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Effect of the altitudinal gradient on the initial development of cocoa (*Theobroma cacao* L.) in Jarabacoa, Dominican Republic

Efecto del gradiente altitudinal sobre el desarrollo inicial de cacao (*Theobroma cacao* L.) en Jarabacoa, República Dominicana

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ABSTRACT

The changes in temperature and reception regimes caused by climate change have resulted in the displacement of production areas, both coffee and cocoa, to areas with more favorable conditions for their development. The objective of this study was to evaluate the adaptation of cocoa cultivation at different altitude levels in the municipality of Jarabacoa, province of La Vega, Dominican Republic, for which its survival and initial development was analyzed in areas where the crop has been degraded of coffee. To meet the stated objectives, different experimental units are established based on a factorial arrangement under a completely random design, with two types of cocoa plants, injector and hybrid, in three altitudinal ranges of the basin. In each sample unit, aerial growth, health condition and survival of the plants were evaluated. It is concluded that altitude significantly affected the morphological variables total height, neck diameter, productivity index, as well as survival. In general, aerial plant growth decreased as altitude above sea level increased, regardless of the type of plant used. The highest survival rates occur in the RA1 and RA3 altitudinal ranges, without distinction of the origin of the plant. The results of this research constitute a contribution to the knowledge of cocoa production, an economically significant crop in the Dominican Republic and worldwide.

KEY WORDS: Cocoa growth, altitude, crop adaptation.

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RESUMEN

Los cambios de temperatura y regímenes de precipitación causados por el cambio climático han traído como consecuencia el desplazamiento de las áreas de producción, tanto de café, como de cacao, a zonas con condiciones más favorables para su desarrollo. El presente estudio tuvo como objetivo evaluar la adaptación del cultivo de cacao en diferentes niveles de altitud en el municipio de Jarabacoa, provincia de La Vega, República Dominicana, para lo cual se analizó su sobrevivencia y desarrollo inicial en áreas donde se ha degradado el cultivo de café. Para cumplir con los objetivos planteados se establecieron diferentes unidades experimentales basadas en un arreglo factorial bajo un diseño completamente aleatorio, con dos tipos de plantas de cacao, injerto e híbrido, en tres rangos altitudinales de la cuenca. En cada unidad muestral se evaluó el crecimiento aéreo, condición sanitaria y sobrevivencia de las plantas. Se concluye que la altitud afectó significativamente las variables morfológicas altura total, diámetro de cuello, índice de productividad, así como también la sobrevivencia. En general, el crecimiento aéreo de la planta fue disminuyendo a medida que aumentaba la altitud sobre el nivel del mar, sin importar el tipo de planta utilizada. Las mayores tasas de sobrevivencia se presentaron en los rangos altitudinales RA1 y RA3, sin distinción del origen de la planta Los resultados de la presente investigación constituyen un aporte al conocimiento de la producción de cacao, cultivo económicamente significativo en la República Dominicana y a nivel mundial.

PALABRA CLAVE: Crecimiento de cacao, altitud, adaptación de cultivos.

Introduction

Climate change is causing glaciers to melt, leading to shifts in the seasonal distribution of water flows, drought event intensification, and crop season changes (IPCC, 2014). One of the most vulnerable sectors to climate change worldwide is agriculture, as it is susceptible to variations in temperature and precipitation patterns (Viguera *et al*., 2017). Rising temperatures and reduced rainfall are expected to decrease agricultural productivity in the short term (2030), threatening food security for the most impoverished populations (FAO, 2014).

One of the most affected agricultural production systems by climatic variations is cocoa (*Theobroma cocoa* L.), with decreasement in yield (Harvey *et al*., 2018; Sada *et al*., 2018; PNUD, 2021), alterations in physiological and reproductive variables (Gourdji *et al*., 2013; Nendel *et al*., 2019), increased pest infestations, weed proliferation, and higher diseases incidence, in addition to a reduction in harvest quality (D'Agostino & Schlenker, 2016; Lachaud *et al*., 2017). These climatic pressures on cocoa cultivation and producers drove the migration of cultivated areas toward higher altitudinal gradients in search of more favorable climates, soils, and water availability (Aguirre, 2013; Bakri *et al*., 2018; Ziska *et al*., 2018), ensuring optimal conditions for crop development as well as sustainable and profitable production (Gram *et al*., 2018).

Regarding cocoa cultivation in the Central American Integration System (SICA) countries, stakeholders in the cocoa subsector classify this activity as highly vulnerable and having low adaptive capacity (Bunn *et al*., 2019a; SICA, 2021). In practice, this has led to the relocation of cocoa plantations to areas with more favorable conditions for its development (Meza, 2015), with production shifting to increasingly higher altitudes to enhance productivity (Núñez-Rodríguez *et al*., 2020). Analyses suggest an urgent need to transition from current farming practices to those adapted to the regional climatic characteristics, known as Climate-Smart Cocoa (CSC) cultivation (Bunn *et al*., 2019b).

In the Dominican Republic, approximately 175,875 hectares of cocoa are cultivated across seven regions of the country, making it the ninth-largest producer in the world, the second-largest in organic production, and the sixth-largest producer of fine and aromatic cocoa (Hinojosa, 2022). The cocoa value chain faces significant challenges in key areas related to productivity, quality, climate change adaptation, phytoprotection, domestic consumption, competitiveness, gender equity, generational renewal, and life quality improvement for cocoa-producing families (MMARN, 2022).

Regarding the impact of climate change on cocoa production, Bunn *et al*. (2019a) indicate that the Dominican Republic is expected to expand areas suitable for cocoa cultivation. As a result, adaptation efforts of the country will be largely incremental, although systemic adaptation or a transition to alternative crops may be necessary in some northwestern regions. Additionally, the authors highlight that the Dominican Republic is the only country in Central America and the Caribbean projected to experience an increase in suitable cocoa-growing areas between 2020 and 2049. This contrasts with the significant decline in suitable cultivation areas observed in other Central American Integration System (SICA) countries during the same period.

Given this background, the primary objective of this study was to assess cocoa cultivation adaptation at three different altitude levels in the Jarabacoa municipality, La Vega province, Dominican Republic. Specifically, the study evaluated cocoa crop survival, early-stage development, and plant health in areas of Jarabacoa where coffee (*Coffea arabica* L.) cultivation has declined, exploring cocoa as an agroforestry adaptation strategy to climate change.

Material and Methods

Study area

The study area corresponds to the Jarabacoa municipality, located in La Vega province, primarily in the upper region of the Yaque del Norte River Basin (CAYN), Dominican Republic (Figure 1). The climate is tropical, with an average annual temperature of 21.4 °C and an

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average annual precipitation of 1,502 mm. Elevations range from 400 to 2,200 masl. Soils are primarily derived from igneous materials and basalts (Milla *et al*., 2014). CAYN is situated on the northern slope of the Cordillera Central in the Dominican Republic (coordinates: 18º 55’ N, 70º 50’ W) and spans a total area of 77,846 hectares, divided into 13 land-use categories. Six of them correspond to forested areas, covering a total of 43,025 hectares, which represents 55.3 % of the basin’s total area. Agricultural land-use accounts for 22,328 hectares or 28.7 % of the total area. Approximately 70 % of the total surface area falls within the geographical boundaries of the Jarabacoa municipality (Acosta, 2017). This region has historically been used for coffee plantations, which have deteriorated due to factors associated with global warming and climate change (MARENA, 2012).

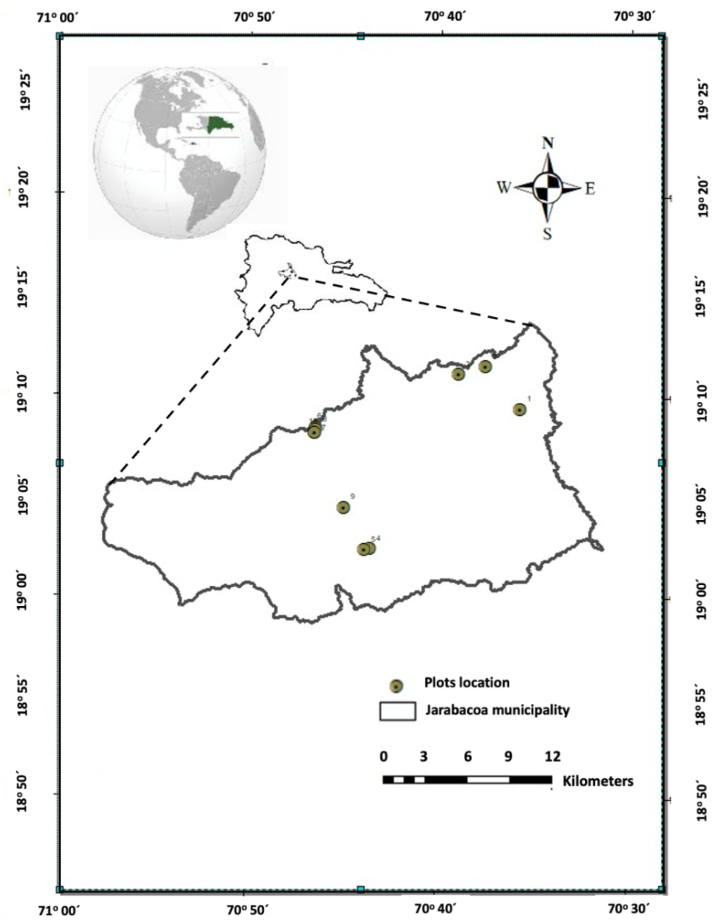

Figure 1. Location of the study area and distribution of sampling units across different altitudinal ranges in Jarabacoa municipality, Dominican Republic.

Selection and characterization of plot installation areas

Within the selected area (characterized by degraded coffee plantations), three sites were identified for establishing experimental units (plots), each differing in elevation by approximately 250 meters (Altitudinal Ranges). At each site, adjacent cocoa plots were established, consisting of hybrid plants used as controls and plots with grafted plants. Before planting, manual weeding was carried out in the immediate plant influence area, and organic bokashi fertilizer was applied following the recommendations of Arvelo *et al*. (2017).

Characteristics of the study sites

The altitudinal extremes where the experimental units were established range from the coffee-producing areas of Buena Vista (520 masl) to Manabao (1,158 masl) in the upper Yaque del Norte River Basin (Table 1).

The soils in the RA1 altitudinal range correspond to low hills with gentle slopes, developed from coarse-grained intrusive igneous rocks, with good surface and internal drainage, originating from tuffaceous materials, and primarily consisting of a brown sandy loam horizon (FAO, 2003). The soils in the RA2 altitudinal range have formed from highly alternating igneous and metamorphic rocks, mainly tuffs and schists, resulting in moderately deep soils. The first horizon has a thickness of 20 to 25 cm, with colors varying from light grayish-brown to dark brown, a clayey to clay loam texture, a subangular blocky structure (medium and weak), and a friable consistency when wet. Soils in the RA3 altitudinal range are found at the highest elevations of the landscape and originate from intrusive igneous rocks, primarily tonalite with trachyandesite intrusions, forming moderately developed soils. The first horizon is 16 cm thick, reddish-brown in color, with a granular and weak structure, and a friable consistency when wet (IDIAF, 2010).

Across the entire study area, land slope values ranged from 16 ° to 41 °. As elevation increased, temperature decreased, and cumulative mean precipitation increased (Table 1).

Table 1. Average values of altitude, slope, temperature, and precipitation by Altitudinal Range in the study area.

Altitudinal Range (RA) (masl)	Average altitude (masl)	Average slope (º)	Average temperature measurement period (ºC)	Accumulated average annual precipitation measurement period (mm)
RA1: 520 - 605	560 ± 35	20.0 ± 4.3	23.1	990.1
RA2: 822 – 850	840 ± 11	25.5 ± 9.2	21.6	1260.8
RA3: 954 - 1158	1085 ± 93	22.0 ± 4.9	20.0	1350.5

Experimental design

The study was based on a factorial arrangement under a completely randomized design. The factors under study were: Altitudinal condition (3 levels) and Plant type (2 types), defining a 3 × 2 experiment (six treatments in total).

Three plots (replicates) of each cultivar (grafted and hybrid) were established in Altitudinal Range 1 (RA1: 520–605 masl), 4 in Altitudinal Range 2 (RA2: 822–850 masl), and 3 in Altitudinal Range 3 (RA3: 954–1158 masl), resulting in a total of 20 experimental units (plots) across the study area.

Planting density for each plant type was determined following the recommendations of Enríquez (2010), CATIE (2012), and Díaz *et al*. (2013). Each grafted cocoa plot (700 m^2) consisted of 76 plants (3 × 3 m), totaling 760 plants across the 10 experimental units. For hybrid cocoa, each plot (625 m^2) contained 100 plants (2.5 × 2.5 m), totaling 1,000 plants across the 10 experimental units.

Data of the experimental unit, geographic coordinates, altitude, and slope were recorded using a Garmin 64s GPS. Temperature and precipitation records for the measurement period (2022–2023) were obtained from the Meteoblue meteorological site (Windy.com Company).

Evaluation of cocoa plant development

For the evaluations related to the adaptation and development of the plants, two measurements were taken, 11 months apart (May 2022 and April 2023), of the following variables: total height in cm, from the root collar of the plant to the branch at the highest height from the ground (with a 1 mm precision tape measure), root collar diameter (Dac) in mm (with a INGCO HDCD01150 digital caliper with a precision of 0.01 mm), number of branches and leaves of each plant, and phytosanitary evaluations were also carried out according to visual inspection. Based on the height and neck diameter of the plant, its d^2h productivity index in cm^3 (biomass indicator) was determined, in addition to the survival in each experimental unit.

Statistical analysis

The effect of each factor under study, as well as the interaction between their levels, was analyzed using an analysis of variance (ANOVA) based on the experimental design. Percentage-based variables were transformed using the expression:

$$y^* = \sin^{-1}\sqrt{0/1}.$$

If significant differences were detected for any source of variation, Duncan's *post hoc* test was applied for multiple comparisons. The diagnosis of the model's residuals (errors) was carried out using the Kolmogorov-Smirnov (normality), Cochran (homoscedasticity), and Durbin-Watson (independence) tests. All analyses were carried out with a significance level of 0.05. The data were analyzed using STATISTICA v.10.0 software (StatSoft Inc., 2004).

Results and Discussion

Morphological Variables and Growth After 11 Months

The ANOVA revealed that only the Altitudinal Range (AR) factor significantly affected the increase in total height (p = 0.009), root collar diameter (Dac) (p = 0.012), and productivity index (d^2h) (p = 0.008). In contrast, the Plant Type (PT) factor did not have a significant effect (p > 0.05), and no interaction effects were detected between the two factors (p > 0.05) (Table 2). These results differ from those reported by Besse *et al*. (2020) in a cocoa plantation at different altitudes in Indonesia, where altitude did not significantly influence plant height, the number of primary branches and flowers, root collar diameter, or canopy diameter.

Regarding the increase in the total height variable, the highest values were recorded in RA2 for both hybrid and grafted plants, followed by RA1, with no statistical differences between them. The lowest growth values were observed in RA3, which was significantly different from the other altitudinal ranges. For Dac and the productivity index (d^2h), the highest values were observed in RA1 for both hybrid and grafted plants, followed by RA2 and RA3, which showed significantly lower values than the rest of the altitudinal ranges (Table 2).

An increase in these growth parameters is highly desirable since height is an indicator of photosynthetic surface area and carbohydrate storage capacity (Orozco *et al*., 2010). Likewise, Dac is considered a reliable predictor of resistance to bending and pest damage tolerance (Mexal & Landis, 1990). According to Almeida & Valle (2007), as cocoa plants grow in height, stem diameter increases, enhancing their structural resistance and nutrient and water uptake from the soil. Similarly, Muñoz *et al*. (2015) emphasize that Dac is the most critical quality trait as it predicts field survival and stem robustness, which are linked to plant vigor.

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Table 2. Effect of altitudinal range and plant type on growth variables: total height increase, root collar diameter (Dac), and productivity index (d^2h).

Plant type	Altitudinal Range (RA)	Total, height measurement (cm)			Neck diameter measurement (mm)			Productivity index measurement (d^2h) (cm^3)		
		Initial	Final	Increase	Initial	Final	Increase	Initial	Final	Increase
Hybrid	RA1	69.1 ± 6.4	86.4 ± 3.9	17.3 ± 8.4^{abc}	7.5 ± 2.4	13.2 ± 1.2	5.7 ± 3.5^{a}	46.7 ± 27.1	163.1 ± 18.5	116.4 ± 43.6^{a}
	RA2	63.3 ± 4.2	81.9 ± 4.7	18.6 ± 6.3^{ab}	7.9 ± 1.5	12.3 ± 0.7	4.4 ± 1.5^{ab}	43.6 ± 13.3	135.0 ± 25.0	91.5 ± 31.4^{ab}
	RA3	73.5 ± 1.1	83.4 ± 5.2	9.9 ± 4.1^{bc}	9.2 ± 0.4	10.9 ± 1.0	1.8 ± 1.1^{b}	68.4 ± 3.6	109.3 ± 25.2	40.9 ± 26.9^{bc}
Graft	RA1	57.0 ± 2.7	71.9 ± 4.5	14.9 ± 6.4^{abc}	7.5 ± 2.5	13.2 ± 1.5	5.7 ± 3.4^{a}	37.2 ± 43.4	138.4 ± 8.3	101.1 ± 45.9^{a}
	RA2	56.2 ± 3.2	76.5 ± 4.8	20.3 ± 2.7^{a}	9.1 ± 0.3	12.7 ± 1.1	3.7 ± 0.8^{ab}	50.9 ± 31.4	131.8 ± 21.4	80.9 ± 22.1^{ab}
	RA3	58.9 ± 9.7	66.9 ± 8.0	8.0 ± 1.8^{c}	8.4 ± 0.4	9.7 ± 0.7	1.3 ± 0.4^{b}	45.8 ± 26.9	68.0 ± 10.7	22.2 ± 6.0^{c}
Pr (F)										
Plant type (PT)		-	-	0.726	-	-	0.658	-	-	0.422
Altitudinal range (RA)		-	-	0.009	-	-	0.012	-	-	0.008
PT × AR		-	-	0.724	-	-	0.938	-	-	0.945

With RA1: 520–605 masl; RA2: 822–850 masl; RA3: 954–1158 masl. Increase = final measurement – initial measurement. d: root collar diameter (mm), h: total height (cm), Pr (F): Fisher's test probability (ANOVA table). Different letters in columns indicate statistically significant differences ($p < 0.05$, Duncan's test). Values are presented as mean ± standard deviation.

The ANOVA determined that none of the factors under study (Plant Type and Altitudinal Range) significantly affected the behavior of the variables branch number, leave number, and sanitary damage, presenting the same situation for the evaluation of the interactions ($p > 0.05$). The survival variable was significantly influenced ($p = 0.008$) only by the factor of Altitudinal Range (Table 3).

Due to the short age of the plantation (approximately one year), it was expected that there would be no flowering nor an increase in the number of branches. In this regard, Arnold *et al.* (2018) remark that cocoa begins flowering and fruit production only at 2 or 3 years of age. The highest values, both in the increase in the number of leaves as well as in the percentage of plants with signs of health damage, occurred in the lowest altitudinal range (RA1), with a tendency to decrease as the altitude increased. It should be highlighted that for RA3, there were no plants with health problems. Regarding plant survival, the highest values occurred in the altitudinal ranges RA3 and RA1 for both plant origins, respectively, being statistically higher than the intermediate altitudinal range (RA2) (Table 3).

Table 3. Effect of altitudinal range and plant type on branch number, leaf number, sanitary damage, and survival.

Plant Type	Altitudinal range (RA)	Number of branches measurement			Number of leaves measurement			Sanitary damage (%)	Survival (%)
		Initial	Final	Increase	Initial	Final	Increase		
Hybrid	RA1	1	2	1	8	13	5[a]	7.4 ± 6.7[a]	80.2 ± 3.3[ab]
	RA2	1	1	0	6	10	4[a]	2.1 ± 4.2[a]	68.4 ± 9.3[b]
	RA3	1	1	0	5	8	3[a]	0.0 ± 0.0[a]	84.4 ± 6.7[a]
Graft	RA1	2	2	0	7	13	6[a]	12.5 ± 21.7[a]	81.9 ± 7.4[ab]
	RA2	2	2	0	7	11	4[a]	0.5 ± 1.0[a]	70.6 ± 6.6[b]
	RA3	1	2	1	7	10	3[a]	0.0 ± 0.0[a]	81.4 ± 9.3[ab]
Pr (F)									
Plant Type (PT)		-	-	-	-	-	0.537	0.855	0.926
Altitudinal Range (RA)		-	-	-	-	-	0.256	0.112	0.008
PT × AR		-	-	-	-	-	0.968	0.976	0.778

With RA1: 520-605 m.s.n.m.; RA2: 822-850 m.s.n.m.; RA3: 954-1158 m.s.n.m Increment: final – initial measurement, d: neck diameter (mm), h: total height (cm), Pr (F): Fisher's probability test (ANOVA table). In columns, identical letters do not differ significantly (*p* <0.05, Duncan's test). Mean ± standard deviation.

Regarding the optimum altitude range for cocoa cultivation, the results of this study coincide with those of different authors, such as García *et al.* (2007), who indicate that in the case of Colombia, the regions classified as highly suitable for cultivation are located at altitudes of 400 to 800 masl. There are also moderately suitable regions, with altitudes of 0 to 400 masl and 800 to 1000 masl; marginally suitable regions, from 1000 to 1200 masl; and unsuitable regions, with altitudes above 1200 masl. Similarly, Paredes (2003) states that cocoa thrives in tropical areas, growing from sea level to 800 meters of altitude. According to INIFAP (2011) and López (2011), in Mexico, cocoa is cultivated from nearly sea level up to 1200 masl, with the optimal range being 300 to 400 masl and 600 to 800 masl. However, in plantations near the equator, cocoa successfully develops at higher altitudes, ranging from 1000 to 1400 masl (Sánchez *et al*., 2017).

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According to Besse *et al*. (2020), elevation and altitude influence the microclimatic conditions surrounding cocoa plants. Mora and Cortés (2021) further emphasize that altitude is the primary factor determining temperature, humidity, and precipitation, exerting a significant influence on cocoa's adaptation to climate variations (Bermeo & Ospina-Noreña, 2017). Additionally, Quiroz and Maestanza (2012) identify temperature and rainfall as the critical climatic factors for cocoa development, including wind, light, and solar radiation. Relative humidity is also crucial as it can contribute to the spread of certain fruit diseases. These climatic requirements explain why cocoa cultivation is concentrated in lowland tropical areas. Regarding temperature, values in the study areas ranged from 20 to 23 °C, with an observed decrease as altitude increased (Table 1). This trend is consistent with González and Garreaud (2017).

Most studies agree that cocoa does not tolerate low temperatures, with a minimum annual average threshold of 21 °C. On the other hand, extremely high temperatures can cause physiological stress, making shade essential to prevent direct solar radiation and excessive heat buildup. Temperatures between 21 °C and 25 °C promote flower formation, while temperatures below 20 °C reduce flowering (Quiroz, 2010; Loli & Cavero, 2011). Paredes (2003) and MAR (2018) highlighted the critical role of temperature in cocoa development, flowering, and fruiting, suggesting an optimal annual mean of approximately 25 °C. Low temperatures slow vegetative growth, fruit development, and flowering intensity while also affecting root and shoot activity. The recommended temperature range for cocoa cultivation is: Minimum 23 °C, Maximum 32 °C, and Optimal 25 °C. García *et al*. (2007) reported that in Colombia, suitable regions maintain temperatures between 24 and 28 °C, whereas areas with temperatures below 18 °C or above 32 °C are considered unsuitable for cocoa cultivation. In precipitation terms, it is observed that values increased with altitude, although the highest recorded value (1350.5 mm in RA3) (Table 1) was still below the recommended threshold. Gómez *et al*. (2014) note that cocoa has a low tolerance to water deficits, and when rainfall drops below 100 mm per month, it can negatively impact flowering and leaf sprouting. As a result, cocoa thrives in tropical climates with high annual precipitation (1500–2000 mm) (Angulo *et al*., 2021). Several studies predict climatic changes in the coming years, especially in tropical and subtropical regions, where low-altitude areas are expected to experience decreased rainfall, contrary to higher-altitude areas, which are expected to increase (IPCC, 2014; Ospina *et al*., 2017).

Conclusions

The studied factor, Altitudinal Range, significantly affected the morphological variables total height, root collar diameter (Dac), productivity index (d^2h), and survival rate. However, the Plant Type factor showed no significant effect, as both factors were found to act independently (absence of interaction). The lower Altitudinal Ranges (RA1 and RA2) exhibited higher values in height growth, Dac, and d^2h, with a decreasing growth trend as altitude increased.

The highest survival rates were observed in RA3 and RA1, regardless of plant origin (hybrid or grafted), and were statistically superior to the intermediate altitudinal range (RA2).

The variables such as the number of branches, leaves, and flowers were not affected by altitude nor the plant type. However, the highest values for leaf number growth and the percentage of plants showing sanitary damage were recorded in the lowest Altitudinal Range (RA1), with a decreasing trend at higher altitudes.

The findings of this study contribute to the knowledge of cocoa production, a crop of economic significance in the Dominican Republic and worldwide.

Author contributions

Work conceptualization: GP, JANA, ENE, and FMA; Methodology development: GP, JANA, ENE, and FMA; Software management: ENE; Experimental validation: GP, ENE, and FMA; Data analysis: ENE, GP; Data handling: GP, ENE; Manuscript writing and preparation: ENE, GP, JANA, and FMA; Drafting, reviewing, and editing: ENE, GP, and JANA; Project administration: GP, JANA; Funding acquisition: GP, JANA.

All authors have read and approved the final published version of this manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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