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ENVIRONMENTS CONDUCIVE TO *THEOBROMA CACAO* IN MARTINIQUE

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Abstract
The current cocoa orchards in Martinique are genetically diversified and enjoy a good health situation. The aromatic properties of chocolates produced from Martinique beans seem exceptional. The cultivation of cocoa on this French island located in the Caribbean achieved international fame in the 18th century. Today, almost fifty farmers continue to grow cocoa, but climate projections indicate that the possibilities for growing this species will have considerably decreased in the coming decades. A geographic information system (GIS) was in fact developed using QGIS software version 3.36.2, to carry out an agro-climatic zoning and show the effect of climatic constraints on the distribution of environments suitable for *Theobroma cacao*, in Martinique. The climatic requirements of the species were defined based on global scientific literature and the environmental data comes from the French national meteorological services. Agroforestry, agro-ecology, plant selection and scientific innovations in agronomy will be the main ramparts to prevent a possible decline of this culture on the island.

Keywords: Martinique, Theobroma cacao, GIS, Climate Change

1. Introduction

Martinique is an island of 1 128 km² located in the Caribbean, which is characterized by a very contrasting topography : mountainous terrain in the north, hills in the south and some plains in the center. This island with a humid tropical climate is marked by a diversity of bioclimates and microclimates, as well as a remarkable diversity of soil types with high agronomic potential (Joseph 2009 ; Venkatapen 2012 ; Fujisaki et al., 2023). Martinique thus offers a heterogeneity of types of environments favoring the establishment of varied ecosystems (Fournet 1978 ; Howard 1989). The native flora of this island comes from tropical America and has been enriched and diversified through the various colonization processes that the island has experienced, from the first pre-Columbian peoples to the present day (Bennett et al., 2000 ; Joseph 2006, 2009). Floristic contributions come as much from tropical America as from Africa and Asia (Joseph 2006, 2009 ; Maunder et al., 2011). Among the introduced species, Martinique has the cocoa tree which makes it possible to obtain the chocolate so coveted by man (Fournet 1978 ; Howard 1989).

The cocoa tree is believed to originate from the lower strata of the humid neotropical forests of equatorial America (Elzebroek 2008 ; Zhang et al., 2016 ; Clément et al., 2018 ; Winters 2022). There are many varieties of cultivated cocoa trees and these would have been spread initially from the Amazon to Central America and the Caribbean, then secondarily to the rest of the (tropical) world in a very differentiated manner (Chevalier 1906 ; Lanaud et al., 2003 ; Elzebroek 2008). In Martinique, the history of the implantation of cocoa (*Theobroma cacao L.*) divides the authors: those who attribute the introduction of the first cocoa trees to the pre-Columbian peoples or those who indicate that cocoa was rather introduced in the seventeenth century (May 1930 ; Banbuck 1935 ; Nicolas 1996 ; Ouellet 2014 ; Adenet et al., 2020).

It seems more likely that the history of cocoa cultivation in Martinique was marked by several waves of introduction, of various origins (Adenet et al., 2020). The 18th century represented "the golden period" for cocoa cultivation on the island which enjoyed international fame (Elisabeth 2003 ; Adenet et al., 2020). A treaty dating from the 18th century mentions the use in Martinique of a mixture of cocoa varieties from our Caribbean islands with those from Venezuela, milder and less bitter (Quélus 1717 ; Hatzenberger 2001 ; Adenet et al., 2020). However, from the 19th to the 20th century, several cyclonic, seismic and health events, or the effects of the two world wars were devastating (Burle 1962 ; Adenet et al., 2020). Production was gradually abandoned in favor of sugar cane, pineapple and banana (Adenet et al., 2020). In 2015, an association of cocoa producers in Martinique called "VALCACO" was created to revive the culture, and there are currently almost fifty producers and a few chocolate factories on the island. Adenet et al., in 2020 also demonstrated that current cocoa orchards in Martinique are genetically diverse (Fig. 1).

This genetic blend seems to promote exceptional aromatic properties in chocolates produced from Martinican beans. The inventory carried out in 2012-2013 by PARM (Martinique Agroresources Technological Resource Center), also confirmed a good health situation of cocoa trees in Martinique, despite the presence of various diseases in the Caribbean islands (Adenet et al., 2020). However, the island has experienced an increase in average temperatures of 0.3°C per decade since 1971, and this warming is expected to continue during the 21st century, according to the national meteorological services (Météo-France Antilles Guyane 2012 ; Madani et al., 2021). The plausible effects

Fig. 1. Illustrations of some varieties of cocoa trees observable in Martinique (commune of Prêcheur, 2023). A and B: Calabacillo-shaped pods, C and D: Amelonado-shaped pods, E and F: Criollo-shaped pods.

of global warming in the Lesser Antilles are increasingly better known (Climate change and its consequences for the French West Indies 2024).

From 2050, Martinique could experience a drop in annual precipitation in the dry season as well as in the rainy season but with geographical contrasts and a continued increase in the number of very hot days and nights (Arnaud et al., 2017 ; Chauvin et al., 2020 ; Cantet et al., 2021 ; Madani et al., 2021). Whatever the climate projections considered, it appears that the new climatic constraints will strongly limit the possibilities for growing *Theobroma cacao* in Martinique. A geographic information system (GIS) was therefore developed to carry out agro-climatic zoning in order to map and show the evolution of suitable environments for this crop from 1971 until 2071-2100. The climate data available from the national meteorological services (Météo-France) for the period 1971-2000 and the climate projections for the period 2071-2100 were used with the GIS software: QGIS version 3.36.2.

By definition, agro-climatic zoning makes it possible to define the agricultural capabilities of a region according to the climate (temperatures and precipitation), and to show the correlation between climate variations and the ideal location of areas remaining suitable for cultivation (Caramori et al., 2001 ; De Carvalho Alves et al., 2013 ; Soto 2013 ; Wollmann et al., 2013 ; Santos et al., 2014). Zoning is carried out in several stages: first defining the ecological requirements of the species, then developing a geographic information system (GIS) including environmental data from the region studied, then defining the basis of zoning using criteria that will make it possible to identify areas, ranging from acceptable to unsuitable for a culture, including optimal (Soto 2013 ; Wollmann et al., 2013 ; Santos et al., 2014 ; Claude 2015). Zonings are known to be approximate because they depend on the precision of the data used but still constitute a modern way to manage crops (Wollmann et al., 2013).

2. Material and Method

Material

The species *Theobroma cacao* whose name means "the food of the gods" belongs to the Malvaceae family, but in the classical classification the species is integrated into the Sterculiaceae family (Fournet 1978 ; Howard 1989 ; Winters 2022 ; Nieves-Orduña et al., 2023). There are around twenty species of cocoa trees including *Theobroma cacao* which is the species mainly cultivated in the world and secondarily *Theobroma bicolor* and *Theobroma grandiflora* (Cupuaçu), (Elzebroek 2008 ; Childéric 2014 ; Zhang et al., 2016 ; Clément et al., 2018 ; Winters 2022). Cacao trees are trees from the lower strata of the Amazon rainforest. It is undoubtedly one of the most studied fruit trees in the world (Elzebroek 2008 ; Zhang et al., 2016 ; Clément et al., 2018 ; Winters 2022 ; Nieves-Orduña et al., 2023).

There are many varieties of cultivated cocoa which are traditionally often divided into three groups: "Criollo, Forastero and Trinitario" (Elzebroek 2008 ; Clément et al., 2018). The "Trinitario" is also a natural hybrid between the Criollo and the Forastero (Elzebroek 2008). In reality, there are 11 newly recognized genetic groups of cocoa trees that can be crossed with each other: Amelonado, Guyana, Iquitos, Cacao Nacional Boliviano (CNB), Contamana, Criollo, Curaray, Marañon, Nacional, Nanay and Purús (Motamayor et al., 2008 ; Kane et al., 2012 ; Winters 2022 ; Nieves-Orduña et al., 2023). Overall, cocoa trees are evergreen trees, which can reach around twenty meters in height but are limited to 4 to 6 meters for cultivation (Elzebroek 2008 ; Childéric 2014 ; Clément et al., 2018). The root system is composed of a taproot penetrating deep into the soil up to 2 meters, and lateral roots developing in the superficial part of the soil which can reach up to 6 meters long (Zuidema et al., 2002 ; Elzebroek 2008). It is possible that there could be an association between the roots of the cocoa tree and a mycorrhizal fungus (Herre et al., 2007 ; Elzebroek 2008 ;

Paguntalan et al., 2020).

The growth of the main stem is sympodial, with orthotropic subterminal shoots (called “chupons”), (Fournet 1978 ; Howard 1989 ; Elzebroek 2008). The leaves are simple, entire and glabrous, with pinnate veins, reticulate. They are oblong or elliptical and are 12 to 50 cm long and 4 to 15 cm wide (Fournet 1978 ; Howard 1989 ; Elzebroek 2008). The young leaves are hanging, then leathery at maturity; those of the main stem and chupons (offspring) are arranged in a spiral, while the others are alternate. We note the presence of deciduous stipules at the base of the petiole, which can be subulate or stellate-puberulent (Fournet 1978 ; Howard 1989 ; Elzebroek 2008). The flowers are borne on an old leafless trunk and on fan-shaped branches. They are solitary or in short fascicles and are small, perfect and hermaphroditic. They can be white, pink to reddish, or even yellowish in color (Fig. 2), (Fournet 1978 ; Howard 1989 ; Elzebroek 2008 ; Ríos-Moyano et al., 2023).

A mature tree can give between 5,000 and 50,000 flowers per year (even 100,000), of which 10 to 50 will develop in the form of ripe fruits (Elzebroek 2008 ; Ríos-Moyano et al., 2023). Pollination is carried out mainly by small midges (Elzebroek 2008 ; Chumacero de Schawe et al., 2018 ; Winters 2022 ; Nieves-Orduña et al., 2023; Ríos-Moyano et al., 2023). The fruit is a drupe commonly called a “pod”, with a lignified, smooth or furrowed wall. It contains 20 to 60 seeds, commonly called “beans,” which are embedded in a mucilaginous, whitish, sweet pulp (Fig. 2). Among young fruits (called “cherelles”), some can stop growing, turn black and wilt (Elzebroek 2008 ; Clément et al., 2018). Cocoa cultivation is mainly located in humid tropical regions (Elzebroek 2008 ; Childéric 2014 ; Nieves-Orduña et al., 2023).

The cocoa tree tolerates a maximum of annual precipitation of 1250 mm to around 3000 mm (optimum of 1500 to 2600 mm), with less than four consecutive months of precipitation less than 100 mm (Elzebroek 2008 ; Childéric 2014 ; Kokou Edoh Adabe et al., 2014 ; Lahive et al., 2018 ; Reyes-Yunga et al., 2024). The species is very sensitive to water deficiency, especially in the event of competition with other plants. The tolerable temperature for its cultivation is between an average maximum of 27-30°C and an average minimum of 18-21°C (optimum of 24° to 26°C), (Elzebroek 2008 ; Childéric 2014 ; Lahive et al., 2018 ; Reyes-Yunga et al., 2024). The absolute minimum temperature must never fall below 10°C (Elzebroek 2008 ; Childéric 2014). A warm and humid atmosphere is therefore essential for the cocoa tree but it is important to limit the effect of drying winds (Childéric 2014). The cocoa tree can grow on very varied soil types but it is preferable to have well-drained, deep (around 1.5 meters), fertile soils with at least 2% organic carbon and a slightly acidic to neutral soil pH, more precisely from 5.5 to 7 (Zuidema et al., 2002 ; Elzebroek 2008 ; Childéric 2014 ; Kokou Edoh Adabe et al., 2014).

Although the cocoa tree is adapted to natural conditions of dense shade, when mature it can withstand high light intensities (Elzebroek 2008 ; Childéric 2014). Indeed, young cocoa plants need dense temporary shade, allowing only 50% of the light to pass

Fig. 2. Illustration of a flower and a cocoa fruit with these seeds (Martinique, 2023)

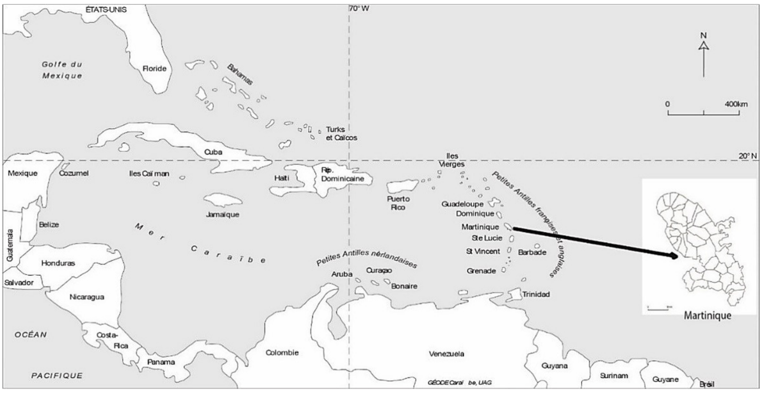

Fig. 3. Location of Martinique in the Lesser Antilles archipelago (Caribbean)

through during the two years after planting, then as they age, their sufficiently developed canopies can reduce up to 100% the need for shade (Elzebroek 2008 ; Childéric 2014). Cocoa is often grown with other crops such as coconut, oil palm and fruit trees (Elzebroek 2008). After planting, the first harvest can take place from the third or fourth year and the full yield from 6 to 7 years, the maximum after 10 to 15 years (Elzebroek 2008 ; Childéric 2014). In many countries, the harvest extends throughout the year but in those with pronounced wet and dry seasons, the harvest takes place 5 or 6 months after the start of the rainy season, corresponding to the time required between the fertilization of flowers and ripening of fruits (Elzebroek 2008).

Located in the Lesser Antilles archipelago (Caribbean), Martinique is a French mountainous island suitable for cocoa cultivation, less than 70 km long and 30 km wide (Fig. 3). The island benefits from excellent ventilation because it is regularly swept by the trade winds of the Northeast and is characterized by relatively high humidity, linked to the influence of the ocean immensity (Météo-France Antilles Guyane 2012 ; Madani et al., 2021). The average annual temperature is 26°C, which gives it a tropical climate. There are two seasons: the dry season going from February to March and the rainy season going from July to October (Météo-France Antilles Guyane, 2012 ; Madani et al., 2021 ; Climate change and its consequences for the French West Indies 2024).

The diversity of geological formations as well as the spatial distribution of precipitation are the basis of a great soil

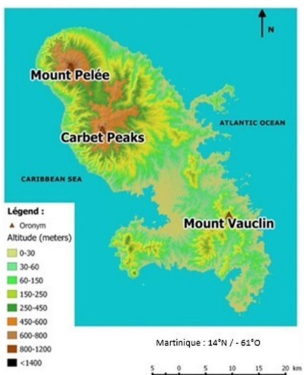

Fig. 4. Hypsometric map of Martinique (Source: IGN)

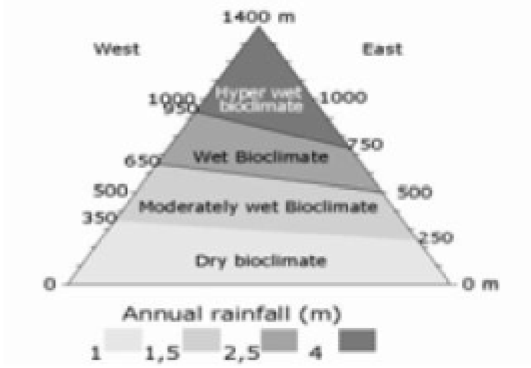

Fig. 5. Bioclimatic stage of Martinique. (Source: JOSEPH, P., 2012)

diversity favorable to agriculture (Joseph 2009 ; Venkatapen 2012 ; Fujisaki et al., 2023). The topography of the island is contrasted with large volcanic massifs to the north, hills to the south while the center is marked by plains (Fig. 4). However, no relief exceeds 1400 meters in altitude in the North and more than 500 meters in the South. The island is generally subject to the same air mass but its topography generates very contrasting orographic rainfall which leads to the establishment of various bioclimates: dry subhumid, humid subhumid, humid and hyper humid (Fig. 5), (Joseph 2006, 2009, 2012). These diverse bioclimates favor the establishment of rich and varied ecosystems including significant useful biodiversity (Joseph 2006, 2009, 2012).

Method

The ecological requirements of Theobroma cacao and particularly its climatic requirements, but also the best conditions to achieve to obtain an excellent culture of this species have been defined using a bibliographic search in the world scientific literature. The main ecological factors determining its cultivation are thus presented in Table 1 below (Zuidema et al., 2002 ; Elzebroek 2008 ; Childéric 2014 ; Kokou Edoh Adabe et al., 2014 ; Lahive et al., 2018 ; Reyes-Yunga et al., 2024). The methodology previously applied for the development of zoning for species of the Coffea genus in Martinique (*Coffea arabica, Coffea canephora and Coffea liberica*) is again applied to develop this time, the agroclimatic zoning of *Theobroma cacao* (Claude 2015, 2016, 2017 ; Claude et al., 2019). This methodology is well known around the world, because it makes it possible to identify the ideal areas for a crop, according to temperatures and precipitation or to show the evolution of the distribution of areas suitable for a crop based solely on climatic variations (Caramori et al., 2001 ; Evangelista et al., 2002 ; De Carvalho Alves et al., 2013 ; Soto 2013 ; Wollmann et al., 2013).

The climate data used to carry out zoning comes from Météo-France: a public institution in Martinique (France) with expertise in the production of climate data. Thus, the only climate data that can be used to date are those produced by Météo-France, from shared data from the DEAL Martinique/Météo-France DIRAG Research and Development Convention N°10/20/30. These are ALADIN-CLIMAT simulations for the Lesser Antilles, at a resolution of 10km, for the period 1971-2000 and climate projections (RCP 4.5 and RCP 8.5 scenarios) for the period 2071-2100 (Météo-France Antilles Guyane 2012 ; Cantet et al., 2014). These data consist of the following variables: average annual minimum and maximum temperatures, and average annual precipitation.

The administrative data (demarcation of municipalities, location of capitals, etc.) comes from the DEAL (Department of Environment, Planning and Housing of Martinique) and the CTM (Territorial Authority of Martinique).

Table 1. Ecological requirements of *Theobroma cacao*, according to world scientific literature

	Ecological requirements of *Theobroma cacao*
Average annual temperatures	Tolerance range: 18-21°C to 27-30°C with an optimum of 24° to 26°C.
Annual rainfall	Tolerance range: 1250 to 3000 mm with an optimum of 1500 to 2600 mm (with less than four consecutive months of precipitation less than 100 mm).
Soil characteristics	Well drained, deep and fertile with at least 2% organic carbon and a soil pH of about 6.5 (precisely between 5.5 and 7). Soils with high moisture storage capacity can compensate for periodic drought.
Light condition	At maturity the species no longer requires low light intensities despite its adaptation to conditions of dense shade. Young cocoa plants need more shade.

Finally, the IGN (National Geographic Institute) database was used for altimetry (BDALTI from IGN). The GIS software, QGIS version 3.36.2, made it possible to process this collected data (Geographic reference: WGS_1984_UTM_20N) and to carry out zoning at 1/500,000 from queries formulated using the raster calculator option of the software (Claude 2015, 2016, 2017 ; Claude et al., 2019).

3. Results

Environments suitable for the cultivation of *Theobroma cacao* in Martinique since 1971 (Agro-climatic zoning, normals from 1971-2000).

According to Météo-France data, from 1971 to the 2000s (Fig. 6), the average minimum temperatures in Martinique were between 15° and 25°C, the average maximum temperatures were between 21° and 32°C. Only the highest peaks in the mountainous north of the island did not exceed more than 26°C for maximum average temperatures, and the minimums could go down to 15°C without ever reaching the risk of freezing. A strong disparity is still observable today, between the mountainous northern part of the island presenting more pleasant, cool and very humid micro-climates while the rest of the island is hotter and drier. This is how the rainfall gradient in Martinique begins at 1200 mm in the South and reaches more than 6000 mm of water in the North (Fig. 6). By determining the climatic requirements of *Theobroma cacao* based on international scientific literature (temperatures and precipitation), we were able to define the basis of our agro-climatic zoning to map the environments suitable for the cultivation of this in Martinique since 1971 (Table 2).

The queries were carried out using the raster calculator option of the QGIS software, but only a map of acceptable environments

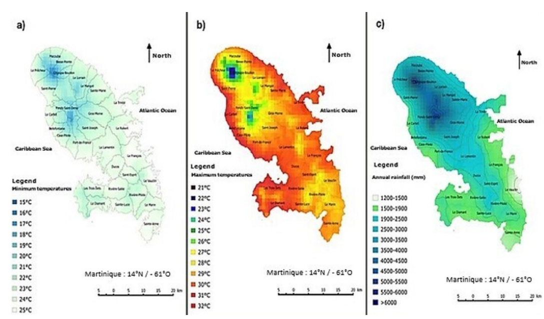

Fig. 6. a) Minimum annual average temperatures; b) Maximum annual average temperatures; c) Annual precipitation (normal 1971-2000, Source: Météo-France)

Table 2. Basis of agro-climatic zoning of *Theobroma cacao*

	Acceptable	Optimal	Unsuitable
Average annual temperatures	18°C to 30°C	24°C to 26°C	<18°C and >30°C
Annual rainfall	1250 to 3000 mm	1500 to 2600 mm	<1250 mm and >3000 mm

for the cultivation of the species could be established (Fig. 7). The query was as follows: [minimum temperatures] ≥18°C and [maximum temperatures] ≤ 30°C and [annual precipitation] ≥1250 mm and ≤3000 mm. An area of 61,283 hectares, or 54.3% of the territory, thus seems acceptable for this crop, strictly from the point of view of climatic conditions, however it was not possible to identify optimal environments.

Environments suitable for Theobroma cacao in Martinique by 2071-2100: Comparison of Météo-France climate projections, RCP 4.5 and RCP 8.5 scenarios (agro-climatic zoning).

The only climate projections available for the period 2071-2100 in Martinique, produced by the national meteorological service (Météo-France), correspond on the one hand to the RCP 4.5 scenario and on the other hand to the 8.5 scenario (Fig. 8 and 9). The RCP 4.5 scenario suggests minimum temperatures between 16°C and 26°C and maximum temperatures between 23°C and 33°C by the end of the century (Fig. 8). The rainfall gradient will correspond to a distribution of precipitation ranging from 1400 mm in the South to 6400 mm in the North. This scenario indicates a continuation of a strong climatic disparity between the cooler and wetter mountainous region of the North and the warmer and drier areas of the rest of the island. In contrast, the more pessimistic RCP 8.5 scenario projects higher temperatures, with maximums reaching 35°C and minimums not falling below 18°C, even on the highest peaks (Fig. 9). Precipitation would be slightly reduced compared to the previous scenario, with a gradient ranging from 1335 mm in the South to a maximum of 6200 mm in the North. The climatic distinction between the North and the rest of the island would be significantly reduced, suggesting a relative homogenization of climatic conditions.

These scenarios reflect contrasting trajectories, where RCP 4.5 preserves more local climatic disparities and a more abundant rainfall distribution, while RCP 8.5 shows a generalized warming accompanied by a reduction in water and thermal contrasts between regions. By taking the basis of our agro-climatic zoning for Theobroma cacao (Table 2), we were unable to obtain maps

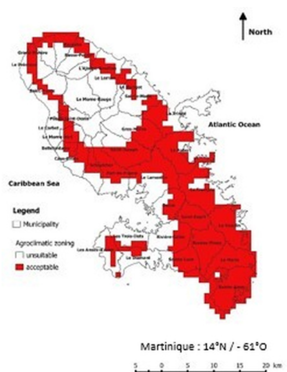

Fig. 7. Agro-climatic zoning of acceptable environments for the cultivation of Theobroma cacao since 1971-2000 (Source: Météo-France)

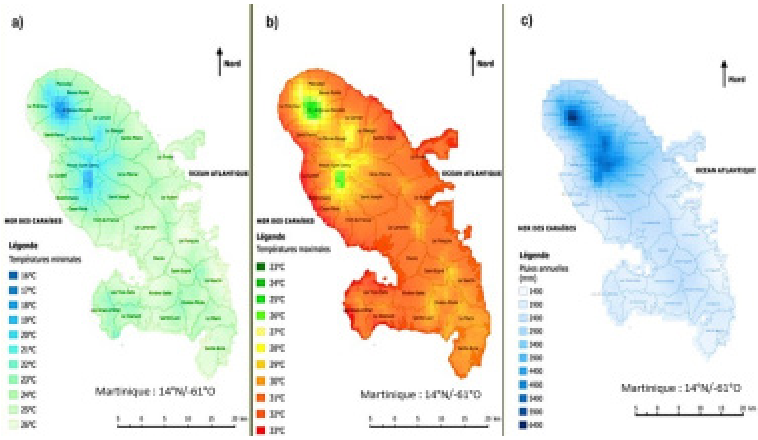

Fig. 8. a) Minimum annual average temperatures; b) Maximum annual average temperatures; c) Annual precipitation (RCP 4.5 scenario, normal 2071-2100, Source: Météo-France)

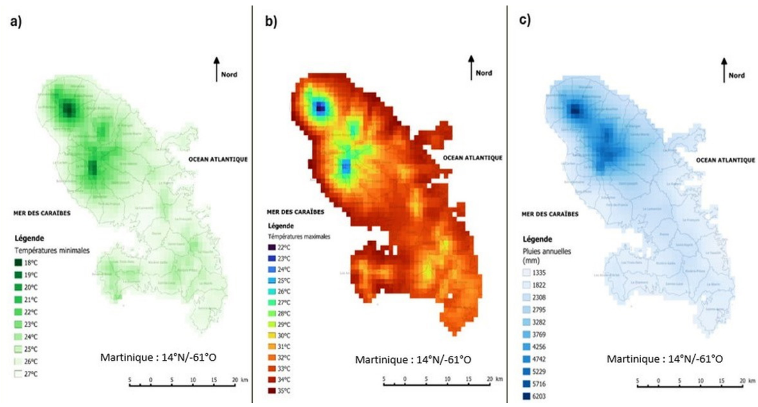

Fig. 9. a) Minimum annual average temperatures; b) Maximum annual average temperatures; c) Annual precipitation (RCP 8.5 scenario, normal 2071-2100, Source: Météo-France)

showing optimal areas for cocoa cultivation by 2071-2100, in Martinique, regardless of the scenario considered. On the other hand, we obtain maps of environments that will remain a priori acceptable for this crop in Martinique. According to the RCP 4.5 scenario, approximately 5,776.73 hectares, in other words only 5.1% of the territory will be acceptable for this crop (Fig. 10). On the contrary, according to the RCP 8.5 scenario, only 2,389 hectares, or 2.1% of the territory, will be acceptable for this crop by 2071-2100 in Martinique (Fig. 10). The query in the software was as follows: [minimum temperatures] ≥18°C + [maximum temperatures] ≤ 30°C + [annual precipitation] ≥1250 mm and ≤3000 mm.

4. Discussion

The vulnerability of *Theobroma cacao* to climate change is undeniable. This species is expected to experience a sharp decline in different parts of the world, of the areas suitable for its cultivation (Elzebroek 2008 ; Walters 2020 ; Ceccarelli et al., 2021 ; González-Orozco et al., 2022 ; Igawa et al., 2022). Increasing temperatures, droughts or irregular rains threaten the survival of cocoa trees, increasing their vulnerability to diseases and pests, disrupting the growth cycle of cocoa trees (flowering, fruiting and pod maturation) and leading to poor quality of beans and a decrease in yields (Elzebroek 2008 ; Avendaño Arrazate et al., 2011 ; Sosa

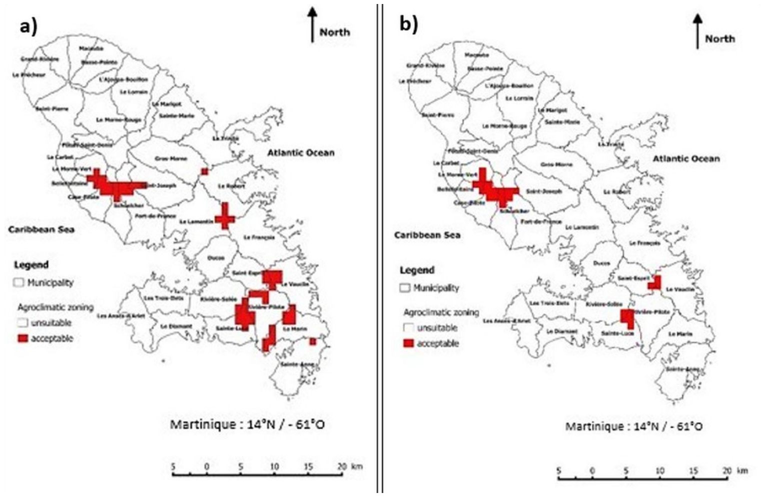

Fig. 10. Agro-climatic zoning of environments acceptable for the cultivation of *Theobroma cacao* by 2071-2100, in artinique : a) RCP 4.5 scenario, b) RCP 8.5 scenario (Source: Météo-France)

et al., 2020 ; Walters 2020). The productivity, phenology and growth of cocoa trees are thus directly impacted by climatic variations (Avendaño Arrazate et al., 2011 ; Sosa et al., 2020).

The sustainability of production, the living conditions of producers and environmental impacts (diseases, climatic constraints, etc.) are the subject of increasing attention for the cocoa sector in the world (Food and Agriculture Organization of the United Nations (FAO) 2024 ; International Cocoa Organization 2024 ; World Bank 2024). The cocoa economy is in fact a major pillar of international trade. In 2021, global production reached 5.7 million tonnes according to the International Cocoa Organization (ICO), generating a global turnover estimated at around $100 billion, according to the World Bank. However, projections from the International Cocoa Organization (ICO) indicate that global production could decrease by 10 to 50% by 2050 due to climate change.

The results of our study confirm this trend for Martinique and show that global warming could lead to a sharp reduction in environments suitable for growing cocoa on the island over the coming decades. We were initially unable to identify optimal environments for cultivation because the climatic conditions of the island do not perfectly correspond to the optimal ecological requirements of Theobroma cacao (Zuidema et al., 2002 ; Elzebroek 2008 ; Météo-France Antilles Guyane 2012 ; Childéric 2014 ; Kokou Edoh Adabe et al., 2014 ; Madani et al., 2021 ; Reyes-Yunga et al., 2024). It is indeed difficult to find areas with temperatures strictly between 24° and 26°C all year round and also with annual precipitation between 1500 and 2600 mm. The mountainous north of the island presents low temperatures which may be suitable for cultivation but the rainfall accumulations are too high; conversely the rest of the territory presents suitable rainfall accumulations but the maximum temperatures far exceed 26°C.

However we were able to identify in a second time 61 283 hectares, or 54.3% of the territory can be considered acceptable for the cultivation of cocoa since 1971. These areas are considered acceptable because the species' tolerance limits for annual temperatures (18°C to 30°C) and annual precipitation (1250 to 3000 mm) are met (Zuidema et al., 2002 ; Elzebroek 2008 ; Childéric 2014 ; Kokou Edoh Adabe et al., 2014 ; Reyes-Yunga et al., 2024). Regardless of the other determining factors to be verified in the field such as soil, insolation, exposure to wind, etc., cocoa is still potentially cultivable over a large part of the territory. The high peaks in the north are an exception, due to excessive rainfall and minimum temperatures which can drop below 18°C; as well as coastal areas where maximum temperatures can exceed 30°C.

The very rugged topography of the island nevertheless makes it easy to find still today, more or less large areas suitable for cocoa cultivation. Currently, despite fragmentary data, it is estimated that the surface area cultivated with cocoa in Martinique is only around 100 hectares with an expected production of between 60 and 80 tonnes.

In 2023, the price of market beans was 26€ for export (including 17€ for the producer), (French Ministry of Agriculture and Food Sovereignty 2024 ; MARTINIQUE COCOA PRODUCERS ASSOCIATION 2024). From 10 producers in 2015, Martinique now has almost fifty cocoa producers, and the farms are small plots of 1 to 5 hectares respecting the principles of agroecology and agroforestry. These farms are found in all the municipalities of the island, but the largest concentrations are located in the center and the north (French Ministry of Agriculture and Food Sovereignty 2024; MARTINIQUE COCOA PRODUCERS ASSOCIATION 2024).

The different agro-climatic zonings carried out around the world, however, predict a significant reduction in areas suitable for cocoa cultivation due to new climatic constraints (Elzebroek 2008 ; Walters 2020 ; Ceccarelli et al., 2021 ; González-Orozco et al., 2022 ; Igawa et al., 2022). We obtain the same results using the climate projections available for the Lesser Antilles including Martinique, by 2071-2100, produced by the national meteorological services (Météo-France). The agro-climatic zoning that we realized using the climate projection of the RCP 4.5 scenario, shows a 90.6% decrease in the acceptable areas for this crop in Martinique. According to this scenario, only 5,776.73 hectares of acceptable surface area will remain, from the point of view of temperatures and precipitation. No optimal area is identifiable. The finding is even more worrying when using the climate projection of the RCP 8.5 scenario. According to this scenario, the acceptable areas will decrease by 96.1%, or more than 2,389 hectares. There is also no identifiable optimal zone.

Several strategies nevertheless exist to mitigate the effects of climate change for cocoa plantations, such as the development of agroforestry and agro-ecology, natural plant selection or by hybridization (use of biotechnologies) and scientific innovation in the field of agronomy (Arévalo-Gardini et al., 2020 ; Fisher-Ortíz et al., 2022 ; Igawa et al., 2022 ; Sinyangwe et al., 2023). Agroforestry systems of cocoa trees in Mexico, for example, combining scientific innovation and contemporary experience of farmers, as well as great agrobiodiversity, demonstrate socio-ecological self-regulation (resources and ecological services provided to farmers) and resilience in the face of climate change (Fisher-Ortíz et al., 2022). Agrobiodiversity underlies on the one hand a genetic diversity of cocoa trees linked to a selection of the varieties most resistant to diseases and water stress, offering better productivity and excellent organoleptic qualities, and on the other hand a biological diversity and a strong structure of associated forest systems (Fisher-Ortíz et al., 2022).

In Martinique, several public and private actors with transversal skills could play a crucial role in the research and implementation of quick but effective solutions to prevent the decline of cocoa cultivation. The development of cocoa tree varieties resistant to diseases and water stress but productive, etc., could be possible through collaboration between the Center for Agronomic Research for Development (CIRAD) and the University of the Antilles. The continued promotion of agroforestry and agro-ecology by the French Ministry of Agriculture and Food (MAA) and its decentralized services, by the Territorial Collectivity of Martinique (CTM) and its decentralized services and by the University of the Antilles, through training and technical support, would help producers to manage their farms even better in a sustainable manner. For example, by continuing practices integrating trees into cocoa plantations, thus improving soil quality, or through efficient water management systems, such as rational irrigation and rainwater harvesting, to optimize the water resource.

Financial and technical support from French State services and local authorities to the association of cocoa producers could make it possible to further develop and optimize the cocoa sector in a sustainable and equitable manner, guaranteeing producers fair prices and promoting their production. Finally, companies and cooperatives could engage in partnerships with producers to promote sustainable and quality cocoa.

By mobilizing the expertise and resources of public and private actors present on the island, Martinique can respond to this challenge by ensuring a sustainable future for cocoa cultivation, thus preserving the quality of its production, its cultural wealth and its unique natural environment.

5. Conclusion

Theobroma cacao's vulnerability to climate change is undeniable. We demonstrate that the surface area of environments suitable for cocoa cultivation in Martinique could be reduced by more than 90%, by 2071-2100, taking into account only future climatic conditions. The current trend increase in temperatures but also the regular drop and uneven distribution of rain could put cocoa cultivation in decline in less than fifty years. To safeguard Martinican chocolate, recognized for its aromatic properties throughout the world, research and implementation of solutions must be quickly put in place. It is essential to continue to promote agroforestry and agro-ecology, to develop resistant varieties of cocoa trees or to promote and support a sustainable and fair trade cocoa sector. By mobilizing the expertise and resources of public and private actors present on the island, Martinique can respond to this challenge by ensuring a sustainable future for cocoa cultivation, thus preserving the quality of its production, its cultural wealth and its unique natural environment.

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