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Environments Conducive to *Coffea liberica* in Martinique

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Abstract: Martinique was recognised as a pioneer in the insular Caribbean for coffee cultivation in the early 18th century. The island is known for its legendary "Martinique" coffee dating from that time but it no longer has coffee-growing industries. As part of a project to revive this cultivation, a geographic information system (GIS) was developed in order to carry out a pedoclimatic zoning and to find environments favourable to species of the Coffea genus. A first zoning resulted in an inability to produce quality Arabica coffee for the future, with rainfall representing a major limiting factor. Because the island contains the three most cultivated species of coffee in the world, a second zoning was carried out and resulted in real but limited opportunities for *Coffea canephora*. A third zoning has now been carried out for the last exogenous species of the Coffea genus: *Coffea liberica*. The edapho-climatic requirements of *C. liberica* have also been defined using the world's scientific literature. Numerical data (isohyets, isotherms, geomorphology) also come from Martinican institutions with expertise in the production of environmental data (IRD, IGN, Météo-France, DEAL, CTM)[1]. This data was processed using the GIS software: QGIS version 2.18.14. The pedoclimatic zoning of *Coffea liberica* reveals more possibilities for cultivation and it appears to be more suited to the environmental conditions of the island than Arabica and Canephora. Based on the forecasts of the National Meteorological Services for the 2071-2100 time horizon, we carried out an agro-climatic zoning showing increased possibilities for the production of this coffee in future years.

Keywords: Martinique, *Coffea liberica*, Edapho-Climatic Requirements, GIS, Pedoclimatic Zoning, Agro-Climatic Zoning, Climate Change

Introduction

Martinique is a mountainous island of the Lesser Antilles (located in the Caribbean, a "hot spot" of world biodiversity) whose geomorphology, bioclimatic staging and the variation of eco-climatic factors determine a heterogeneity of environments, conditioning the establishment of rich and varied ecosystems (Joseph, P., 1997, 2009; Claude, J.P. et al., 2017, (a)).

Its autochthonous flora, native to tropical America, has been enriched by the settlements and colonisation processes it has witnessed (Joseph, P., 2009). Floristic exchanges and the spread of species on the surface of the planet as a result of human mobility over the years have contributed to the diversification of its flora and its useful biodiversity (Kricher, J.C., 1999; Bennett, B.C., et al., 2000; Joseph, P., 2006, 2009). The floristic additions come from tropical America, Africa and Asia (Joseph, P., 2006, 2009; Maunder, M., et al., 2011). Among those coming from Africa, three species of coffee trees which are extensively cultivated in the world have been introduced in Martinique and are among the useful plants present on the island: *C. arabica*, *C. canephora* and *C. liberica* (Fournet J., 2002).

The historical sources relating the history of coffee in Martinique are numerous. The introduction of coffee, its cultivation and its decline in Martinique (18th to 19th century) are, however, very generally associated with one species: *Coffea arabica* (D'Aulnay, G.-E. C., 1832; Louis Du Bois, 1855; Jeanguyot M., et al., 2003; Elzebroek A.T.G., 2008; Hardy, M., 2014). If the history of the introduction of *Coffea arabica* on the island is well recounted, this is not the case for

[1] IRD: Research Institute for Development (France)/ IGN: National Geographic Institute (France)/Météo-France: French Meteorological Organisation / DEAL: Directorate of the Environment for Planning and Housing / CTM: Territorial Collectivity of Martinique.

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the other two species. In any case, Arabica was the first and the most cultivated species in the world and remains so today, providing a popular sweet and flavoured drink. Its origin, its stories and its distribution in the world are well known (D'Aulnay, G.-E. C, 1832; Louis Du Bois, 1855; Willson et al., 1985; Puerta, G. I., 1998; Tulet, J., 1998; Teketay, D., 1999; Jeanguyot M., et al., 2003; Leroy T., et al., 2006; DaMatta, F.M., et al., 2007; Barel, M., 2008; Elzebroek A. T. G., 2008; Pinard, F., 2008; Gomez, C., 2009; Pohlan, H. A. J., et al., 2010; Zullo et al., 2011; Aguilar P., et al., 2012; Clifford, M. N., 2012; Lamah, D., 2013; Hardy, M., 2014; Jean-Philippe, C., 2015; Claude, J.P., 2016). The history of Canephora coffee - also called Robusta and which is known for its energising character - is more recent and dates from the end of the 19th century (Teketay, D., 1999; Bart, F., 2007; Pinard, F., 2008; Pohlan, H. A. J., et al., 2010; Claude, JP, 2017, (b)). Liberica coffee was discovered late in Africa and presents very different forms or varieties which have been discussed from a genetic and taxonomic point of view (*Coffea dewevrei*, *Coffea excelsa* ...) (Clifford, M. N. (Ed.), 2012). Nevertheless, it is recognised that *Coffea liberica* is native to Liberia and was initially cultivated in West Africa (Teketay, D., 1999; Pohlan, H. A. J., et al., 2010; Clifford, M. N. (Ed.), 2012). This coffee was only distributed around the world from the 19th century, despite it having a more bitter taste than that of other cultivated coffee trees (Muhamad Ghawas, et al., 1991; Teketay, D., 1999). It was used initially in Java to replace the Arabica coffee destroyed by coffee rust before itself becoming equally sensitive and making room for Robusta coffee among others. Liberica coffee cultivation in the world has remained marginal, contributing less than 1% to the world coffee market, unlike Arabica and Canephora (Teketay, D., 1999; Pohlan, H. A. J., et al., 2010). Coffee is one of the world's major agricultural crops, fourth among agricultural trade and the second or third largest export after oil (Pinard, F., 2008; Gomez, C., 2009). Whatever the case may be, Martinique has only witnessed a very short "coffee era"- so called by historians - of less than a century and a half (18th to 19th century) (Hardy, M., 2014).

As part of an attempt to revive coffee cultivation in Martinique, a geographic information system (GIS) was developed in order to carry out a pedoclimatic zoning and find suitable environments for species of the Coffea genus. A first pedoclimatic zoning was carried out for *Coffea arabica* and resulted in an inability to produce quality Arabica coffee for the future, with rainfall representing a major limiting factor (Jean-Philippe, C., 2015; Claude, J.P., 2016). Because the island contains the three most cultivated species of coffee in the world, a second zoning was carried out and resulted in real but limited possibilities for *Coffea canephora* (Claude, J. P., 2017, (b)). A third zoning has now been carried out for the last exogenous species of the Coffea genus: *Coffea liberica*.

The same methodology previously applied for the pedoclimatic zoning of *Coffea arabica* and *Coffea canephora* has been applied for the zoning of *Coffea liberica* (Jean-Philippe, C., 2015; Claude, J.P., 2016; Claude, J.P., 2017, (b)). The conducting of the zoning follows the same steps, consisting first of all of defining the ecological requirements of the species according to the physical factors considered essential for cultivation. These are the thermal and rainfall ranges as well as the types of soils that form the basis of zoning, which then makes it possible to categorise our study area (Martinique) into two distinct zones: suitable or unfit for cultivation. Zoning is obtained using requests in a GIS software (Geographic Information System) allowing to overlay and manipulate monofactorial maps treated at 1/500,000 representing the eco-climatic factors selected and considered essential (Temperature, Rainfall, Soil), (Pinto, H. S., et al., 2001; Evangelista et al., 2002; Barros, M. A., et al., 2006; Meireles, E., et al., 2007; Rosa, 2007; Petek, M. R., et al., 2009; Andrade, G. A., et al., 2012; Carvalho Alves, M., et al., 2013; Medeiros, R. M., et al., 2013; Soto, F., 2013; Wollmann, C. A., et al., 2013; Santos, L. D. P., et al., 2014). The edapho-climatic requirements of *Coffea liberica* were therefore defined using the world's scientific literature. Numerical data (isohyets, isotherms, geomorphology) also come from Martinican institutions with expertise in the production of environmental data (IRD, IGN, Météo-France, DEAL, CTM)[2]. This data was processed using the GIS software: QGIS version 2.18.14. Based on the forecasts of the National Meteorology Services (Météo-France), considering the new climatic constraints expected for Martinique for the 2071-2100 time horizon, we have tried to evaluate the likely effects of climate change for the cultivation of Liberica coffee by developing an agro-climatic zoning. The pedoclimatic zoning of *C. liberica* reveals more potential for cultivation than the other two species of coffee, and the agro-climatic zoning demonstrates increased production potential for this coffee in future years. *Coffea liberica* appears to be more suited to the environmental conditions of the island than Arabica and Canephora.

[2] IRD: Research Institute for Development (France)/ IGN: National Geographic Institute (France)/Météo-France: French Meteorological Organisation / DEAL: Directorate of the Environment for Planning and Housing / CTM: Territorial Collectivity of Martinique.

Material

Coffea liberica is native to West Africa (Liberia) and its distribution in the world dates back to the 19th century (Muhamad Ghawas, et al., 1991; Teketay, D., 1999; Pohlan, H. A. J., et al., 2010; Clifford, M. N. (Ed.), 2012). Among more than one hundred species of the Coffea genus (Rubiaceae family) identified so far, *C. liberica* is among the few coffee trees cultivated by man but without contributing significantly to the global coffee market (Teketay, D., 1999; Hue T. T. M., 2005; MEKONEN HAILEMICHAEL SALLA, 2009; Razafinarivo et al., 2013). Its cultivation contributes to less than 1% of the world coffee market (Teketay, D., 1999; Pohlan, H. A. J., et al., 2010). It is an arboreal vegetation that can reach 10 metres in height, or even more, with leaves which are obovate to oblanceolate or elliptical (Figure 1). They are flat and smooth and can reach up to 30 cm long and 15 cm wide. The stipules are present, sometimes truncated, obtuse or subacute. The flowers, 1 to 12, are in subsessile groups and reach 3 to 4 cm in length before anthesis. The fruits are ellipsoid to oblong and their length ranges from 18 to 30 mm (Fournet J., 2002).

Figure 1: Photos: Coffea liberica (Martinique, 2015).

C. liberica is suited to warm, humid tropical lowland forests, low altitude rainforests or even open scrub vegetation (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012). It requires heavy rains and high temperatures.

It can be found at altitudes of up to 600 metres or even greater than 1000 metres. Annual daytime temperatures between 24° and 30°C and an average annual rainfall ranging from 1600 to 2400 mm are optimal for its cultivation. However, according to the scientific literature, *C. liberica* can tolerate annual temperatures between 18° and 36°C and an annual rainfall of 1,100 to 3,500 mm (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop). It grows best in the shade and does not tolerate temperatures below 5°C. The species can be grown on a variety of soil types, from peat to clay, on well-drained soils but also on poorer soils. It tolerates a pH between 4.3 and 8. Its cultivation requires less vigilance than the other two coffee trees (Arabica and Canephora), (Purseglove, J. W., 1968; Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012). *Coffea liberica*, like *Coffea canephora*, tolerates the heat and humidity of low-lying regions (lower than 1000 metres) and seems to correspond more closely to the environmental conditions of Martinique, unlike Arabica which requires the coolness of high tropical mountains (Jean- Philippe, C., 2015; Claude, JP., 2016; Claude, J. P., 2017, (b)).

The study took place in Martinique, a French island located in the Caribbean, in the Lesser Antilles archipelago (Figure 2). It is situated between Dominica in the north and Saint Lucia in the south, and is surrounded on the west by the Caribbean Sea and on the east by the Atlantic Ocean. It is a mountainous territory with an area of 1128 km^2. The north of the island is very mountainous, composed of large volcanic massifs exceeding 800 metres altitude. The south is composed of hills of altitudes lower than 500 metres. This contrasts with the centre of the island which is marked by plains (Figure 3). The average annual temperature is 26°C in Martinique. The island has excellent ventilation. It is regularly swept by trade winds from the northeast. It is characterised by high humidity (Albert, P., et al., 1999). The climate is of humid tropical type, defined by two seasons: the dry season from February to March and the rainy season (also corresponding to the hurricane season) from July to October (Albert, P., et al., 1999). There are also shorter transition periods with less marked characteristics. The diversity of geological formations and the contrasting spatial distribution of rainfall are the basis for a large pedological diversity (Portecop, J., 1978; Atlan, Y., 1990; Venkatapen, C., 2012).

The island is subject to the same mass of air but its topography generates highly contrasting orographic rains which lead to the establishment of various bioclimates (Figure 4), (Joseph, P., 2006, 2009, 2012). These diverse bioclimates condition the staging of plant formations and favour the establishment of rich and varied ecosystems with significant biodiversity.

Figure 2: Location of Martinique in the Caribbean[3].

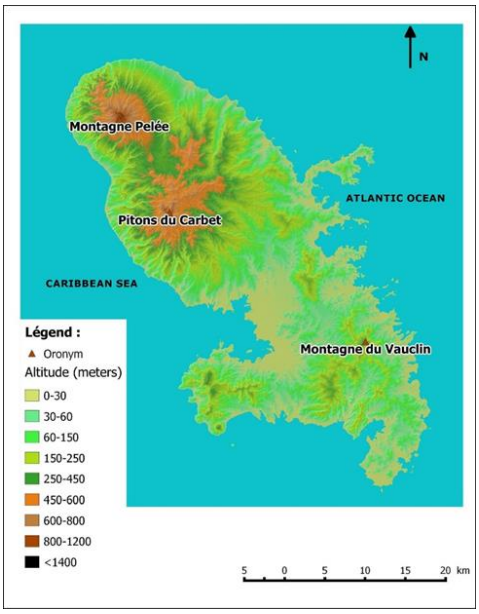

Figure 3: Hypsometric map of Martinique. (Source: IGN)[4]

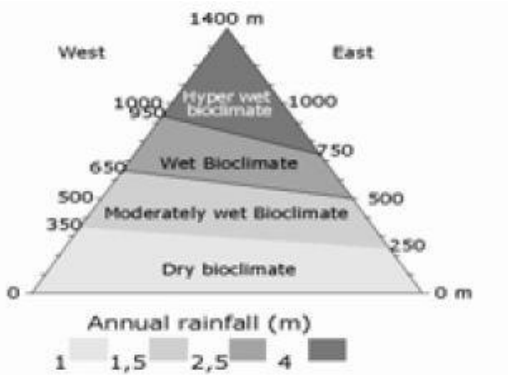

Figure 4: Bioclimatic development of Martinique. (Source: JOSEPH P., 2012) [33].

Method

The methodology previously applied for the development of the pedoclimatic zoning of *Coffea arabica* and *Coffea canephora* is again applied for the zoning of *Coffea liberica* (Jean-Philippe Claude, 2015; Claude, J. P., 2016; Claude, J. P., 2017, (b)).

The ecological profile of *C. liberica* has therefore also been defined based on the world's scientific literature. Physical determinants and values are presented in Table 1 (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E.; 1988, Onwueme, I. C., 1991; Website: Ecocrop; Teketay D., 1999; Clifford M. N., 2012). The eco-climatic data (average minimum and maximum annual temperatures, annual rainfall, soils and altimetry) that can be used in the GIS software: QGIS version 2.18.14, were provided by the Martinican institutions with expertise in the production of environmental data. Therefore, climate data for 2015, and projections for 2071-2100 come from the National Meteorological Services[5] (Météo-France Antilles Guyane, D. M., 2012; Cantet, P., et al., 2014). The soil map of Martinique comes from the IRD[6], in the form of GIS data named: "pedo_IRD_2006". Orographic GIS, administrative data and toponymy come from the DEAL[7] and the Territorial Community of Martinique. The altimetric data from the IGN[8] were reused (BDALTI 25 metres from the IGN, BD ORTHO® Version 2 of the IGN). The QGIS version 2.18.14 software enabled the processing of data (at geographical reference: WGS_1984_UTM_20N) and the production of thematic maps at 1/500 000.

Table 1: Ecological requirements of Coffea liberica, according to the world's scientific literature (temperature, rainfall and soils only).

Edapho-climatic requirements of *Coffea liberica*	
Average annual temperatures	Tolerance range: 18° to 36°C with an optimum of 24° to 30°C
Annual rainfall	Tolerance range: 1100 to 3500 mm with an optimum of 1600 to 2400 mm
Soil types	Soils must be permeable, well drained and well ventilated, and have good depth. The species can be cultivated on a variety of soil types, from peat moss to clay, on poorer soils. It tolerates a pH between 4.3 and 8.

[3] and [5] Illustration from: Claude, J. P., Baillard, K., Ely-Marius, S., & Jean-Francois, Y. (2017). Contribution to the knowledge of the Rubiaceae of the Lesser Antilles : Martinique's case. Journal Of Advances In Biology, 9(4), 1976-1993.

[5] Météo-France: French meteorological organisation
[6] IRD: Research Institute for Development (France)
[7] DEAL: Directorate of the Environment for Development and Housing.
[8] IGN: National Geographic Institute (France)

Results

1. **Pedoclimatic zoning for *Coffea liberica* (1971-2000 climatic data and 2006 pedological data).**

1.a. Temperatures

The average annual temperature in Martinique is 26°C (Albert, P., et al., 1999). Mean annual minimum temperatures in Martinique do not fall below the 15°C mark; this eliminates any risk of frost for the island (Figure 5). There is, however, a contrast in terms of the average minimum temperatures between the very mountainous north of the island (more than 800 metres altitude) and the rest of the territory consisting of hills (below 500 metres of altitude) and plains (Figure 3). The highest peaks of the island (in the north) are the only ones to experience minimum average annual temperatures ranging from 15° to 19°C. For the rest of the territory the minimum is around 20° to 25°C (Figure 5).

Mean annual maximum temperatures can reach 27° to 32°C over the majority of the territory (Figure 6). Only the highest peaks of the island experience mean annual maximum temperatures not exceeding 26°C (Figures 3 and 6).

Coffea liberica appears to be suited to the thermal gradient of Martinique, since it tolerates annual temperatures between 18° and 36°C with an optimum between 24° and 30°C (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012), just like *Coffea canephora*, which also prefers heat and humidity and tolerates temperatures around 30°C. On the other hand, only *Coffea arabica* requires coolness, needing average annual temperatures between 16° and 25°C (optimum of 18° to 22°C) and it suffers in temperatures around 30°C (DaMatta, F. M., et al., 2007; Meireles, E., et al., 2007; Barel, M., 2008; Bart, F., 2007; Elzebroek A. T. G., 2008; Pinard, F., 2008; Pohlan, H. A. J., et al., 2010; Zullo Jr, et al., 2011; Soto, F., 2013).

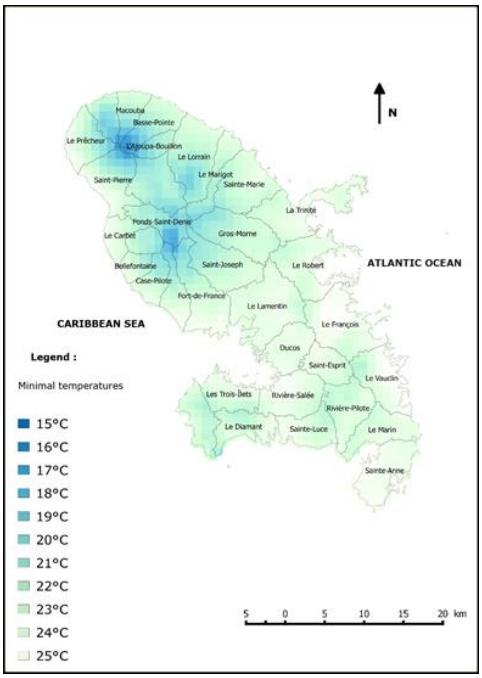

Figure 5: Minimum annual average temperatures (1971-2000)[9].

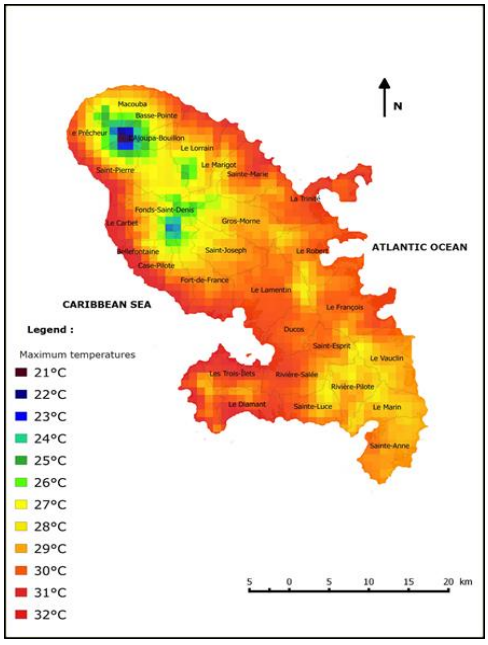

Figure 6: Maximum annual average temperatures (1971-2000). (Source: Météo-France)[10].

[9 and 11] Illustration from: Claude, J. P. (2016). Environments Suitable for the Species of the Coffea genus in Martinique (The case of Coffea Arabica Typica Variety). International Journal of Recent Research and Review.

1. b. Rainfall

The annual rainfall of Martinique is between 1200 mm and more than 6000 mm of water. This strong rainfall gradient correlates with the altitudinal gradient of the island (Figures 3, 4 and 7), which is distinct from the north to the south and from sea level to the highest peaks by means of a bioclimatic staging (Joseph, P., 2006, 2009, 2012). Indeed, the coastal region (from west to east, from the town of Saint-Pierre in the west, to the Trinidad peninsula in the east, figure 7) is marked by the lowest cumulative annual rainfall ranging from 1200 to about 1900 mm of water characterising the dry subhumid bioclimate (formerly called dry bioclimate, figure 4). The southern part of the island, from the coastal region to the interior, consists of mountains not exceeding 500 metres altitude (Figure 3), the annual rainfall ranges from 1200 to 2500 mm of water characterising the transition to humid subhumid bioclimate (formerly called moderately humid bioclimate, figures 4.7). Finally, the northern part of the island has the highest rainfall, ranging from 2500 to more than 4500 mm of water and exceeding 5000 mm at the highest peaks, and is characterised by humid and hyperhumid bioclimates (Figures 3,4,7).

C*offea liberica* appears to be suited to the rainfall gradient of Martinique, more precisely to bioclimates ranging from dry subhumid to humid, since it tolerates an average annual rainfall ranging from 1100 to 3500 mm with an optimum ranging from 1600 to 2400 mm (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein J. C., 1987; Hensleigh T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012).

It should be noted that *Coffea canephora* is also suited to bioclimates ranging from dry subhumid to humid because it tolerates annual rainfall of up to 3000 mm with an optimum of 1200/1500mm to 2400 mm according to the world's scientific literature. Arabica requires, according to the authors, an optimum ranging from 1200/1800 to 2400 mm of water and is therefore suited to subhumid dry and subhumid humid bioclimates (Figure 4), (Willson, K. C., et al., 1985; Evangelista, A. W., et al., 2002; Barros, M. A., et al., 2006; DaMatta, F. M., et al., 2007; Meireles, E., et al., 2007; Barel, M., 2008; Bart, F., 2007; Elzebroek A. T. G., 2008; Pinard, F., 2008; Pohlan, H. A. J., et al., 2010; Zullo Jr, et al., 2011; Andrade, G. A., et al., 2012; de Carvalho Alves, M., et al., 2013; Soto, F., 2013).

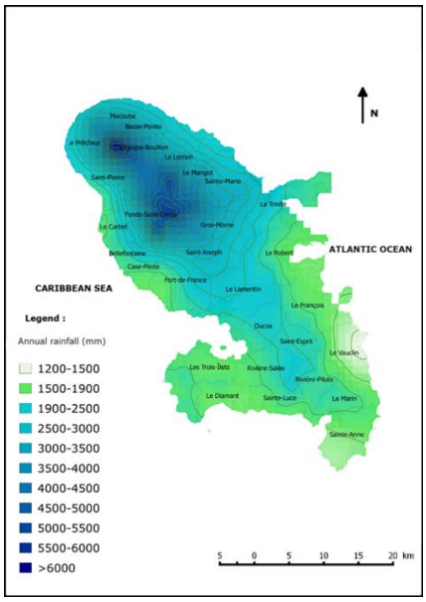

Figure 7: The rainfall pattern in Martinique. (Source: Météo-France)[11].

1. c. Soils

Martinique has a wide variety of soil types with very diverse characteristics (Figure 8), (Portecop, J., 1978; Atlan, Y., 1990; Venkatapen, C., 2012). The north of the island has soils from recent volcanic projections and variable evolution, while the centre and south of the island consist of soils derived from the weathering of older volcanic rocks, and the valley bottoms and the plain of Lamentin are composed of alluviums (Venkatapen, C., 2012).

Coffee trees generally require permeable, well-drained and aerated soils and good soil depth. However, they can be cultivated on soils of varying depth, pH, and mineral content, provided appropriate cultivation techniques are used (Rutunga, V., et al., 1994; Tulet, J. C., 1998; Harorimana, D., et al., 2007; ROSA, V., 2007; Pohlan, H. A. J., et al., 2010; Solórzano, N., et al., 2010; Chemura, A., 2014). Poorly developed ash soils, vertisols and urban areas are soils unfit for growing coffee (Jean-Philippe, C., 2015; Claude, JP., 2016; Claude, J. P., 2017, (b)).

[11] Illustration from: Claude, J. P. (2016). Environments Suitable for the Species of the Coffea genus in Martinique (The case of Coffea Arabica Typica Variety). International Journal of Recent Research and Review.

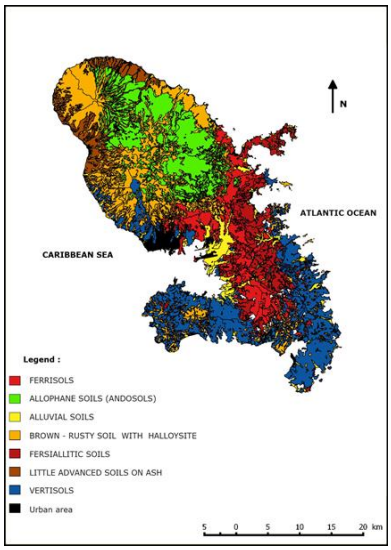

Figure 8: Map of the soils of Martinique. (Source: IRD)[12].

1. d. Zoning

The methodology applied for this zoning of *Coffea liberica* is the same as that applied previously for that of *C. arabica* and *C. canephora* (Jean-Philippe, C., 2015; Claude, JP., 2016; Claude, J. P., 2017, (b)). The edapho-climatic requirements of *C. liberica* have been defined using the world's scientific literature (Table 1), (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012). Thermal and rainfall range as well as soil types form the basis of pedoclimatic zoning (Table 2).

Table 1 : Basis of pedoclimatic zoning Coffea liberica.

	Acceptable
Minimum annual average temperatures	Minimum limit of the thermal tolerance range: 18°C (optimum 24°C)
Maximum annual average temperatures	Maximum limit of the thermal tolerance range: 36°C (optimum 30°C)
Annual rainfall	1100 to 3500 mm (optimum 1600 to 2400 mm)
Soil types	Ferrisols, Andosols, Alluvial Soils, Rusty-Brown Soils with Halloysite, Fersiallitic soils

The requests in the QGIS version 2.18.14 software were made using the raster calculator option. To obtain the pedoclimatic zoning of *C. liberica* with the widest possible values of the ecological profile of this species (Table 2), the request was formulated as follows: [minimum temperatures] ≥ 18 + [maximum temperatures] ≤ 36 + [annual rainfall] ≤ 3500 + [soils] = 1. The soils map was pre-selected in order to retain only soils considered suitable (Ferrisols, Andosols, Alluvial Soils, Rusty-Brown Soils with Halloysite, Fersiallitic soils). This gave a simplified map with two identifiers: 0 corresponding to unfit soils and 1 corresponding to soils suitable for cultivation. A map of acceptable areas for *Coffea liberica* cultivation in Martinique is obtained (Figure 9). The pedoclimatic zoning of *C. liberica* reveals more potential for cultivation than the other two species of coffee: Arabica and Robusta.

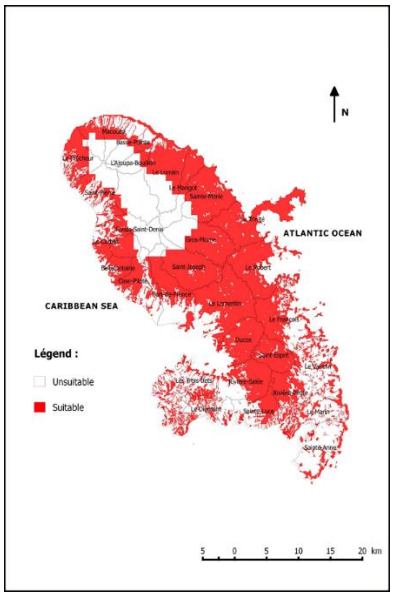

Figure 9: Pedoclimatic zoning of Coffea liberica in Martinique.

2. Agro-climatic zoning for *Coffea liberica* in the 2071-2100 time horizon.

2.a. Temperatures

The climate projections for the 2071-2100 time horizon used here come again from the National Meteorology Services (Météo-France). This is the RCP 4.5 scenario. According to these projections, average minimum temperatures in Martinique are expected to increase throughout the country. No area, not even the highest peaks of the island, will be unaffected.

The average annual minimum temperatures expected on the island for the latter part of the century (2071-2100) will not drop below 16°C. The risk of freezing will continue to be non-existent (Figure 10). The average minimum temperatures will be even higher than today for the entire territory and may reach up to 26°C. If minimum temperatures increase everywhere,

[12] Illustration from: Claude, J. P. (2016). Environments Suitable for the Species of the Coffea genus in Martinique (The case of Coffea Arabica Typica Variety). International Journal of Recent Research and Review.

only the highest peaks in the north of the island will have minimum temperatures below 20°C (Figures 3 and 10). Mean annual maximum temperatures will increase significantly across the entire territory, from the 21° to 32°C currently measured to 23° to 33°C in 2071-2100 (Figures 6 and 11). Most of the island is expected to experience average maximum temperatures often between 29° and 33°C (Figure 11). The highest summits of the island (in the north) will not be exempt either from the rise in temperatures but will always present the lowest figures. Furthermore, the average maximum temperatures that will be measured on the highest peaks in 2071 will begin at 23°C, an increase on 21°C today (Figure 11). This RCP Scenario 4.5 from the national meteorological climate projections (the most optimistic scenario used here, among others) predicts an overall rise in temperatures for the entire island. This thermal gradient of Martinique will clearly be favourable neither to *Coffea arabica* nor to *Coffea canephora* but appears suitable for *Coffea liberica*.

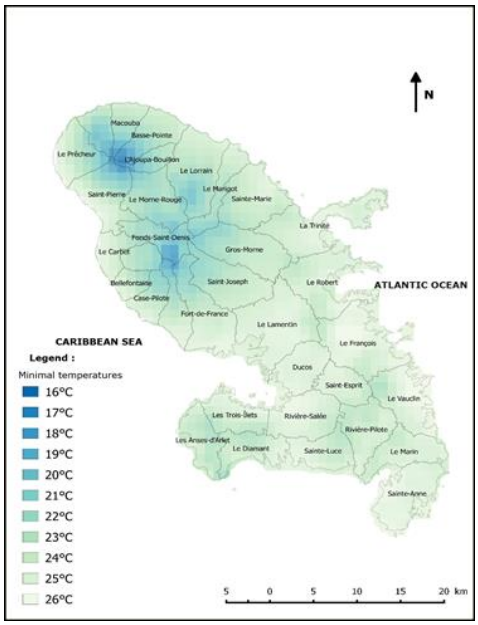

Figure 10: Minimum annual average temperatures (scenario RCP 4.5, 2071-2100). (Source: Météo-France)[13].

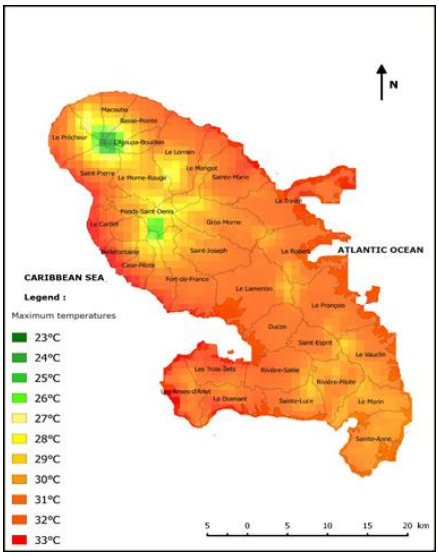

Figure 11: Maximum annual average temperatures (scenario RCP 4.5, 2071-2100). (Source: Météo-France)[14].

2. b. Rainfall

The climate projections for the 2071-2100 time horizon used here also come from the National Meteorology Services (Météo-France, scenario RCP 4.5). For the 2071-2100 time horizon, Météo-France predicts a significant change in the rainfall gradient of the island, specifically in the dry subhumid and hyper-humid bioclimate (Figures 4 and 12). The rainfall gradient of Martinique is currently between 1200 mm in the coastal region and more than 6000 mm of water on the highest peaks in the north of the island and should increase to 1500 mm in the coastal region and more than 5000 mm of water on the highest peaks (Figures 3 and 12).

Météo-France is therefore forecasting a significant rise in rainfall in the coastal region, with the lowest cumulative annual rainfall corresponding to the dry subhumid bioclimate. This should not disappear either. Simultaneously, Météo-France is also predicting a decrease in rainfall on the highest peaks corresponding to the hyperhumid bioclimate, which should not disappear either. If an increase in rainfall in dry subhumid bioclimate will not be significant for coffee cultivation (with it being already favourable), the expected decrease in the hyper-humid bioclimate will not change the delineation of the coffee-friendly environments in Martinique. Only *C. liberica* tolerates heavy rains, but the cumulative annual rainfall does not exceed 3500 mm ((Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987;

[13] Illustration from: Claude, J. P. (2016). Environments Suitable for the Species of the Coffea genus in Martinique (The case of Coffea Arabica Typica Variety). International Journal of Recent Research and Review.

[14] Illustration from: Claude, J. P. (2016). Environments Suitable for the Species of the Coffea genus in Martinique (The case of Coffea Arabica Typica Variety). International Journal of Recent Research and Review.

Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop).

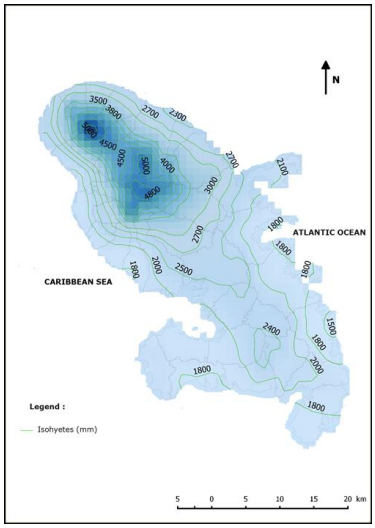

Figure 12: Annual rainfall (scenario RCP 4.5, 2071-2100). (Source: Météo-France)[15].

2. c. Zoning

The methodology applied for this agro-climatic zoning of *Coffea liberica* is the same as that applied previously for that of *C. arabica* and *C. canephora* (Jean-Philippe, C., 2015; Claude, J.P., 2016; Claude, J.P., 2017, (b)). Based on the ecological profile of *C. liberica* defined in the world's scientific literature (Table 1), we establish the basis of our agro-climatic zoning (Table 3), according to the average minimum and maximum annual temperatures and rainfall (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012).

Table 2: Basis of agro-climatic zoning for Coffea liberica.

	Acceptable
Minimum annual average temperatures	Minimum limit of the thermal tolerance range: 18°C (optimum 24°C)
Maximum annual average temperatures	Maximum limit of the thermal tolerance range: 36°C (optimum 30°C)
Annual rainfall	1100 to 3500 mm (optimum 1600 to 2400 mm)

Using the GIS software QGIS 2.18.14, the "raster calculator" function was used again to perform the request. To obtain the zoning, the request was formulated as follows: [minimum temperatures] ≥ 18 + [maximum temperatures] ≤ 36 + [annual rainfall] ≤ 3500. We obtain Figure 13 which shows the areas suitable for the cultivation of Liberica coffee for the 2071-2100 time horizon.

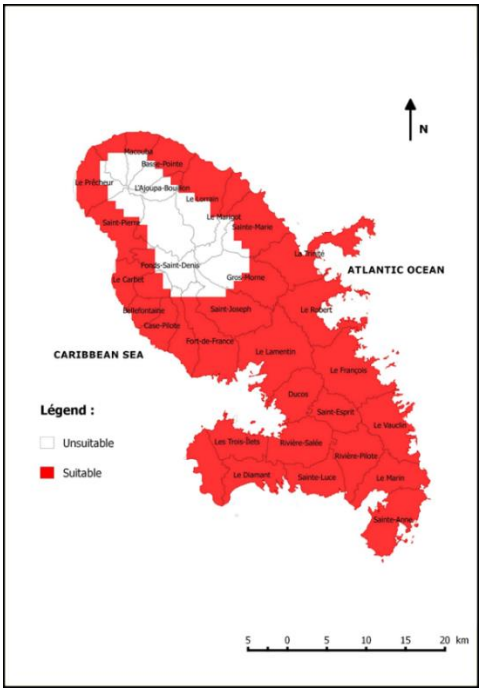

Figure 13: Agro-climatic zoning for Coffea liberica in Martinique.

Discussion

The first pedoclimatic zoning that was carried out for the first species of coffee tree: *Coffea arabica*, resulted in an inability to produce a quality coffee for the future, with rainfall representing a constraining and limiting factor and the species requiring lower annual average temperatures and which do not approach 30°C (Jean-Philippe Claude, 2015 ; Claude, J. P., 2016). The second zoning carried out for the second species of coffee: *Coffea canephora*, was more fruitful and resulted in real but limited possibilities for its cultivation (Claude, J. P., 2017, (b)). The tolerance of *C. canephora* to temperatures around 30°C gave it, according to the results obtained, more possibilities for adaptation to the environmental conditions of Martinique than Arabica.

This third pedoclimatic zoning carried out for the last exogenous species of the Coffea genus shows more possibilities for cultivation than for the other two species of coffee. *Coffea liberica* seems the most suited to the environmental conditions of the island (Figure 14). In fact, it is the only species that tolerates or even thrives in temperatures around 30°C and above (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988;

[15] Illustration from: Claude, J. P. (2016). Environments Suitable for the Species of the Coffea genus in Martinique (The case of Coffea Arabica Typica Variety). International Journal of Recent Research and Review.

Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012). Its optimum is between 24° and 30°C unlike Canephora and Arabica, whose optimums are 22° to 26°C and 18° to 22°C respectively (Jean-Philippe Claude, 2015; Claude, J. P., 2016; Claude, J. P., 2017, (b)).

Overall, these three coffee trees appear to be suited to these bioclimates: dry subhumid and humid subhumid (formerly dry and moderately humid bioclimate, figure 4). They require and tolerate overall annual rainfall between 1200 and 3000 mm, which corresponds to the zones between the coastal region and the maximum altitudes of 600 to 800 metres in Martinique (DaMatta, F. M., et al., 2007; Meireles, E ., et al., 2007; Barel, M., 2008; Bart, F., 2007; Elzebroek A. T. G., 2008; Pinard, F., 2008; Pohlan, H. A. J., et al., 2010; Zullo Jr, et al. , 2011; Soto, F., 2013; Jean-Philippe Claude, 2015; Claude, J. P., 2016; Claude, J. P., 2017, (b)). Only *Coffea liberica* tolerates very heavy rains and can grow at heights where annual rainfall can reach 3500 mm (Purseglove, J.W., 1974; Landon, J. R., 1984; Roecklein, J. C., 1987; Hensleigh, T. E., 1988; Onwueme, I. C., 1991; Website: Ecocrop; Teketay, D., 1999; Clifford, M. N., 2012).

The coffee trees are also generally able to grow on several types of soils. These can be corrected if they are not suitable using appropriate cultivation techniques (Rutunga, V., et al., 1994; Tulet, J. C., 1998; Harorimana, D., et al., 2007; ROSA, V 2007, Pohlan, H. A. J., et al., 2010. Solórzano, N., et al., 2010; Chemura, A., 2014).

Our results are therefore in line with the descriptions in the world's scientific literature that *Coffea arabica* requires coolness and can only be found at sufficiently high altitudes. However, rainfall in Martinique is a highly limiting factor when it comes to its expansion (Jean-Philippe Claude, 2015; Claude, J. P., 2016). *Coffea Canephora* thrives in warmth and humidity and is found at low altitudes, finding suitable environments for its installation on the island (Claude, J. P., 2017, (b)). *C. liberica* presents essentially the same ecology but is the most suited to Martinique (Figure 4).

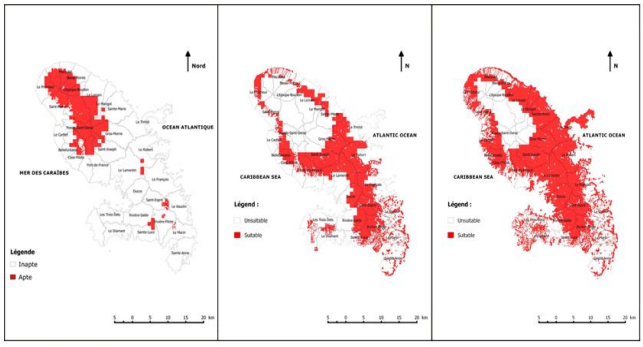

Figure 14 : Pedoclimatic zoningof Coffea arabica, Coffea canephora and Coffea liberica.

These pedoclimatic zonings have on the whole made it possible to highlight the highly restrictive nature of Martinqiue's environmental conditions. This has led to difficulties in identifying optimal areas for the cultivation of species from the Coffea genus. Only zones which are acceptable and not optimal have been identified. Firstly, the amount of rainfall in the northern part of the island, particularly at the level of the high peaks, is too high (from 3000 mm to more than 6000 mm of annual water accumulation), while the lowest average annual maximum temperatures are experienced there (Figures 3, 5, 6, 7). The rest of the island is more conducive to the cultivation of the coffee tress because the rainfall level is much lower (1200 mm to 3000 mm of cumulated annual water). However, the highest average maximum temperatures are experienced there, which represents a highly restrictive factor, especially for Arabica.

Finally, it was also possible to evaluate the likely effects on coffee cultivation of the new climatic constraints predicted for Martinique for the 2071-2100 time. Unsurprisingly, the forecasts of the National Meteorology Services are not favourable for coffee cultivation in Martinique, with the exception of *Coffea liberica* (scenario RCP 4.5, one of the two simulations of Aladin-Climat for the Lesser Antilles, at a resolution of 10km), (Météo-France Antilles Guyana, D.M., 2012; Cantet, P., et al., 2014). Indeed, these forecasts predict a rise in temperatures throughout the territory making it impossible to envisage the production of a quality Arabica coffee and possibilities which are too limited for Canephora for the time horizon 2071-2100 (Claude, J. P., 2016; Claude, J. P., 2017, (b)). Once more it is only Liberica which presents increased possibilities for cultivation because of its tolerance to very high temperatures and heavy rainfall.

Three centuries after the introduction and cultivation of coffee in Martinique, the results obtained after drawing up these various pedoclimatic and agro-climatic zonings carried out for *Coffea arabica, canephora* and *liberica* pose questions to us

regarding the coffee era that the island of Martinique would have witnessed. The famous "Martinique" coffee, which was able to be produced from the 18th to the 19th century, probably had to be produced exclusively by mixing grains from several coffee trees.

Figure 15: Photos: Coffea arabica, Coffea canephora, Coffea liberica (Martinique, 2015).

Conclusion

This study was conducted using eco-climatic data collected from the Martinican institutions with expertise in the production of environmental data for Martinique. The limits regarding carrying out pedoclimatic and agro-climatic zonings are known in the world: namely approximation or the neglect of microclimates (Wollmann, C. A., et al., 2013). Zoning for species of the Coffea genus (Rubiaceae family) come under macroecology. They rely on the use of geographic information systems (GIS) whose efficiency has been proven around the world.

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