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## *Topoclimates of coffee agroecosystem for adaptation to climate change in Cuba*

*Topoclimas de agroecosistema de café para la adaptación al cambio climático en Cuba*

*Topoclimas do agroecosistema cafeeiro para adaptação às mudanças climáticas em Cuba*

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### ABSTRACT

Cuba is implementing the "Tarea Vida" (Task Life) State Plan to address climate change, which requires knowledge of local climatic characteristics. However, limitations persist in incorporating these characteristics into agricultural policies, hindering the adaptive



management of coffee agroecosystems. This study aimed to characterize the topoclimates associated with coffee agroecosystems in the mountain ranges of central and eastern Cuba, projecting their evolution under climate change scenarios. Methodologically, the spatial delimitation of topoclimates, obtained through local climate patterns and unsupervised machine learning, was integrated with the current and future climate characterization. The characterization was performed using an assembly of five global climate models (GCMs), forced under Shared Socioeconomic Trajectories (SSPs): SSP2-4.5 and SSP5-8.5, using the WorldClim version 2.1 dataset. Ten topoclimates were identified, where 86% of Cuba's total coffee-growing area is concentrated: two in the Guamuhaia Massif and eight in the eastern highlands. Projections indicate increased temperatures and alterations in rainfall patterns, with a potential increase in evapotranspiration. These changes in topoclimates reduce moisture availability in coffee agroecosystems. The findings provide a scientific basis for designing effective climate change adaptation policies for the coffee sector in Cuba.

**Keywords:** agroecosystems, climate change, local scale, topoclimate.

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## RESUMEN

Cuba implementa el Plan de Estado "Tarea Vida" para el enfrentamiento al cambio climático, lo que exige el conocimiento de las particularidades climáticas a escala local. No obstante, persisten limitaciones para incorporar estas singularidades en las políticas agrícolas, lo que dificulta la gestión adaptativa de los agroecosistemas cafetaleros. Este estudio tuvo como objetivo caracterizar los topoclimas asociadas a los agroecosistemas de café en los macizos montañosos del centro y oriente de Cuba, proyectando su evolución bajo escenarios de cambio climático. Metodológicamente, se integró la delimitación espacial de topoclimas, obtenida mediante patrones climáticos locales y aprendizaje automático no supervisado, con la caracterización climática presente y futura. La caracterización se realizó a partir de un ensamblaje de cinco modelos climáticos globales (MCG), forzados bajo las Trayectorias Socioeconómicas Compartidas (SSP): SSP2-4.5 y SSP5-8.5, utilizando el conjunto de datos de WorldClim versión 2.1. Se identificaron 10 topoclimas donde se concentra el 86 % del área total cultivada de café en Cuba: dos en el macizo Guamuhaia y ocho en los macizos orientales. Las



proyecciones indican incremento de la temperatura y alteraciones en los regímenes pluviométricos, con un potencial aumento de la evapotranspiración. Estos cambios en los topoclimas reducen la disponibilidad de humedad en los agroecosistemas de café. Los hallazgos aportan bases científicas para el diseño de políticas efectivas de adaptación al cambio climático del sector cafetalero en Cuba.

**Palabra clave:** agroecosistemas, cambio climático, escala local, topoclima.

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## RESUMO

Cuba está implementando o Plano de Estado "Tarea Vida" para enfrentar as mudanças climáticas, o que exige o conhecimento das características climáticas locais. No entanto, ainda existem limitações na incorporação dessas características às políticas agrícolas, dificultando a gestão adaptativa dos agroecossistemas cafeeiros. Este estudo teve como objetivo caracterizar os topoclimas associados aos agroecossistemas cafeeiros nas cordilheiras do centro e leste de Cuba, projetando sua evolução sob cenários de mudanças climáticas. Metodologicamente, a delimitação espacial dos topoclimas, obtida por meio de padrões climáticos locais e aprendizado de máquina não supervisionado, foi integrada à caracterização climática atual e futura. A caracterização foi realizada utilizando um conjunto de cinco modelos climáticos globais (MCGs), forçados por Trajetórias Socioeconômicas Compartilhadas (TSCs): TSC2-4.5 e TSC5-8.5, com base no conjunto de dados WorldClim versão 2.1. Dez topoclimas foram identificados, onde se concentra 86% da área total de cultivo de café em Cuba: dois no Maciço de Guamuhaia e oito nas terras altas orientais. As projeções indicam aumento das temperaturas e alterações nos padrões de precipitação, com um potencial aumento da evapotranspiração. Essas mudanças no topoclima reduzem a disponibilidade de umidade nos agroecossistemas cafeeiros. Os resultados fornecem uma base científica para o desenvolvimento de políticas eficazes de adaptação às mudanças climáticas para o setor cafeeiro em Cuba.

**Palavras-chave:** agroecossistemas, escala local, mudanças climáticas, topoclima.



## INTRODUCTION

One of the most important agroforestry systems for mountain development is coffee cultivation. However, several studies predict significant changes in suitability for this crop due to climate change (Parada-Molina *et al.*, 2022; Ferrás-Negrín *et al.*, 2024). Additionally, authors such as Quiroz Antunez *et al.* (2022) identify climate variability as one of the main factors responsible for annual fluctuations in the production of this crop

Coffee-producing countries are establishing national strategies to address climate change. Cuba, through its "Tarea Vida " plan, is developing studies of the current climate, future projections, and impacts. However, from a local perspective, analyses are still limited in addressing present and future climate singularities. Consequently, they are insufficient for activities such as agriculture and the effective management of biodiversity and water, a situation that influences the planning of coffee agroecosystem development in a climate change environment (Planos-Gutiérrez, 2020).

Coffee agroecosystems in Cuba, especially the *Coffea species Arabica*, are located in the mountains and are strongly linked to the local climate, the topoclimates (Peña-de la Cruz *et al.*, 2021). Topoclimates define critical areas for this crop and determine differentiated patterns of productive susceptibility to climate variability and climate change (Planos-Gutiérrez, 2020). Therefore, the characterization of topoclimates, both present and projected for the future, should be considered in the design of local strategies for adapting coffee cultivation to climate variability and climate change.

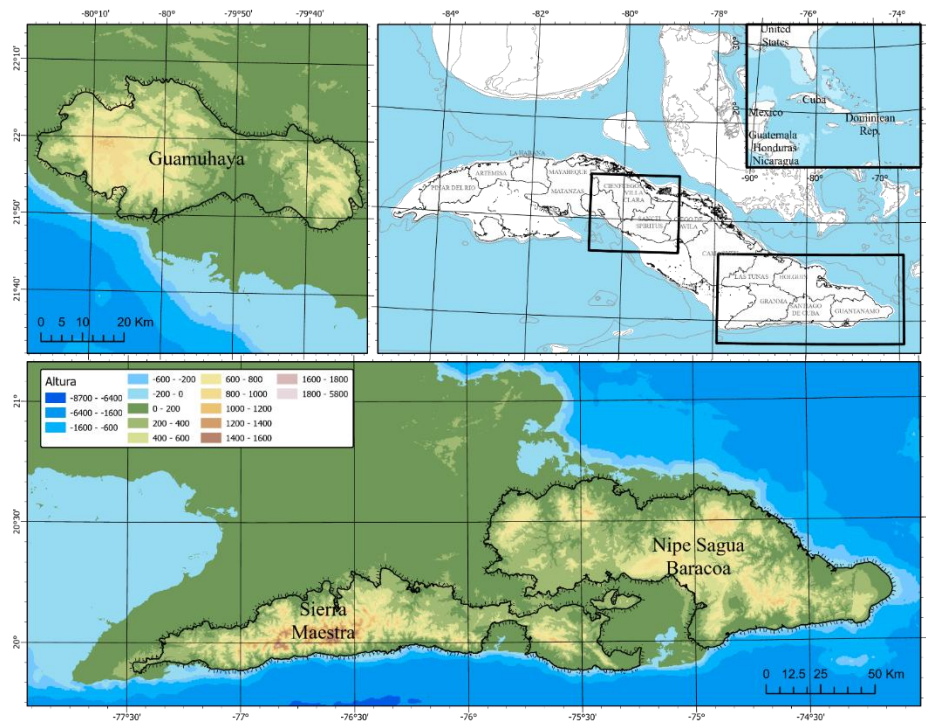
The research aims to characterize the topoclimates associated with coffee agroecosystems in the central and eastern mountain ranges of Cuba, projecting their evolution under climate change scenarios.

## MATERIALS AND METHODS

The research was conducted for the Guamuhaya , Sierra Maestra, and Nipe Sagua Baracoa mountain ranges, located in central and eastern Cuba (Figure 1). These ranges exhibited differences in their geomorphology, a geographical factor that modifies the



local climate (Peña-de la Cruz *et al.*, 2021). The Guamuhaaya range is an isolated and relatively circular mountain system; Sierra Maestra is a long and narrow mountain range with the highest peaks in the country; and the Nipe Sagua Baracoa range is the most extensive and heterogeneous in its geomorphology, with relatively low mountains and very steep slopes.



**Figure 1.** - Location of the study areas and hypsometric map. The official boundaries of the mountainous regions are delimited. agroecosystems

The study was carried out in two stages: i) the spatial delimitation of the topoclimates associated with coffee agroecosystems; and ii) the characterization and projection of the mean annual maximum temperature and interannual accumulated precipitation in said topoclimates. Both bioclimatic variables were selected because they directly affect critical phenological processes such as flowering, fruit filling and ripening, stages in which extreme thermal conditions or altered water regimes can significantly reduce yields (Benti, F. *et al.*, 2022). In the first stage, the methodology of Delineation of the topoclimates of eastern Cuba by local climate patterns and unsupervised machine learning (Peña-De La Cruz *et al.*, 2024, 2025). In the characterization, current and projection, the WorldClim v2.1 product was used (Cerasoli *et al.*, 2022). This product uses the 1970-2000 series as reference period data for the current climate. In the medium-



term future climate projection, it uses the 2040-2060 series and the 2080-2100 series for the long-term projection.

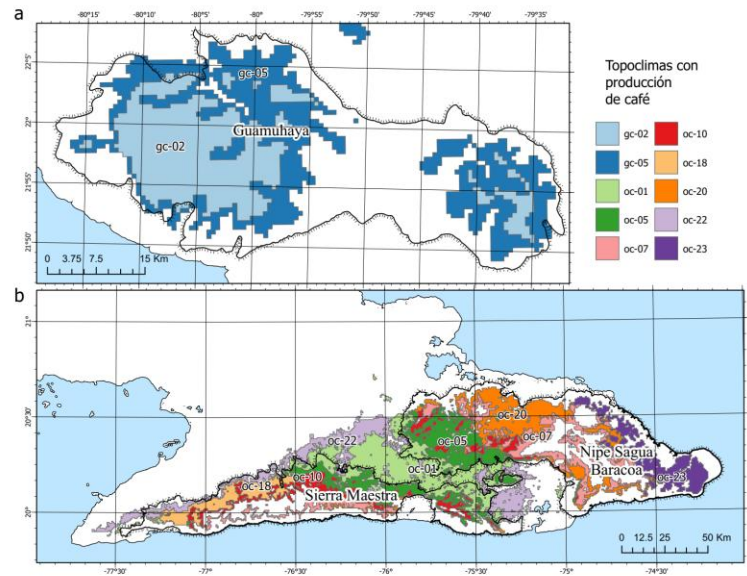
Intercomparison Project version 6 (CMIP6) were used for future climate projections : HadGEM3, MIROC6, MPI-ESM1-2-HR, FIO-ESM-2-0, and BCC-CSM2-MR . All models performed well in Central America and the Caribbean. Two shared socioeconomic trajectory (SSP) scenarios were considered for each GCM. Scenarios SSP2-4.5 and SSP5-8.5 were selected based on the occurrence trends as judged by Hausfather and Peters (2020). These authors described SSP2-4.5 as the most likely trajectory and SSP5-8.5 as being of interest because it simulates the negative extreme.

Bioclim package, implemented in R v3.0, was used . Spatial data for coffee-producing farms are in hectares (ha) and were obtained from the National Land Use Cadastre, Agricultural Cultivated Area Nomenclature, Permanent Crop: coffee, IDEPA2019 metadata. Additionally, the mathematical analysis systems R and Matlab were used for post-processing the WRF outputs. Spatial analysis and cartographic processing were performed using the GIS software ArcGIS desktop 10.7.

## **RESULTS AND DISCUSSION**

During the process of identifying the topoclimates associated with coffee agroecosystems in central and eastern Cuba, 10 were identified as relevant based on the extent of the production areas: two in the Guamuhaya massif and eight in the eastern massifs. These 10 topoclimates account for approximately 86% of the total coffee-producing area in Cuba (Figure 2). The geographical delimitation of the topoclimates in the Guamuhaya and Sierra Maestra massifs is consistent with the findings of Peña-de la Cruz *et al.* (2021), who propose that altitude is the geographical factor that best explains its spatial distribution. In contrast, in the Nipe-Sagua-Baracoa massif, it is the geomorphological features and exposure to the trade winds that dominate the distribution of topoclimates in the northeastern region of Cuba (Peña-de la Cruz *et al.*, 2021).

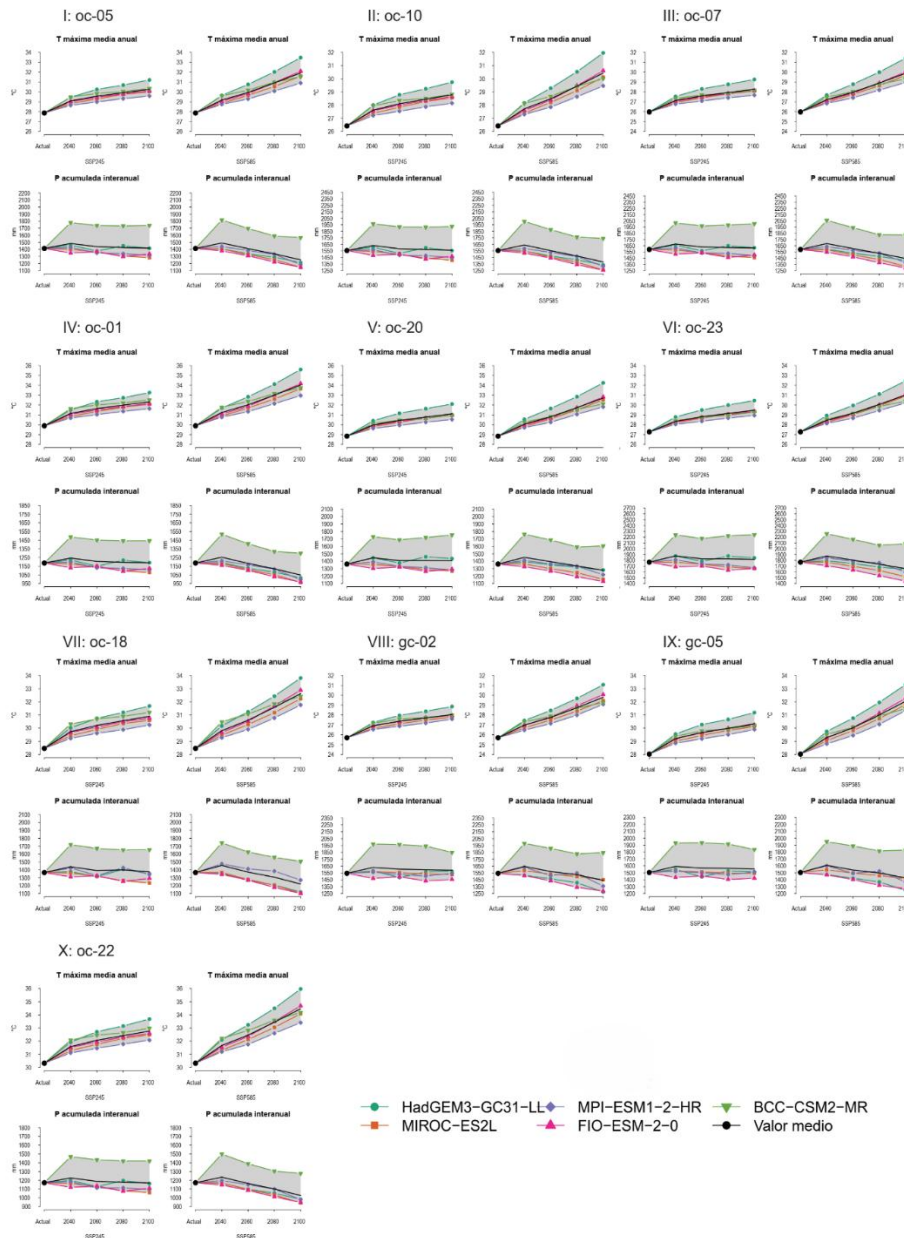




*Figure 2. - Relevant topoclimates associated with coffee agroecosystems in central (a) and eastern (b) Cuba*

Ten topoclimates account for approximately 86% of the coffee-producing areas: oc-05, oc-10, oc-07, oc-01, oc-20, oc-23, oc-18, gc-02, gc-05, and oc-22, listed from largest to smallest by total area in hectares. Figure 3 shows the current and projected average annual maximum temperature and cumulative interannual precipitation for the topoclimates of interest, broken down by period, scenario, and global climate model. The projection assumed the spatial boundaries of the topoclimates remained constant. In all cases, future climate projections indicate an increase in the average annual maximum temperature and alterations in the accumulated interannual rainfall regimes (Figure 3).





**Figure 3.** - Behavior of the average annual maximum temperature and accumulated interannual precipitation, for the SSP2-4.5 and SSP5-8.5 scenarios, in the relevant topoclimates associated with coffee agroecosystems in central and eastern Cuba

The projected results for mean annual maximum temperature at the local scale are consistent with the increase in their values (Figure 3) and reinforce the conclusions of other research included in the IPCC reports for the Caribbean region (Almazroui *et al.*, 2021; Cavazos *et al.*, 2024). The projected increase indicates that, by 2040, the oc-22



topoclimates , oc-01, oc-20 and oc-18 *present* the highest probability of negative impacts for *Coffea arabica*, with average values above the critical threshold for this species ( $\geq 28$  °C) (Quiroz Antúnez *et al.* (2022). Similarly, the increase in average maximum temperature values will potentially cause an increase in evapotranspiration values, reflected in a loss of the amount of water available for biological processes in coffee agroecosystems.

For all topoclimates, the cumulative values of interannual precipitation show appreciable divergences among the models in the suite used. This discrepancy is consistent with the poor performance of global models in predicting this climatic element. In general, this variable is projected to increase slightly by 2040, with a decline in the long term (Figure 3). This behavior is more pronounced in the less favorable SSP5-8.5 trajectory.

In the precipitation projection, it is noteworthy that the BCC-CSM2-MR model predicts an increase in interannual precipitation accumulations, contrary to the consensus of the other models. However, the model's performance in the current climate consistently represents the climate characteristics of the Greater Caribbean region (Nie *et al.*, 2020). These results corroborate studies by other authors on the potential impact of global temperature increase on the water cycle, which would manifest as an increase in atmospheric water vapor and a positive feedback loop affecting precipitation (Buis, 2022; Jiang *et al.*, 2023). A direct consequence of these effects could be the occurrence of greater volumes of precipitation within severe atmospheric phenomena common in the Caribbean, such as tropical cyclones or troughs. The results of this analysis reinforce the arguments indicating that the greatest expected disturbances in precipitation as a result of climate change in the region will be concentrated in extreme hydrometeorological events, such as severe drought episodes alternating with intense precipitation events (Iturbide *et al.*, 2020).

## CONCLUSIONS

Ten topoclimates account for 86% of Cuba's coffee-producing area: two in the Guamuhaia massif and eight in the eastern Sierra Maestra and Nipe-Sagua-Baracoa



massifs. This distribution highlights the spatial heterogeneity of local climatic conditions that influence the suitability of coffee production in the country.

Climate projections under the SSP2-4.5 and SSP5-8.5 scenarios show, in all the analyzed topoclimates, a progressive increase in the mean annual maximum temperature and alterations in interannual precipitation patterns. These changes increase evapotranspiration and reduce moisture availability in coffee agroecosystems, impacting the crop.

The documented heterogeneity in topoclimates necessitates differentiated agricultural management and planning strategies at the local level. These strategies must consider the particularities of each topoclimate as a basis for designing effective climate change adaptation policies for the coffee sector in Cuba, prioritizing the most vulnerable topoclimates identified in this study.

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***Conflicts of interest:***

The authors declare no conflicts of interest.

***Authors' contribution:***

The authors have participated in the writing of the work and analysis of the documents.



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