

Physiographic attributes affect cacao yield in renovated orchards in southern Bahia, Brazil

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Abstract: In southern Bahia, Brazil, cacao (*Theobroma cacao* L.) is cultivated in landscapes with diverse physiographic attributes which may influence yield. This study aimed to evaluate the relationship between physiographic attributes — terrain slope, slope orientation relative to the sun, transmittance of photosynthetically active radiation, and rainfall — and cacao yield from the 4th to 7th year of cultivation across 15 farm field trials in southern Bahia. These trials were conducted in renovated clonal orchards under different light conditions, ranging from full sun to agroforestry systems with varying levels of shading. The results indicated that rainfall accumulated from March of the previous year to February of the analyzed year had a significant positive correlation with cacao yield. Terrain slope and slope orientations facing west and south were negatively associated with productivity, while east-facing slopes had a positive influence. The most productive areas exhibited an average transmittance of photosynthetically active radiation of approximately 70% to 80%, suggesting that light shading can enhance the microclimate and favor cacao yield. These findings highlight the importance of topography and shade management, indicating that physiographic attributes should be considered in site selection for cacao orchard renovation to support the development of high-yielding orchards.

Index terms: Cacao Cabruca, Climate Resilient Crop, Shade Canopy Density, Topographic Relief, Cocoa Clones.

Atributos fisiográficos afetam a produtividade de cacau em lavouras renovadas no sul da Bahia, Brasil

Resumo: No sul da Bahia, Brasil, o cacaueiro (*Theobroma cacao* L.) é cultivado em paisagens com ampla variabilidade de atributos fisiográficos que podem influenciar a produtividade da cultura. Este estudo teve como objetivo avaliar a relação entre atributos fisiográficos — declividade, orientação das encostas em

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relação ao sol, transmitância da radiação fotossinteticamente ativa e precipitação pluvial — e a produtividade do cacauzeiro do 4º ao 7º ano de cultivo em 15 áreas experimentais instaladas em fazendas no sul da Bahia. A pesquisa foi conduzida em lavouras clonais renovadas e cultivadas sob diferentes condições de sombreamento, variando de pleno sol a sistemas agroflorestais com sombra rala a densa. Os resultados indicaram que a precipitação pluvial acumulada de março do ano anterior a fevereiro do ano analisado apresentou correlação positiva significativa com a produtividade do cacauzeiro. A declividade do terreno e as encostas voltadas para oeste e sul apresentaram correlação negativa com a produtividade, enquanto encostas voltadas para leste mostraram correlação positiva. As áreas mais produtivas apresentaram transmitância média de radiação fotossinteticamente ativa entre aproximadamente 70% e 80%, sugerindo que o sombreamento leve pode melhorar o microclima e favorecer a produtividade do cacauzeiro. Esses resultados destacam a importância do relevo e do manejo do sombreamento, indicando que a seleção de áreas para renovação de lavouras deve considerar atributos fisiográficos para garantir maiores produtividades.

Termos para indexação: Cacau Cabruca, Cultura Resiliente ao Clima, Densidade do Dossel, Relevo, Clones de Cacau.

Introduction

Cacao (*Theobroma cacao* L.) is a perennial tropical crop that exhibits shade tolerance (ARÉVALO-GARDINI et al., 2021) and sensitivity to both drought and waterlogging (CARR; LOCKWOOD, 2011; NIETHER et al., 2020). The characteristics of the growing environment significantly affect its physiological responses (HERNÁNDEZ-NUÑEZ et al., 2024; LAHIVE et al., 2019; SHIFLETT et al., 2025) which can, in turn, influence productivity and orchard longevity. Notably, physiographic attributes such as slope orientation have been associated with increased cacao tree mortality during droughts in southern Bahia (SOUZA JÚNIOR et al., 2023), yet their effects on productivity remain poorly understood.

Southern Bahia is Brazil's main cacao-producing region, covering approximately 400 thousand ha (IBGE, 2024). In this region, cacao is predominantly cultivated in the traditional cacao Cabruca agroforestry system, under thinned native Atlantic Rainforest trees, which play a crucial role in biodiversity

conservation. Additionally, cacao is grown in agroforestry systems alongside other crops such as banana (*Musa* spp.), açai palm tree (*Euterpe oleracea* Mart.), coconut (*Cocos nucifera* L.), rubber trees (*Hevea brasiliensis*), and timber species such as *Khaya ivoriensis*, as well in monoculture under full sunlight. Due to the advanced age of the cacao orchards and poor management, the average yield is low, at approximately 300 kg ha⁻¹ year⁻¹ (IBGE, 2024).

Renovating old orchards with high-yielding clonal cultivars is a recommended strategy to boost productivity. However, variability in physiographic attributes—such as topographic relief, shading, and rainfall—may influence productivity. Solar radiation is particularly relevant, as it is affected by shading and topographic relief (SOMARRIBA et al., 2022). Although numerous studies have examined the impact of shade on cacao production, the findings are notably varied (BENJAMIN et al., 2025; OROZCO-AGUILAR et al., 2024). There is no consensus on the optimal range of light

intensity, referred to as photosynthetically active radiation transmittance ($PAR_{t\%}$), for cultivating cacao clones in agroforestry systems.

In the context of rising global cacao demand and the intensification of adverse climatic events, particularly a reduction in water availability, research on the influence of physiographic attributes on crops can provide strategic insights to enhance crop yield and resilience to weather. This study aimed to evaluate the relationship between physiographic attributes and cacao yield in southern Bahia, with the goal of optimizing the selection of areas for the renovation of old orchards with high-yielding clonal cultivars.

Material and Methods

Study site and experimental design

The experiment was carried out from January 2019 to December 2022 across 15 farm field trials (FT) in 11 municipalities of southern Bahia, Brazil (13°11'35"–15°26'00" S, 39°06'36"–39°35'18" W). The region has a humid tropical climate (Köppen Af), with mean annual rainfall >1,500 mm, monthly rainfall >60 mm, and mean temperatures ranging from ~18 °C (coldest month) to ~24 °C (warmest month) (SANTOS FILHO et al., 2019). The FT had different levels of shading, from thinly shaded to densely shaded *Cabruca* agroforestry systems, and also included full-sun areas.

Three no-till renovation methods were applied: R1, grafting onto basal shoots of old cacao trees; R2, planting seedlings before removing old cacao trees; and R3, planting seedlings after removing old cacao trees. For R2 and R3, seedlings derived from open-pollinated seeds of clone TSH1188 were grafted in a nursery 60–90 days after

sowing, using side grafting above the cotyledon and below the first pair of leaves. For all renovation methods, plagiotropic branches of the five tested clonal cultivars (CCN51, CP49, FA13, PS1319, and SJ02) were used as grafting material (scions) and re-grafted if the initial graft failed. In R1 and R2, the removal of old cacao trees was carried out gradually over two years via successive pruning until complete suppression, whereas in R3 old cacao trees were removed prior to seedling planting.

Each FT comprised six experimental plots (three renovation methods × two replications) arranged within two blocks, totaling 90 plots in a randomized complete block design. Each plot contained 50 cacao trees, with 10 trees per clonal cultivar. Cacao yield was assessed using 25 cacao trees, five from each clonal cultivar.

Analysis of physiographic attributes

Analyses were conducted to explore the relationship between physiographic attributes—specifically, terrain slope, slope orientation relative to the sun (SORS), photosynthetically active radiation transmittance ($PAR_{t\%}$), and rainfall—and cacao productivity.

Rainfall

Monthly and annual rainfall data for each FT were estimated using the Inverse Distance Weighted (IDW) interpolation method, which is recommended for spatial interpolation of rainfall data (XAVIER et al., 2016). Data were obtained from the meteorological databases of the National Meteorological Institute (INMET), the State Environmental Institute (INEMA), the Executive Commission of the Cocoa Farming Plan (CEPLAC), and the Michelin Ecological Reserve. Weather stations locat-

ed near each FT were considered for interpolation. The interpolation was performed using QGIS software version 3.28.7 (QGIS Development Team, 2023).

Photosynthetically active radiation transmittance ($PAR_{t\%}$)

Incident photosynthetically active radiation (PAR_i) corresponds to the photosynthetically active radiation (PAR , $\mu\text{mol m}^{-2} \text{s}^{-1}$) transmitted through the shade tree canopy and reaching the upper layer of the cacao canopy. Measurements were conducted in the 15 FT between 25 March and 13 May 2022 using light radiation sensors (HOBO S-LIA-M003; Onset Computer Corp., Bourne, MA, USA) positioned randomly at a height of ~ 3.5 m. Measurements were taken between 11:00 and 13:00 h at 20 locations per experimental plot. A quantum sensor placed in full sun near each FT was used as a reference. The sensors were connected to data loggers (HOBO USB Micro Station H21-USB; Onset Computer Corp.) programmed to record data every 10 seconds. Photosynthetically active radiation transmittance ($PAR_{t\%}$) was estimated by dividing the PAR at each position (PAR_i , $\mu\text{mol m}^{-2} \text{s}^{-1}$) by the full sun PAR (PAR_{fs} , $\mu\text{mol m}^{-2} \text{s}^{-1}$) and multiplying by 100. The mean $PAR_{t\%}$ for each experimental plot was obtained from the average of the 20 measurement points, as shown in Equation 1.

$$PAR_{t\%} = \frac{\sum_{n=20}^c \left(\frac{PAR_i}{PAR_{fs}} * 100 \right)}{n}$$

Equation 1

in which:

$PAR_{t\%}$ = photosynthetically active radiation transmittance (%)

PAR_i = photosynthetically active radiation incident on cacao canopy within the experimental plot ($\mu\text{mol m}^{-2} \text{s}^{-1}$)

PAR_{fs} = photosynthetically active radiation in full sun ($\mu\text{mol m}^{-2} \text{s}^{-1}$)

Slope orientation relative to the sun (SORS)

Slope orientation relative to the sun (SORS) data was collected using a magnetic compass, with three readings taken per FT. The magnetic declination was estimated based on the World Magnetic Model (NOAA, 2022), and magnetic azimuths were converted to cartographic azimuths. SORS was calculated using the four cardinal points as a reference (N = 0° ; L = 90° ; S = 180° ; west = 270°), following the methodology of Souza Junior et al. (2023).

Terrain slope

Terrain slope data was obtained using a clinometer (ORIENT ABL2), with three measurements taken for each FT.

Calculating the relative yield of cacao beans

Relative yield ($Yield_{ry}$, %) was calculated to standardize yield performance across sites and harvest years. $Yield_{ry}$ was determined as the ratio between the average dry cacao bean yield ($Yield_{rcy}$, kg ha^{-1}) and the maximum yield ($Yield_{max_{rcy}}$, kg ha^{-1}) for clones within each renovation method (R1, R2, R3) and year (4th–7th). Thus, the highest annual yield for a given clone, method, and year was set to 100%, and the relative yield of all other plots was scaled accordingly. For each plot, relative yields were then averaged across the five clones, and finally a four-year mean relative yield was computed for each of the 90 experimental plots.

Statistical analysis

All analyses were conducted in R version 4.0.5 (R Core Team, 2021). Both descriptive and inferential statistical analyses through univariate and multivariate procedures. Descriptive statistics included measures of central tendency (mean, median) and dispersion (minimum, maximum, coefficient of variation).

Pearson’s linear correlation analysis was performed between average relative yield and physiographic attributes. Correlation coefficients were tested for significance at $p < 0.05$ using a t-test. Principal component analysis (PCA) was performed considering yield for each evaluated year (4th–7th).

The 90 experimental plots were grouped based on productivity similarity using hierarchical cluster analysis. Euclidean Distance matrices were generated and clusters were produced using Ward’s linkage method as the agglomerative criterion. Group means of physiographic attributes were compared using Tukey’s HSD test ($p < 0.05$).

Results and Discussion

Relative yield ($Yield_{ry}$), photosynthetically active radiation transmittance ($PAR_{t\%}$), terrain slope, and slope orientation relative to the sun (SORS) showed significant variability (Table 1), highlighting the heterogeneity of the cocoa production systems in southern Bahia. The mean $PAR_{t\%}$ was 72%, with an average incident radiation level of $1,429 \mu mol\ m^{-2}\ s^{-1}$ in the experimental plots (PAR_i) and $1,983 \mu mol\ m^{-2}\ s^{-1}$ in full sun (PAR_{fs}). The physiographic attributes had mean values close to their medians, suggesting that the mean is a suitable measure of central tendency.

Table 1. Descriptive statistics of the physiographic attributes for 15 farm field trials (FT) in rehabilitated cacao orchards in southern Bahia, Brazil, from the 4th to the 7th year (2019–2022) following the establishment of the experiment.

Physiographic attributes		Minimum	Maximum	Mean	Median	CV%
Yield (%)	Year 4th	2	100	30	27	75
	Year 5th	8	100	44	43	48
	Year 6th	20	100	58	54	58
	Year 7th	20	100	57	55	32
$PAR_{t\%}$, %		25	100	72	77	28
Terrain slope, %		3	45	20	18	74
SORS	North face, %	0	98	14	0	171
	South face, %	0	94	32	28	102
	East face, %	0	91	30	0	122
	West face, %	0	77	24	6	122

Physiographic attributes: $PAR_{t\%}$, photosynthetically active radiation transmittance; SORS, slope orientation relative to the sun.

Rainfall was relatively well distributed but increased from 2020 to 2022 (Figure 1), coinciding with the La Niña Southern Oscillation (LNSO) events. LNSO events typically enhance rainfall in Northeast Brazil and reduce crop yield losses, whereas El Niño Southern Oscillation (ENSO) events are associated with drought-induced declines in cacao productivity (GATEAU-REY et al., 2018).

Pearson’s linear correlation analysis

(Table 2) indicated that rainfall accumulated from March of the previous year to February of the harvest year was associated with cacao yield ($r = 0.26$; $p < 0.05$). Although the correlation coefficient was low, the relationship was statistically significant. Overall, rainfall in one year is a key determinant of yield in the subsequent year and can therefore serve as a reliable indicator for predicting cacao harvests (WILSON et al., 2019). However, this

relationship is particularly stronger with the vegetative growth phase, especially with regard to the main flush (September-October), which is critical for photo-as-

simulates production in the following-crop year. Additionally, rainfall influences yield by affecting both flowering and number of pods (ADET et al., 2024).

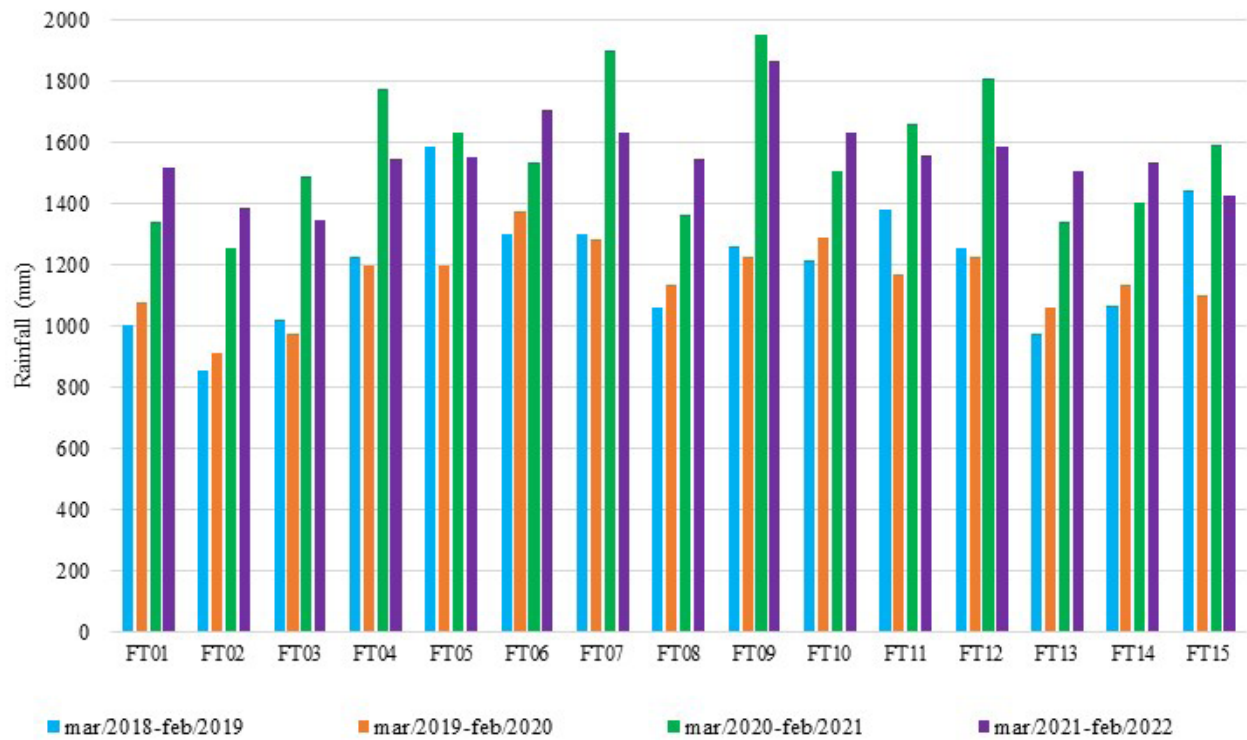


Figure 1. Estimated rainfall across the 15 farm field trials (FT) from 2018 to 2022. Source: Generated based on the methodology detailed in the text.

Table 2. Correlation between relative yield of cacao beans and physiographic attributes across 15 farm field trials (FT) from the 4th to the 7th year (2019–2022) following the establishment of the experiment.

Year	Annual rainfall (mar-feb)	Terrain slope	Slope orientation relative to the sun (SORS)				PAR _{t%}
			North face	South face	East face	West face	
4th	0.26*	-0.37*	0.02	-0.20	0.40*	-0.28	0.13
5th		-0.28	0.17	-0.17	0.07	-0.05	0.16
6th		-0.29	0.07	0.02	0.10	-0.21	0.36
7th		-0.27	0.24	-0.21	0.21	-0.22	0.25

Variables: Annual rainfall between March and February; slope orientation relative to the sun (SORS) - north, south, east, west faces; photosynthetically active radiation transmittance (PAR_{t%}). * indicates significance by Pearson's correlation (p<0.05).

Yield in the 4th year (2019) showed a significant negative correlation with terrain slope ($r = -0.37$, $p < 0.05$) and a positive correlation with east-facing slopes ($r = 0.40$, $p < 0.05$), while west-facing slopes correlated negatively ($r = -0.28$, $p < 0.05$). These trends

were corroborated by principal component analysis (PCA, Figure. 2), which highlighted the positive association between yield and east-facing slopes and the negative relationship with slope steepness and west-facing orientations.

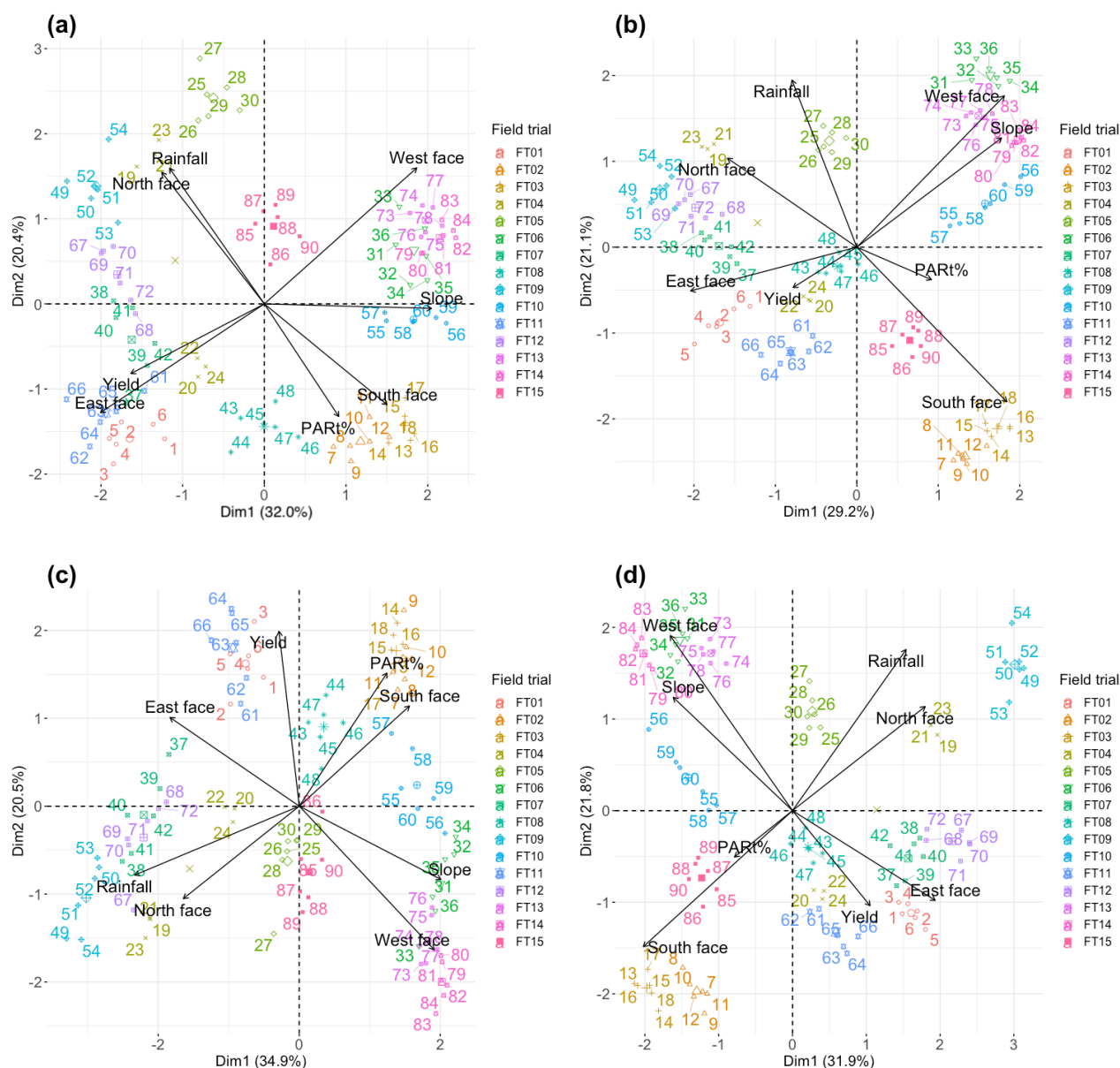


Figure 2. Graphical dispersion (biplot) produced by principal component analysis (PCA) of physiographic attributes and cacao bean yield from 15 farm field trials (FT) during the (a) 4th, (b) 5th, (c) 6th, and (d) 7th years following the establishment of the experiment (2019 to 2022).

Variables: Relative yield of cacao beans from the 4th to the 7th year (Yield); physiographic attributes including photosynthetically active radiation transmittance (PAR_%), terrain slope (Slope), annual rainfall (Rainfall), and slope orientation relative to the sun (SORS)—North face, South face, East face, and West face.

Relief attributes such as slope and SORS affect both radiation and water availability. Steeper slopes reduce water infiltration and, depending on orientation, may increase evaporation (OORTHUIS et al., 2021). Research on the impact of relief on crop yields is prevalent in the Northern Hemisphere, where south-facing slopes receive more intense solar radiation throughout the year, resulting in higher tempera-

tures and evaporation rates compared to north-facing slopes (FAN et al., 2020; OORTHUIS et al., 2021). In contrast, in the Southern Hemisphere, where this study is located, north-facing slopes receive greater solar input, which may benefit productivity when water is not limiting (RODY et al., 2016). However, these slopes are also more prone to water stress during dry spells, explaining their association with higher cacao

mortality during droughts (SOUZA JÚNIOR et al., 2023). Hence, slope orientation is a relevant factor in site selection for cacao cultivation, particularly under variable rainfall regimes.

The hierarchical cluster analysis divided the 90 experimental plots into four distinct groups based on cacao relative yield, using data from the 4th to 7th year (Figure 3). The groups were defined as follows: Group 1 (G1), blue, high productivity; Group 2 (G2), green, medium-high productivity; Group 3 (G3), yellow, medium-low productivity; and Group 4 (G4), red, low productivity. G1 consisted of 12 experimental plots (mean yield = 74%, equivalent to 2,758 kg ha⁻¹); G2 included 26 plots (mean yield = 58%, 1,878 kg ha⁻¹); G3 comprised 37 plots (mean yield = 37%, 1,557 kg ha⁻¹); and G4 contained 15 plots (mean yield = 17%, 792 kg ha⁻¹).

Tukey's test confirmed significant differences ($p < 0.05$) among the groups for physiographic attributes such as slope, SORS, and $PAR_{t\%}$ (Table 3), directly linking these variables to yield. This finding reinforces the PCA results (Figure 2). Group 1 (G1) had a significantly lower mean slope and a higher frequency of east-facing slopes (50.6%) compared to Group 4 (G4, 18.1%). Notably, G4 had no north-facing slopes, and its average slope was the steepest (24.5%), underscoring the adverse impact of these conditions for cacao productivity. The more productive groups (G1 = 80.5%, G2 = 76.5%, and G3 = 72.3%) had significantly higher $PAR_{t\%}$ than G4 (54.3%). While G1 and G4 received similar annual rainfall, Group 2 (G2) experienced lower rainfall in three of the four years analyzed, suggesting that favorable relief attributes and radiation conditions can partly offset suboptimal rainfall.

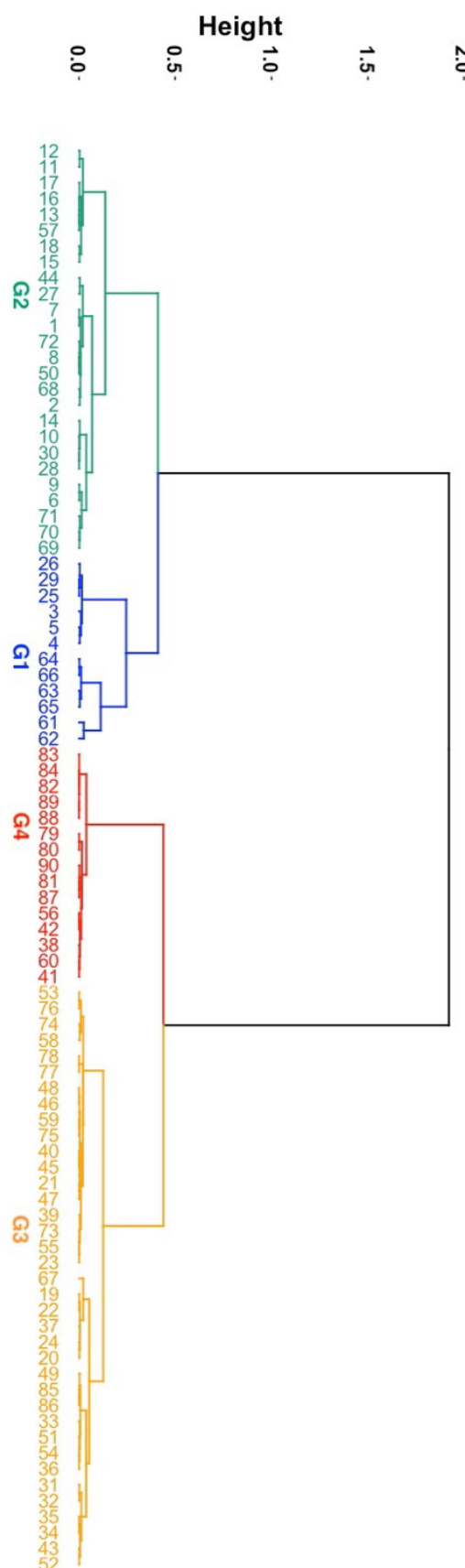


Figure 3. Dendrogram illustrating the hierarchical cluster analysis of cacao bean relative yield from 90 experimental plots over four years (4th to 7th year, 2019 to 2022) following the establishment of the experiment.

The analysis is based on Euclidean distance and Ward's agglomerative method, resulting in the formation of four groups: Group 1 (G1), in blue, high productivity; Group 2 (G2), in green, medium-high productivity; Group 3 (G3), in yellow, medium-low productivity; and Group 4 (G4), in red, low productivity.

The high proportion of south-facing slopes (45%) and steep terrain in G4 likely contributed to its poor performance, as these conditions limit solar radiation availability for crops in the Southern Hemisphere. Generally, there is a negative correlation between terrain slope and solar radiation availability, with this effect being even more pronounced in south-facing landscapes in the Southern Hemisphere (RODY et al., 2016). In the absence of drought events during the study period, the unfavorable topographic conditions in G4 likely contributed to its reduced productivity relative to Group 1 (G1), which had a lower proportion of south-facing slopes (20.2%) and a milder mean terrain slope (7.3%).

The high productivity group (G1) was predominantly composed of east-facing slopes (50.6%), and the PCA supports the positive correlation between yield and SORS (Fig. 2). East-facing slopes receive more solar radiation in the morning, while west-facing slopes are characterized by increased solar exposure in the afternoon. In the morning, cacao leaves typically exhibit higher water potential due to overnight rehydration, lower vapor pressure deficit (VPD), and reduced evapotranspiration rates. In contrast, the afternoon brings rising temperatures and increased VPD, leading to decreased stomatal conductance and photosynthetic rates (ACHEAMPONG et al., 2013; GATTWARD; ALMEIDA, 2018). Studies in vineyards indicate that the western portion of the fields is more prone to damage from higher afternoon temperatures, potentially altering fruit composition and quality (STRACK et al., 2021; WEBB et al., 2010). These mechanisms likely partly explain the yield differences observed among slope orientations in this study.

Table 3. Grouping of experimental plots based on cacao bean relative yield from the 4th to the 7th year (2019 to 2022) following the establishment of the experiment, along with Tukey's test of means for physiographic attributes of the growing environments.

Group	Yield (%)	SORS (%)				Terrain slope (%)	PAR _{t%} (%)	Annual rainfall (mm)			
		North face	South face	East face	West face			mar/18 - feb/19	mar/19 - feb/20	mar/20 - feb/21	mar/21 - feb/22
G1	74	11.1ab	20.2a	50.6a	18.1a	7.3b	80.5a	1,339a	1,154ab	1,573a	1,547ab
G2	58	14.8ab	44.3a	26.6ab	14.5a	16.6ab	76.5a	1,109b	1,073b	1,510a	1,484b
G3	37	21.1a	21.8a	29.8ab	27.3a	24.3a	72.3a	1,198ab	1,209a	1,614a	1,618a
G4	17	0.00b	45.0a	18.1b	36.9a	24.5a	54.3b	1,233ab	1,176a	1,568a	1,540ab

Variables: Cacao bean relative yield from the 4th to the 7th year (Yield); physiographic attributes: slope orientation relative to the sun (SORS), photosynthetically active radiation transmittance (PAR_{t%}). Experimental plots (n = 90) were grouped based on cacao bean relative yield from the 4th to the 7th year (2019 to 2022) using Ward's method and Euclidean distance: Group 1 (G1), high productivity; Group 2 (G2), medium-high productivity; Group 3 (G3), medium-low productivity; Group 4 (G4), low productivity. Different lowercase letters denote significant differences between means of the attributes in each group, as determined by Tukey's test (p<0.05).

Although shade trees can mitigate cacao vulnerability in regions prone to water deficits, high temperatures, and strong winds (ALVIM, 1977; HEMING et al., 2022), this study indicates that heavy shading com-

promises cacao yields due to low photosynthetically active radiation transmittance (PAR_{t%}). The most productive experimental plots (G1) exhibited an average PAR_{t%} of 80.5%, significantly higher than the 54.3%

average of the least productive units (G4) (Table 3). The intermediate groups (G2 and G3) also demonstrated $PAR_{t\%}$ values exceeding 70% (G2: 76.5% and G3: 72.3%).

A study conducted under semi-arid and sub-tropical conditions in Bahia, Brazil, found that moderate shading of approximately 30% optimizes production while reducing water requirements, aligning with the findings of this research (WALDBURGER et al., 2019). Additionally, Blaser et al. (2018) recommend that shade levels in cacao agroforestry systems should not exceed 30%, which corresponds to a PAR threshold surpassing 70%. Earlier studies conducted in Ghana demonstrated a positive linear relationship between cocoa productivity and $PAR_{t\%}$ within the range of 30% to 60%, while a quadratic relationship persisted up to 100% $PAR_{t\%}$ (VERNON, 1967). Our findings reinforce that light shading, ensuring $PAR_{t\%}$ between 70–80%, can enhance cacao productivity.

Understanding optimal shade-tree density and species composition is crucial to minimize competition for water, nutrients, and light (ABDULAI et al., 2025; KOHL; NIETHER, 2024). In dry years, excessive shading can lead to increased mortality of cacao trees due to water competition between cacao and shade trees (SOUZA JÚNIOR et al., 2023). Although N_2 -fixing legume shade trees enhance soil nitrogen availability, certain species may compete with cacao depending on site conditions (BLASER et al., 2017; WARTENBERG et al., 2020).

Accordingly, effective shade management is crucial to balance microclimate benefits and resource competition, particularly under increasingly variable rainfall regimes expected with climate change. At the same time, because cacao agroforestry systems underpin biodiversity conservation and carbon storage (DEKEGEL et al., 2025; FARIA et al., 2025),

shade management must adhere to Brazilian law and align production goals with ecological requirements. Taken together, our results indicate that site selection for cacao renovation should incorporate physiographic attributes to secure higher yields.

Conclusions

This study showed that physiographic attributes, particularly slope orientation relative to the sun (SORS) and photosynthetically active radiation transmittance ($PAR_{t\%}$), significantly influence cacao productivity. By demonstrating how terrain features and shade trees modulate the availability and distribution of solar radiation throughout the day, the research establishes a direct link between these attributes and yield variation. The findings support the conclusion that site-specific terrain and radiation management are critical for optimizing the performance of cacao agroforestry systems. Therefore, incorporating physiographic criteria into planting site selection and shade management decisions can substantially improve the outcomes of cacao renovation initiatives.

Acknowledgments

We would like to express our gratitude to the farmers who hosted the field trials and to all the personnel involved in the Renova Cacau Project.

Funding

This work was supported by the Mondelez International, Cocoa Innovation Center (CIC) and State University of Santa Cruz (UESC), based on agreement RD-18216.

Data Availability: The data that support the findings of this study are available from the corresponding author, Porto, B.H.C., upon reasonable request.

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