



# Cacao (*Theobroma cacao* L.) climate zones and its associated agrobiodiversity in Arauca, Colombia

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## Abstract

## Background

Cacao (*Theobroma cacao* L) is one of the most relevant crops in terms of economy and social rural development in Colombia. Cacao is also an important crop due to its potential to replace illicit crops and it is related to less deforestation and preserves the biodiversity. There are several cacao districts in Colombia, one of these being Arauca. The Department

of Arauca is the second largest cocoa producing region in Colombia; however, it is heavily affected by armed conflict. To raise the knowledge and technology available in the region, integrating data on the occurrence of cocoa farms with climatic variables becomes a powerful socioeconomic mapping tool for maintaining agrobiodiversity and food security in the region. Consequently, this type of agrodiversity data and agroclimatic approaches help to better manage agrobiodiversity, as in the cocoa region of Arauca. These tools are even more relevant in biodiverse regions, such as flooded savannahs and tropical forest ecosystems, which are currently undergoing drastic changes due to agricultural expansion and climate change. One of the knowledge gaps in Colombia's cocoa regions is that there are currently no agroclimatic maps made with a social and scientific approach. This study aimed to provide a database of the spatial distribution of cocoa farms in Arauca, as well as agroclimatic maps that identify and locate cocoa climate regions in Arauca. We also present a presence-only matrix consisting of twenty-six tree species, or agrobiodiversity, distributed across the study region and specifically associated with the cocoa forestry systems in Arauca.

## New information

We present the first database of both climate and agrobiodiversity data related to cocoa farms in Arauca, developed with a research and socioeconomic vision that generated a novel approach for the agroclimatic zoning of cocoa in the Arauca Region and Colombia. Using 1,538 cocoa farms at the regional scale, we identified two national and six regional-scale climate and soil regions. The selection at the local scale allowed us to classify 180 cocoa farms comprising nine agroclimatic clusters in Arauca. We found twenty-six tree species distributed across the cocoa climate zones. This dataset and its related maps also represent the agrobiodiversity of cultivated cocoa locally. This is the most complete climate and agrobiodiversity dataset of cocoa farms distribution in one of the top cocoa-producing regions in the country. These outputs are crucial because they constitute a baseline for developing research in the biodiversity of agroforestry systems, pests and diseases, pollutant presence, genetics, post-harvest processing and cocoa quality and safety.

## Keywords

agrobiodiversity, conservation of cocoa, chocolate, soils, climate, Arauca, Colombia

## Introduction

Cacao (*Theobroma cacao* L.) is a globally important staple crop. However, tropical regions where it thrives face challenges, such as a lack of steady production and increased risks due to climate change. Cacao farmers in Colombia, a country that produces fine flavour cocoa worldwide, experience these challenges daily. The Arauca Region, in northeast Colombia and part of the Orinoco River plains, has the ideal environmental and social conditions to produce premium cacao. Over the last decade, Arauca has been recognised

as the second-largest cocoa-producing area in the country and has won more than one medal at the Salon du Chocolat in Paris, France, for its fine and balanced flavour profile, characterised by speciality and distinctive aromatic notes. Research in spatial analysis for mapping the agrobiodiversity of cacao and its climate zone are necessary to provide solid, science-based support to cocoa-producing communities in Arauca.

The Cacao Arauca Regalias project is an excellent example of how regional agencies can generate impact with quality research and community work. One of the project's fundamental research questions was "Where are the climate cocoa-growing regions"? These regions would be used to plan the sampling efforts and data collection of cacao varieties and diversity. Given that the territory is vast and diverse in cacao agriculture, this article presents an approach to effectively map agrobiodiversity zones and identify the areas where data collection campaigns could be carried out in Arauca.

## General description

**Purpose:** Our aim is to present a spatial database of climate and agrobiodiversity cacao farms in Arauca, along with the corresponding agroclimatic zones.

**Additional information:** Our selection of cacao farms, agrobiodiversity data and climate mapping approach are based on a decision-making process discussed with a multidisciplinary team of researchers with expertise in topics such as cacao production, cacao agronomy, geospatial mapping, socio-economic models, climate suitability, suitable soils and landscape, best genetic cacao varieties and productivity and post-harvest transformation. The farm-scale dataset presents a table with the diversity of tree species associated with the cacao crop in Arauca. We reported twenty-six agroforestry species that were traditionally used as canopy shade in Arauca's cacao plantations.

## Sampling methods

### **Description: Selecting farms and mapping climate regions**

First, we developed various datasets of cacao farms occurrences. In the sampling description methods, more details are provided about the farms' selection process. Then, the following step involved extracting the values of environmental variables that corresponded to the geographical locations of cacao farms. Next, an online statistics calculator (<https://www.statskingdom.com/pca-calculator.html>) was used to generate a standard Principal Component Analysis (PCA) separately for the macro and microclimate variables. The loading values of PCA Axis 1 were utilised to create a gridded map of macro- and microclimate regions using the QGIS software (QGIS 2019). These geospatial methods enabled us to identify the Arauca cacao regions through a national scale analysis.

## Results

### National and regional scale

We identified two national and six regional climate regions for cacao in Arauca (Fig. 1). High temperatures and low rainfall are reported on the east of the region creating a clear east to west climate pattern, as shown in Fig. 1C-D. The Arauquita Region in the northeast is hotter than the western extremes of Saravena. The foothills of Saravena, Fortul and Tame have cooler and wetter conditions. A transition zone is observed in the central region of Arauca, with mixed conditions shared by the boundaries of Saravena, Fortul and Tame. The southeast of the region, mainly covering areas of Tame, showed different conditions from the rest of the region, with a predominance of maximum temperature during the dry season and low precipitation during the wet season as key variables (Fig. 1B). A lower degree of spatial grouping was recovered, based on soil temperature regions (Fig. 1C). However, a northeast and west group of similar soil temperature conditions in Saravena and Arauquita was identified, likely influenced by the specific conditions of the Arauca riverbanks. The foothills of Fortul and Tame show similar conditions, whereas Tame seems to follow the river lines with a clear east to west gradient. Temperature seasonality shows a higher percentage of influence on the northern areas of Arauquita and Saravena, suggesting that soil temperature conditions are more variable in these areas than in the southwest foothills of Tame and Fortúl. The eastern part of Tame also seems to have a high degree of variance explained by temperature seasonality (Fig. 1D).

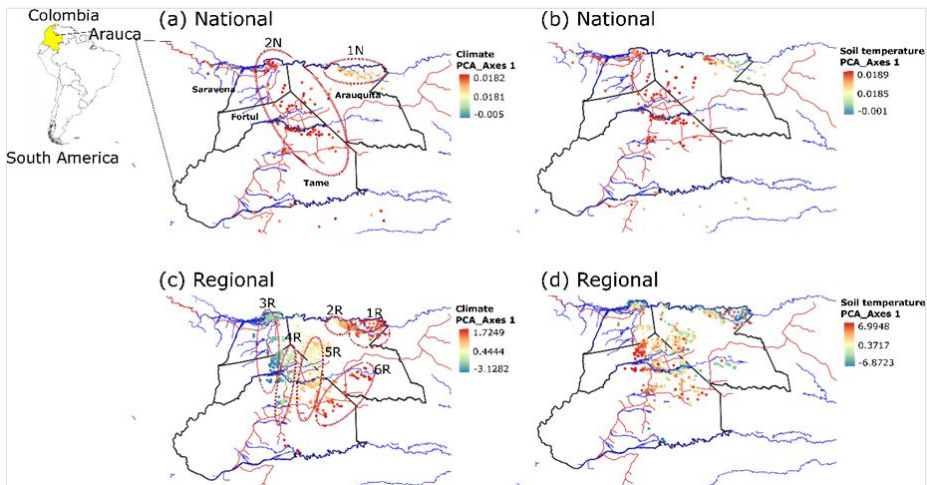


Figure 1. [doi](#)

Maps of cacao climate regions in Arauca, Colombia. National (a-b) and regional (c-d) scale maps of cacao farms according to climate and soil temperature in Arauca Department, Colombia. Blue lines are rivers and red lines roads. Blue dots are indicative of negative values of the PCA, cream and red dots are indicative of positive PCA values. Cream to orange dots are indicative of mixed conditions.

## Local scale

We identified nine clusters comprising 180 farms (Fig. 2). Based on the specific climate clusters (Fig. 2A), it was possible to identify the highest minimum and average temperature, wind velocity and solar radiation in clusters 2 and 3, located in the northeast of the study area. In contrast, the lowest values of these variables were identified in clusters 4, 5 and 7, which are in the northwest and southwest of the study area. Regarding rainfall, during the dry season, the lowest volumes were identified in clusters 1, 2, 3 and 9 (mainly in the west), while during the rainy season, the highest values were found in clusters 1, 6, 7, 8 and 9, in the central study area. The results of the nine soil clusters (Fig. 2B) revealed that, in the topsoil, there are clusters associated with riverbanks following floodplains (Clusters 1 to 5) and non-flooding foothills or rough plains (Clusters 6 to 9). We also considered other critical factors or cacao crop, such as the presence of cadmium in both soils and cacao beans (Bravo 2022).

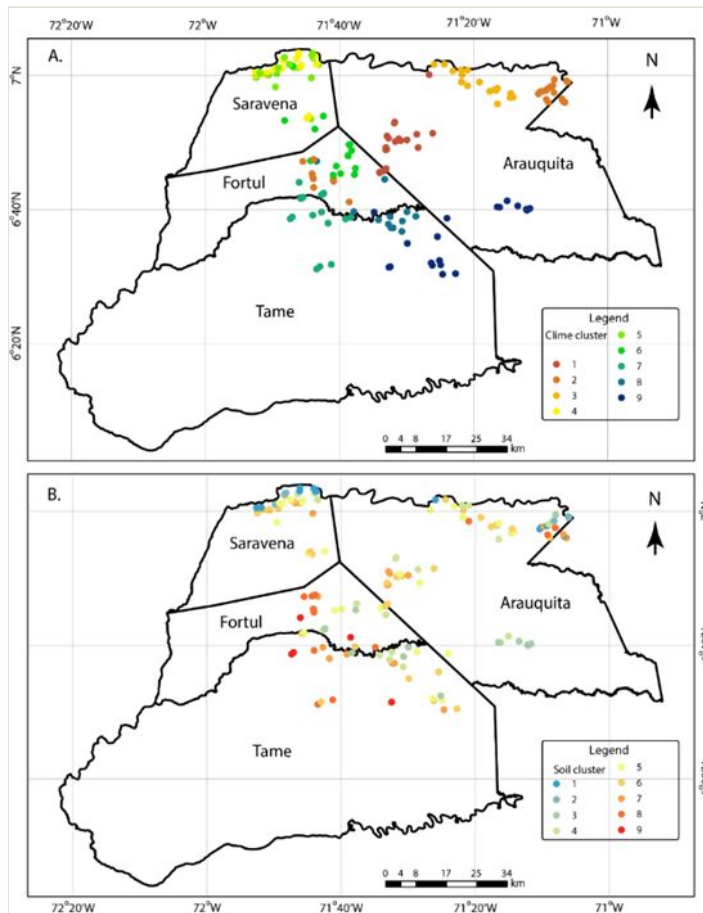


Figure 2. [doi](#)

Maps of climate clusters in Arauca, Colombia. Climate (A) and soils temperature (B) clusters at local scale across the sampling area of 180 cacao farms in Arauca.

**Sampling description:** A national scale mapping was conducted using a previously-published occurrences dataset comprising 3,141 cacao farms in Colombia (González-Orozco and Pesca 2022). To establish the climate regions, a spatial analysis method derived from González-Orozco et al. (2014) was applied to the selected national cacao farms dataset. Seven macroclimate (Fick and Hijmans 2017) and eleven microclimate soil temperature variables at a depth of 0-5 cm were used to characterise the agrobiodiversity and the climate zones (Lembrechts 2022) of the cacao regions in Arauca. The spatial resolution of the environmental variables was 1 km<sup>2</sup>.

This method involved extracting the values of environmental variables that corresponded to the geographical locations of cacao farms. Next, a Principal Component Analysis (PCA) was separately conducted for the macro- and microclimate variables. The loading values of PCA Axis 1 were utilised to create a gridded map of macro- and microclimate regions using the QGIS software (QGIS 2019). These geospatial methods enabled us to identify the Arauca cacao regions through a national scale analysis.

At the regional scale, a dataset of 1,538 cacao farms in Arauca was developed (regional scale dataset). Eleven local agronomy professionals visited cacao farms in the Municipalities of Saravena, Arauquita, Tame and Fortul in Arauca. Each farm was georeferenced and uploaded to a GIS desktop. Then, the González-Orozco et al. (2014) climate mapping method was applied to the cacao farms dataset. The analysed climate variables were subdivided into temporal groups representing the dry (Nov-Feb) and wet (Mar-Oct) seasons that Arauca experiences throughout the year. The grouped macroclimate and soil temperature databases and all farms were used to map the climate and soil temperature regions using a PCA spatial mapping method (González-Orozco et al. 2014).

At the local scale, a combined effort amongst cacao farmers, agronomy field workers and a multidisciplinary team of researchers pre-selected a subset of 180 cacao farms as the best cases for future sampling efforts of cacao and other environmental variables from the 1,538 farms. The selected farms were chosen to represent good variability in climate and soil temperature conditions (Fick and Hijmans 2017, Lembrechts 2022), cadmium soil hotspots (Bravo et al. 2021), landscape types, cacao varieties and healthy cacao plantations. Other parameters, such as proximity to the road network, were also considered. Additionally, the criteria for choosing the local-scale farms included agronomic, socioeconomic, territorial and environmental traits. A second-step process was applied to classify the 180 local-scale farms selected into spatial clusters, resulting in the identification of nine clusters that were used as the sampling regions (Local-scale dataset).

A presence-only matrix of tree species (Farm-scale dataset) associated with cacao was presented as part of the agrobiodiversity assessment done across the Arauca climate zones.

## Geographic coverage

**Description:** Department of Arauca, Colombia. Municipalities: Saravena, Fortul, Tame and Arauquita.

**Coordinates:** 6.97 and 7.00 Latitude; -71.76 and -71.61 Longitude.

## Taxonomic coverage

**Taxa included:**

| Rank    | Scientific Name                                 | Common Name        |
|---------|---|--------------------|
| species | <i>Theobroma cacao</i> L.                       | Cacao              |
| species | <i>Cariniana pyriformis</i> Miers.              | Abarco             |
| species | <i>Acacia mangium</i> Willd.                    | Acacia             |
| species | <i>Persea americana</i> L.                      | Aguacate           |
| species | <i>Eugenia stipitata</i> McVaugh.               | Arazá              |
| species | <i>Borojoa patinoi</i> Cuatrec.                 | Borojó             |
| species | <i>Erythrina fusca</i> Lour.                    | Bucaré ceibo       |
| species | <i>Erythrina poeppigiana</i> Walp & OF Cook.    | Bucaré             |
| species | <i>Swietenia macrophylla</i> King.              | Caoba              |
| species | <i>Cedrella odorata</i> L.                      | Cedro              |
| species | <i>Pachira quinata</i> Jacq.                    | Ceiba tolúa        |
| species | <i>Handroanthus chrysanthus</i> Jacq.           | Flor amarillo      |
| species | <i>Annona muricata</i> L.                       | Guanábana          |
| genus   | <i>Ficus</i>                                    | Higuerón           |
| species | <i>Spondias mombin</i> L.                       | Jobo               |
| species | <i>Leucaena leucocephala</i> Lam. & De Wit      | Leucaena           |
| species | <i>Mangifera indica</i> L.                      | Mango              |
| species | <i>Albizia guachapele</i> Kunth & Dugand        | Masaguaro - Amusco |
| species | <i>Glixicidia sepium</i> Jacq. - Kunth ex Walp. | Matarratón         |
| species | <i>Gmelina arborea</i> Roxb.                    | Melina             |
| species | <i>Citrus sinensis</i>                          | Naranja            |
| species | <i>Cordia gerascanthus</i> L.                   | Nogal cafetero     |
| species | <i>Artocarpus altilis</i> Parkinson & Fosberg.  | Pandeaño           |

| Rank    | Scientific Name                                 | Common Name   |
|---------|---|---------------|
| species | <i>Cordia alliodora</i> Ruiz & Pavon            | Pardillo      |
| genus   | <i>Musa</i>                                     | Plátano       |
| species | <i>Tabebuia rosea</i> Bertol- Bertero ex A. DC. | Roble         |
| species | <i>Samanea saman</i> Jacq & Merr.               | Samán         |
| species | <i>Tectona grandis</i> L.                       | Teca          |
| species | <i>Guarea guidonia</i> C. DC.                   | Trompillo     |
| species | <i>Pourouma cecropiifolia</i> Mart.             | Uva caimarona |
| species | <i>Matisia cordata</i> Bonpl.                   | Zapote        |

## Temporal coverage

**Notes:** Climate and soil temperature data covered the historical period between 1979 and 2020 (Lembrechts 2022). The cacao farms mapped here represented a temporal coverage of approximately 100 years of the Arauca cacao growing region.

## Usage licence

**Usage licence:** Creative Commons Public Domain Waiver (CC-Zero)

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## Data resources

**Data package title:** Cacao (*Theobroma cacao* L.) climate zones and its associated agrobiodiversity in Arauca, Colombia

**Resource link:** <https://doi.org/10.5281/zenodo.8302237>

**Number of data sets:** 3

**Data set name:** Regional scale

**Data format:** .shp

**Description:** This dataset contains 1,538 occurrences of cacao farms with ID, latitude, longitude, Principal Component Analysis 1 values, municipality name and sampling sites.



| Column label      | Column description                          |
|-------------------|---|
| ID                | Farm Identifier #                           |
| Latitude          | Geographic Coordinates.                     |
| Longitude         | Geographic Coordinates.                     |
| PCA1              | Principal Component Analysis Axis 1 values. |
| Municipality name | Municipios.                                 |
| Sampling Sites    | Collection sites.                           |

**Data set name:** Local scale

**Data format:** .shp

**Description:** This dataset contains 180 occurrences of cacao farms with ID, municipality, latitude, longitude, climate cluster number.

| Column label      | Column description         |
|-------------------|----------------------------|
| ID                | Farm Identifier #          |
| Municipality      | Municipio.                 |
| Latitude          | Geographic Coordinates.    |
| Longitude         | Geographic Coordinates.    |
| Climate cluster # | Number of climate cluster. |

**Data set name:** Farm scale

**Data format:** .csv

**Description:** This dataset contains georeferenced occurrences of 30 tree species across 180 farms and climate clusters. A .csv file name species\_names is attached to this farm-scale dataset.

| Column label | Column description          |
|--------------|-----------------------------|
| Code         | Farm ID.                    |
| ID_geo       | Farm ID.                    |
| Latitude     | Geographic Coordinates.     |
| Longitude    | Geographic Coordinates.     |
| Cluster      | Cluster number.             |
| Species      | Common and scientific name. |

## Additional information

Project title in Spanish: Cacao Regalías Arauca or Sistema General de Regalías SGR Cacao Arauca: implementación de estrategias Agroforestales y vinculación de avances en el manejo agronómico y postcosecha de nuevos clones, para mejorar la productividad y calidad del cacao en el departamento de Arauca. This Project is composed of three technical components: agroforestry, cadmium and post harvesting. The farms' occurrence datasets are available for all components.

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## Author contributions

Draft preparation: CE-GO; Analyses and preparation of climate data: CE-GO, MP, GA-AC; Data preparation of cacao farms occurrences: all listed authors; Visualisation: CE-GO, GA-AC; Review and editing: all listed authors.

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