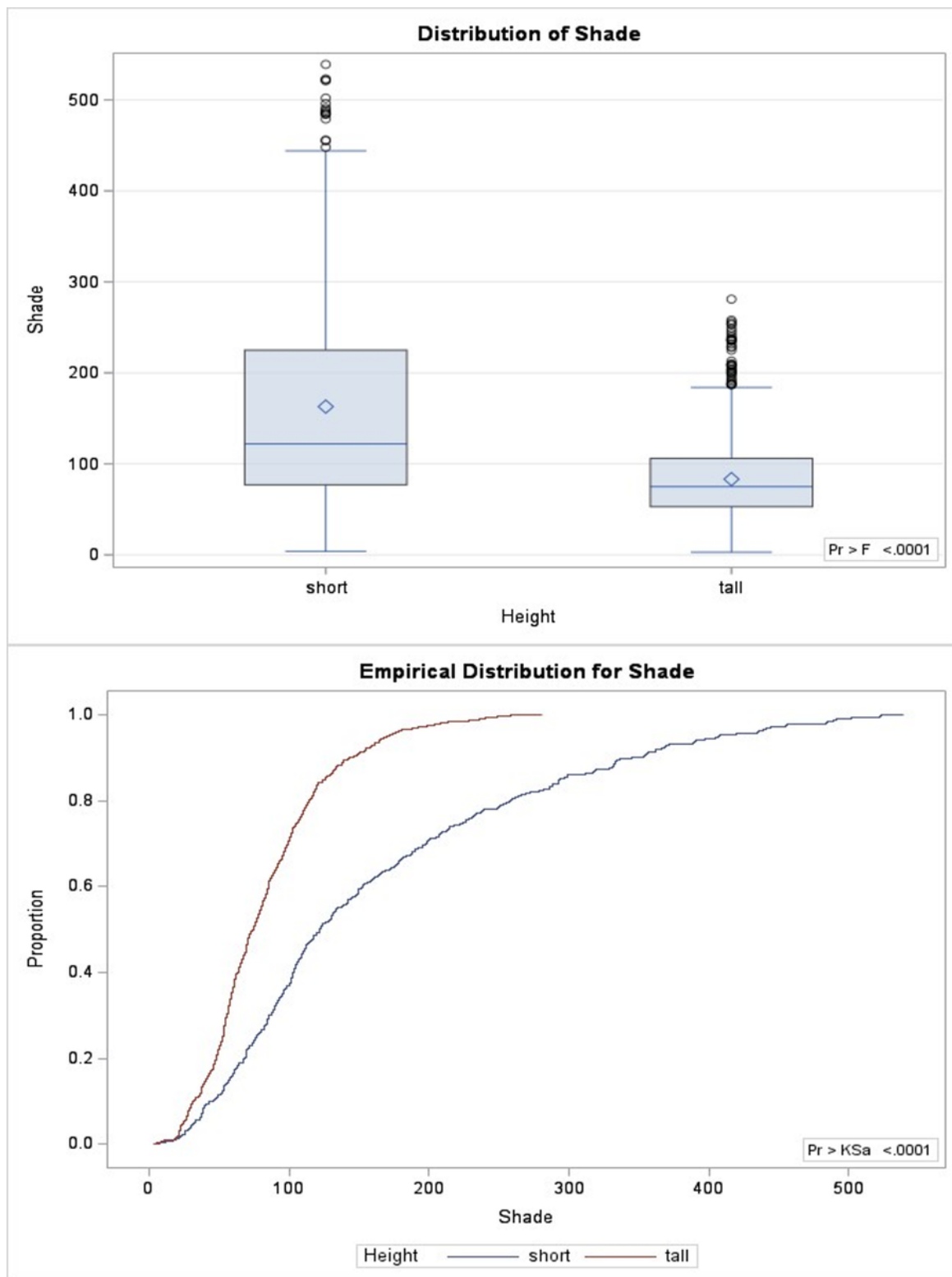


Figure 4

The effect of the position of the crown above the ground (trunk height) on the average and 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).

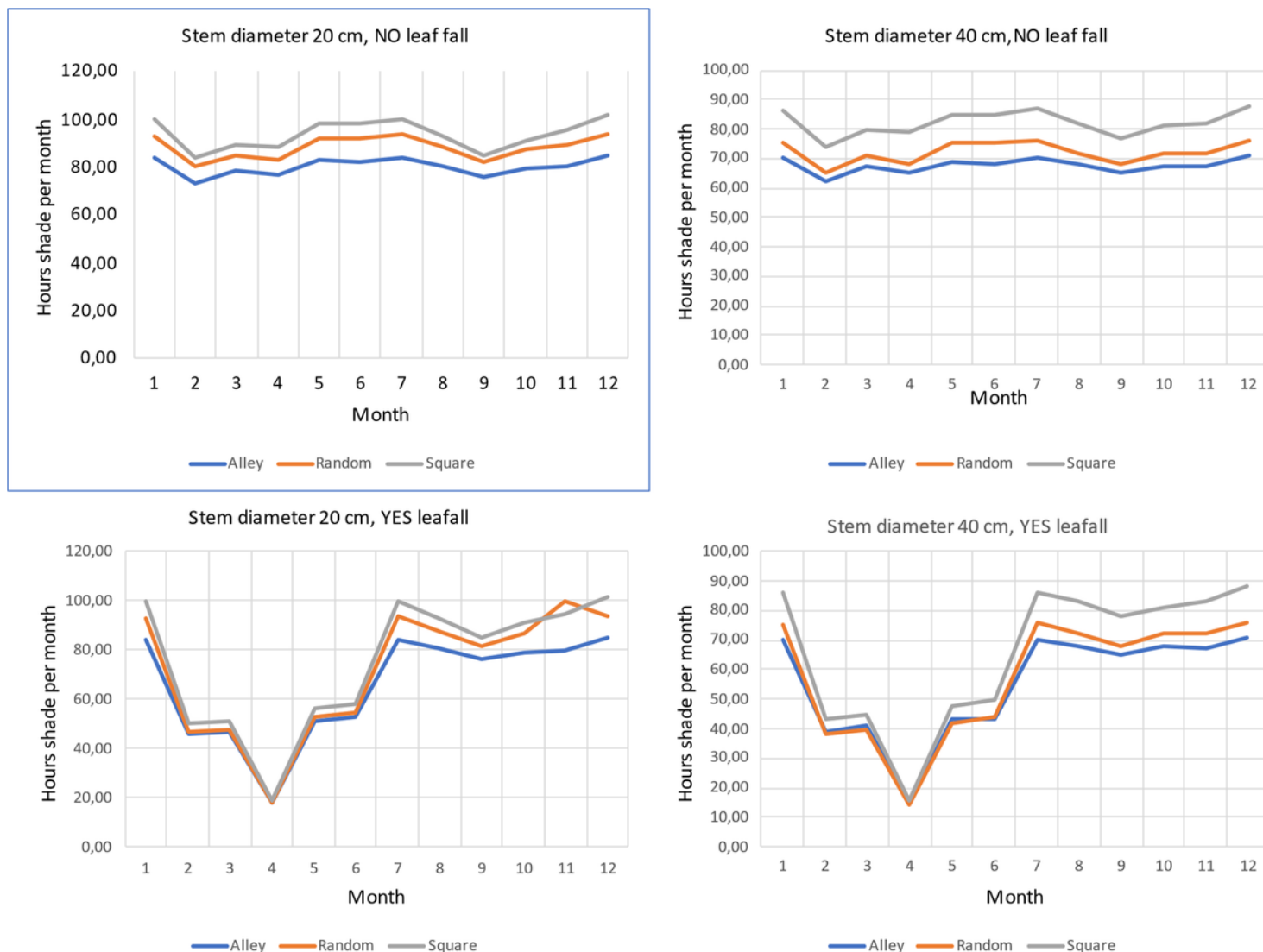


Figure 5

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

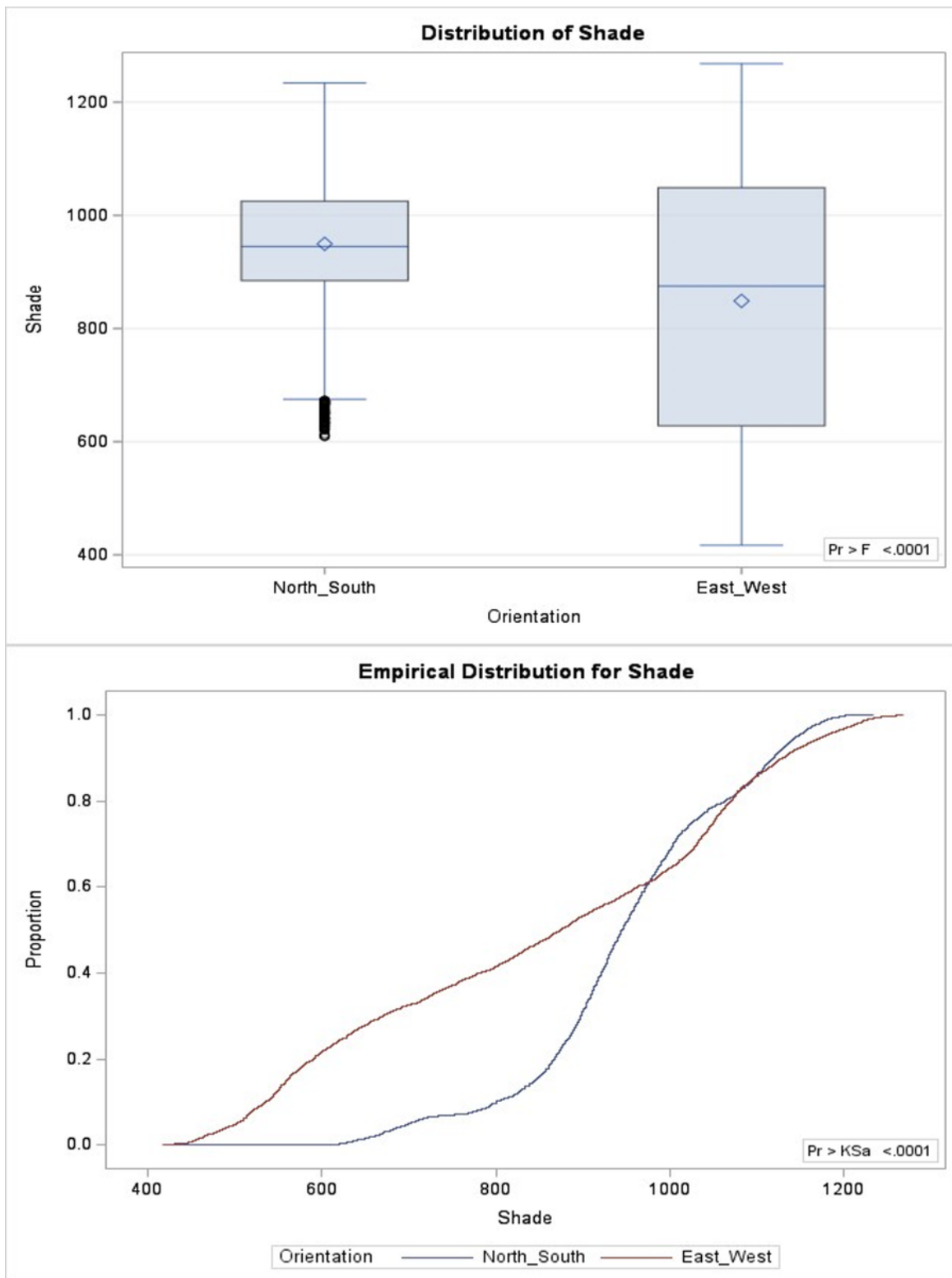


Figure 6

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, trunk tree height 19 m, crown height 8 m, 10 m crown diameter, with leaf fall, and planted in alleys (22.5 m x 5.6 m) with orientation North-South or East-West. with d = 40 cm, normal height and considering monthly leaf fall

Supplementary Files

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- [S1SupplementaryMaterial.pdf](#)