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CLIMATIC CHANGES AND DISTRIBUTION OF PLANT FORMATIONS IN THE STATE OF PARAIBA, BRAZIL

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ABSTRACT. The state of Paraíba in northeast Brazil contains four of the seven biomes present in the country: Mata Atlântica, Cerrado, Caatinga and Matas Serranas. On the other hand, Amazônia, Pantanal and Pampa were not found in this area. This special situation allows us to analyse changes in the distribution of these four large Brazilian biomes according to bioclimatic conditions, using the methodology of bioclimatic regime types. Based on the analysis of variables from periods of hydric and thermal vegetation stagnation, obtained from hydric and bioclimatic balances, average monthly temperature and rainfall, that methodology enables us to establish a typology of 27 types of bioclimatic regimes and 243 bioclimatic regime subtypes with the 9 Thornthwaite ombrothermal levels. In Paraíba 4 types of bioclimatic regimes are currently identified (mesophyllo, tropophyllo, xerophyllo and eurythermophilous) and 9 subtypes according to ombrothermal levels. In order to analyse the changes, extreme change situations were chosen: a past scenario with the Last Glacial Maximum (40 ky); and an RCP 8.5 climate change scenario for the CMSS 4.0 model for the year 2070. This enabled 3 bioclimatic regime maps of each of the 3 aforementioned situations to be obtained, providing a map of potential distribution of the plant formations of Paraíba state according to the specific field knowledge and bioclimatic mapping obtained for the present. This paper concludes that a retrocession of the Mata Atlântica can be seen from the Last Glacial Maximum up to the present, losing its optimal bioclimatic conditions and therefore remaining in a highly fragile relict situation in the face of anthropic pressure (sugarcane cultivation and urban expansion); an advance toward 2070 of the Caatinga in its shrub form as a predominant formation is indicated by the projection of climate change in 2070 for the analysed situation, specifically resulting from anthropic pressure, in this case due to livestock activities which have affected this biome in Paraíba since the mid-19th century.

Cambios climáticos y distribución de las formaciones vegetales en el Estado de Paraiba, Brasil

RESUMEN. El estado de Paraiba en el nordeste del país, recoge cuatro de los siete biomas presentes en Brasil: la Mata Atlántica, el Cerrado, la Caatinga y las Matas Serranas. Por otro lado, Amazonia, Pantanal y Pampa no se encontraron en esta área. Esta situación especial nos permite hacer un análisis de los cambios en la distribución de estos cuatro grandes biomas brasileños en función de las condiciones bioclimáticas con el uso de la metodología de tipos regímenes bioclimáticos. Dicha metodología, a partir del análisis de las variables de los periodos de paralización vegetativa hídrica y térmica, obtenidos de los balances hídricos y bioclimáticos, la precipitación y la temperatura media mensual, nos permite establecer una tipología de 27 tipos de regímenes bioclimáticos y 243 subtipos de regímenes bioclimáticos con los 9 niveles ombrotérmicos de Thornthwaite. Se identifican actualmente para Paraiba 4 tipos de regímenes bioclimáticos (mesophyllo, tropophyllo, xerophyllo y euritermophyllo) y 9 subtipos en función de los niveles ombrotérmicos. Para poder hacer un análisis de cambios se han elegido situaciones extremas de cambio: por un lado, un escenario del pasado con el Ultimo Máximo Glaciar (40 ky), y por otro un escenario de cambio climático RCP 8.5 para el modelo CMSS 4.0 para el año 2070. Se obtienen así 3 cartografías de regímenes bioclimáticos de cada una de las tres situaciones citadas y se aporta una cartografía de la distribución potencial de las formaciones vegetales del estado de Paraiba en función de los propios conocimientos de campo y de la cartografía bioclimática que se ha obtenido para la actualidad. Como conclusión de este trabajo se puede ver un retroceso de la Mata Atlántica desde el Ultimo máximo Glaciar hasta la actualidad, perdiendo son condiciones bioclimáticas óptimas y quedando por lo tanto en una situación relicta de alta fragilidad ante la presión antrópica (cultivos de caña de azúcar y expansión urbana) y un avance hacia el 2070 de la caatinga en su forma arbustiva como formación predominante según marca la proyección del cambio climático en el 2070 para el escenario analizado, y como resultado de la propio acción antrópica, en este caso con actividades ganaderas, que se viene ejerciendo sobre este bioma en Paraiba desde mediados del siglo XIX.

Key words: Bioclimatic regimes, climate change, Caatinga, Mata Atlântica, Paraíba.

Palabras clave: Regímenes bioclimáticos, cambio climático, Caatinga, Mata Atlântica, Paraíba.

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1.Introduction

The idea of potential vegetation is based on the existence of non-restrictive bioclimatic values of field capacity at a given temperature and precipitation for the respective place. We do not include the climax concept of Clements (1916), whereby each climate zone presents a single possible climax community, though the state of maturity implies an edaphic evolution which in turn interacts on the vegetation itself, and all this considering that the climate conditions remain stable over time, something which, as is known, does not happen. It is currently accepted that mature plant formations change as a result of climate change and are continually subject to changes in factors which could be defined as disruptive (such as anthropic management) or naturals.

Potential vegetation enables us to establish what the specific and structural vertical and horizontal composition and state of the plant formations are for some given bioclimatic conditions, without considering the textural soil conditions which mark the field capacity and hence the availability of subsurface water (Mather and Yoshioka, 1966; Tuhkanen, 1980). In other words, in optimal conditions: dense or open forest, shrub and grassland formations.

Using data from inventories of vegetation and current vegetation coverage in those places as anthropically unchanged as possible, to obtain, based on potential conditions, significant interpretations and results, which are fundamental in order to undertake more scientifically precise interventions for conservation, preservation and recovery of degraded areas.

Numerous vegetation and bioclimatic classifications exist in scientific literature, though none of them establish a direct relationship between the bioclimatic variables of thermal and hydric vegetation stagnation and the type of corresponding plant formation.

This paper presents the application of new methodology developed by Cámara *et al.* (2020) in which those variables are considered and applied to the state of Paraíba, Brazil. Its aim is to establish a potential bioclimatic framework so that, based on it, analogies can be drawn between some vegetation inventories done in that state and to thereby attain and identify distribution patterns according to bioclimatic variables, ultimately determining just how far local conditions of the physical environment and anthropisation have influenced that distribution. But it also allows, based on continuous climate data, the evolution or dynamics of the potential vegetation to be established from the past up to the present, along with the respective projection into the future, depending on the climate change scenarios. This can help raise society's awareness about the value of those plant formations and their conservation, and about humankind's own natural living resources. The most characteristic plant formations of the State of Paraiba range from very humid situations (ombrophyllas) with the Atlantic Forest on the coast, to extreme arid situations such as the caatinga xerophylla in the continental interior.

2.Materials and methods

To carry out this work, the methodology of Cámara (1997) and Cámara *et al.* (2020) was used, based on the completion of 1,500 bioclimatic diagrams of North America, South America, Central America, the Caribbean, Europe, Africa and Asia, identifying the bioclimatic indicators to establish the bioclimatic regime conditions for each plant formation in its corresponding bioclimatic zone. This is a geo-botanic research method based on analysis of parametric data, expressed by means of two graphs showing the hydric balance of (HB) of Thornthwaite (Thornthwaite *et al.,* 1956, 1957) and the bioclimatic balance (BB) of Montero de Burgos and González Rebollar (Montero and González, 1974).

It is grounded on the combination of information about the texture of the geomorphologic surface formations (expressed by means of field capacity or water available for plants until soil saturation), with the vegetation coverage/root depth. The monthly value obtained for runoff in the HB is used to correct the monthly useful precipitation (p) value for plants in the BB. With this contribution the balances are mutually related to each other and in turn to the surface formations that sustain the vegetation and the specific vegetation type in the respective vertical and horizontal structure.

When the bioclimatic limits and values (precipitation, temperature and thermal and hydric vegetation stagnation) of the plant formations and their distribution are related to the bioclimatic ranges, an environmental description is obtained, adjusted to seasonal time factors (months of the year): temperature/rainfall (mean T and monthly P), edaphic/sediment (field capacity) and spatial (vegetation distribution). We call this environmental description the bioclimatic regime. Each of these bioclimatic regimes can be subject to further nuances as the edaphic/sediment factor is more precisely detailed, along with the scale in which it is considered; this enables multi-scale application of this method. On small continental or regional (1:1,000,000-1:200,000) scale and also medium (1:50,000) scale, the potential values are considered, i.e., with no restriction by field capacity or vegetation coverage (FC = 400 mm). If we work at a detailed scale (1:10,000-1:5,000), the real coverage and field capacity values are considered.

The edaphologic factor is not considered in this paper due to its scale of detail and treatment; the altitudes are reflected in the data obtained in the Worldclim continuous climate database (http://worldclim.org/version2) (Fick y Hijmans, 2017), from which mean annual and monthly temperature values and monthly and annual precipitation values were extracted.

Depending on the thermal conditions, vegetation situated in a place according to thermal limitation is defined in the classification based on the postulates of Schimper (1903), Warming (1909) and Huguet del Villar (1929) in Cámara *et al.* (2020):

- Thermophyllo: located in places with no thermal restrictions and with reduced annual thermal range. Hydric vegetation stagnation may exist;

- Eurythermophyllo: substantial thermal variation during the year and in each month, but without thermal vegetation stagnation occurring;
- Criophyllo: presents when there is short to medium thermal stagnation lasting from 1 to 5 months, with deciduous species predominating;
- Mesocriophyllo: presents in places where thermal stagnation lasts from 6 to 9 months, conditioning the distribution of broadleaf vegetation;
- Hypercriophyllo: limiting the development of woody species, with from 10 to 12 months of thermal vegetation stagnation.

As with temperature, depending on the limitation imposed by the lack of water in a space, different situations will present (Cámara *et al.,* 2020), also following the above postulates:

- Ombrophyllo, presenting in places where there is no water deficit throughout the year (precipitation is more than 60 mm in all months);
- Mesophyllo, more hydric scarcity but without that leading to vegetation stagnation. Some months may present a hydric deficit in the soil;
- Tropophyllo, when there is an edaphic hydric deficit that gives way to vegetation stagnation, as long as it lasts from 1 to 4 months. In the case of the tropics, this concerns tropical deciduous forests, which may present thorns;
- Xerophyllo, if the hydric conditions lead to a longer vegetation stagnation, lasting from 5 to 8 months. Thorny *crassulaceae* and shrubs predominate;
- Hyperxerophyllo, with 9 to 12 months of hydric vegetation stagnation, with shrub vegetation and open *crassulaceae*, very dispersed, or practically without it.

For the procedure of calculating and obtaining the mapping of Paraíba's climate regimes the Worldclim database was used (Fick and Hijmans, 2017); the mapping algebra in the ArcGis software was employed to obtain the different bioclimatic regimes present in the state's territory. To do so, the mapping of months with hydric and thermal vegetation stagnation, total precipitation, potential evapotranspiration and average monthly temperature were used as variables. Based on those variables, algorithms were used to establish each type of bioclimatic regime (Cámara *et al.,* 2020).

In accordance with the presented characteristics, 5 major macro-scale zonal categories were identified, along with 27 meso-scale 'bioclimatic regime' types. Likewise, based on the ombrothermal index of Thornthwaite and crossing it with the 27 BRTs, 162 subtypes are obtained (of the 243 possible). This is a typology that closely represents the distribution of the large groups of biomes: tundra, boreal coniferous forests, mixed forests, deciduous forests, cold prairies, warm steppes, subtropical forests and humid and dry tropical forests (Table 1).

Using this methodology, three maps of the study area were developed: one of the Last Glacial Maximum (22 ky), with a pixel size of 4.61 km, and two others with a pixel size of 0.92 km, showing the present and the RCP 8.5 scenario for the CCSM4.0 coupled climate change model, to simulate the climate system of the Earth. It is a cooperative effort between climate researchers from the USA, supported by the National Science Foundation (NSF) and centred at the National Centre for Atmospheric Research (NCAR), comprising five separate models which simultaneously simulate the Earth's atmosphere, ocean, land, terrestrial ice and sea ice, plus a central coupling component. The CCSM enables researchers to conduct fundamental studies about past, present and future states of the Earth's climate.

Table 1. Bioclimatic regimes related to terrestrial biomes. Months of hydric vegetation stagnation (first column) and months of hydric vegetation stagnation (first row). Own production.

PVH/ PVT	**0**	**0**	**1 to 4**	**5 to 8**	**9 to 12**
0	OMBROPHYLLO Rainforest	MESOPHYLLO Semi-deciduous forest	TROPOPHYLLO Dry forest	XEROPHYLLO Thorny scrub	HIPERXEROPHYLLO Warm desert
0	EURITERMO OMBROPHYLLO Laurisilva forest	EURITERMO MESOPHYLLO Subtropical deciduous forest	EURITERMO TROPOPHYLLO Subtropical sclerophyllous forest	EURITERMO XEROPHYLLO Subtropical sclerophyllous shrubland	EURITERMO HIPERXEROPHYLLO Warm steppe
1 to 5	CRIO OMBROPHYLLO Broadleaf deciduous forest	CRIO MESOPHYLLO Mixed broadleaf deciduous and coniferous forest	CRIO TROPOPHYLLO Mixed coniferous and broadleaf deciduous forest	CRIO XEROPHYLLO Conifer shrubs	CRIO HIPERXEROPHYLLO Cold steppe
6 to 9	MESOCRIO OMBROPHYLLO coniferous forest (firs)	MESOCRIO MESOPHYLLO Mixed coniferous forest	MESOCRIO TROPOPHYLLO Deciduous coniferous and coniferous forest	MESOCRIO XEROPHYLLO *Ericaceae* scrub	MESOCRIO HIPERXEROPHYLLO Cold desert
10 to 12	HIPERCRIO OMBROPHYLLO Tundra Open shrub coniferous	HIPERCRIO MESOPHYLLO Tundra (deciduous shrub)	HIPERCRIO TROPOPHYLLO Tundra (*Ericaceae* and *Cyperaceae*)	HIPERCRIO XEROPHYLLO Tundra (lichens and bush willow)	HIPERCRIO HIPERXEROPHYLLO tundra/ice

3. Study area

The state of Paraíba is situated in the northeast of the Federated Republic of Brazil, with an area of 56,585 km^2 (Fig. 1). It stretches from east to west from the Atlantic Ocean to the interior of the Brazilian Shield, presenting ecosystems that gradually change from the Mata Atlântica and Cerrado de Tabuleiro by the coast to the Caatinga in the inland sector. The Caatinga biome dominates much of its territory and is associated to a tropophyllo bioclimatic regime, and in more arid conditions to the xerophyllo regime. In coastal areas where the Mata Atlântica and Cerrado are found, they are only present in mesophyllo bioclimatic regimes, even though the Atlantic forest is actually a refuge of an ombrophyllo forest developed in other more humid past climate conditions (Fig. 2). This methodology allows to establish which are the changes in the bioclimatic regimes and their relationship with the plant formations, which also implies changes in the anthropic agricultural uses of the territory. Xerification, for example, not only affects natural vegetation, but also soil uses that are practiced in that territory. In intertropical environments these changes in soil use can be very important, because they change economic relations. It also can lead, in less developed countries, to food crises.

Paraíba's relief is formed by four large units (Carvalho, 1982) that condition the state's bioclimatic features and hence the distribution of plant formations:

- the littoral unit with the Low Coastal Plain and the table-like relief of the Tabuleiro;
- the Brazilian Shield, which with its levels of pediplanation in this sector forms the Boroborema highlands (400 to 600 m altitude), mainly drained by the basin of the Paraíba River, which flows into the Atlantic;
- the Sertão depression (200 to 400 m altitude) in the western part, also on the Brazilian Shield, drained by the Piranhas River;
- the mountain reliefs south of the Sertão and the Cariri, which reach 1,000 m altitude, and the Areia range in the Agreste, where the bioclimatic conditions become more humid.

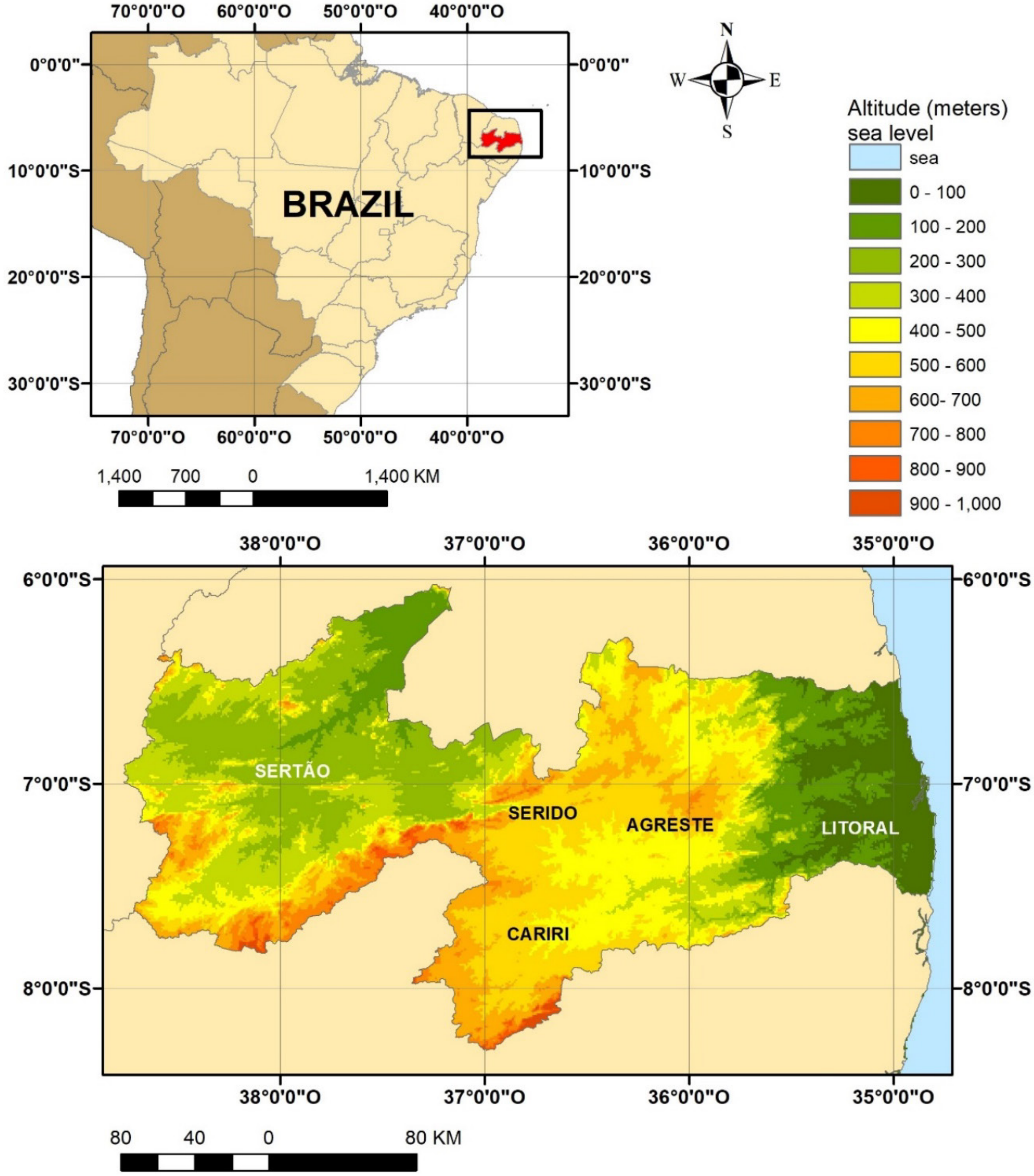

Figure 1. Location of the state of Paraíba in the Federative Republic of Brazil and its physiography. Own production based on SRTM 30 ascseg of the United States Geological Survey.

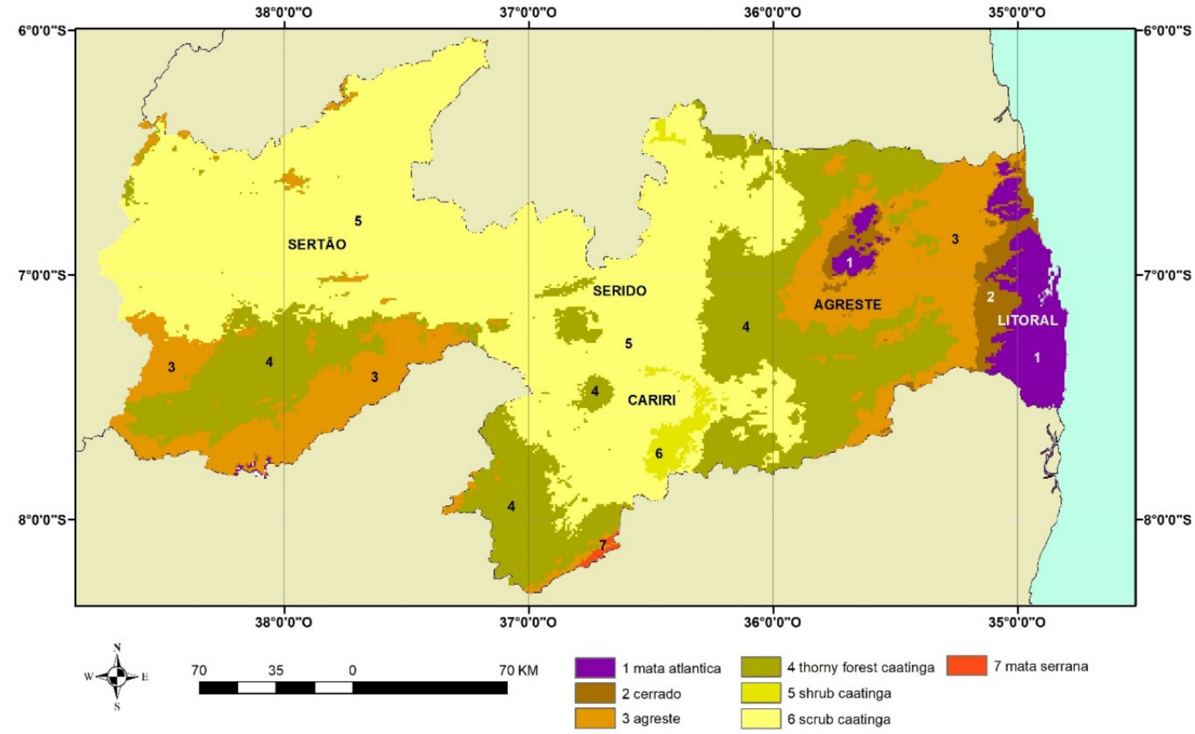

Figure 2. Distribution of plant formations in Paraíba state according to bioclimatic conditions. Own production.

The Mata Atlântica is a humid forest situated along the coast of Brazil, extending southward from the state of Rio Grande do Norte as far as Paraguay and Argentina (Misiones province) (Peres *et al.,* 2020; Morellato *et al.,* 2000; Mori *et al.,* 1981) in an inferior humid to subhumid-humid mesophyllo bioclimatic regime. It is highly threatened and very fragmented by anthropic action, especially sugarcane cultivation. In Paraíba state the impact is very high and only fragments remain (Ranta *et al.,* 1998; Thomas, 2008; Oliveira, 1993), which in the capital João Pessoa have been absorbed by urban sprawl, remaining as islands in the middle of the city (Mata do Buraquinho) (Paladini and Cámara, 2015; Paladini, 2016) (Fig. 3).

The vegetation inventory plots done in this area (Paladini, 2016) identified the following dominant species: *Ephedranthus pisocarpus, Campomanesia dichotoma, Blepharocalyx salicifolius* and *Cupania revolute*; the most abundant families were *Myrtaceae* and *Sapindaceae*, typical of the Mata Atlântica, though there were also Cerrado species, with *Eugenia punicifolia, Hancornia speciosa, Maytenus obtusifolia* and *Anacardium occidentale* standing out, with the families *Apocynaceae, Myrtaceae, Celastraceae* and *Malpigiaceae* the most abundant.

The Agreste is a transition plant formation between the Mata Atlântica and the Caatinga, with a predominance of deciduous species, mainly from the Caatinga. It is distributed as a narrow fringe parallel to the coast in the Brazilian states of Bahía, Sergipe, Alagoas, Pernambuco (Rodrigues de Lira *et al.,* 2010), Paraíba (Rodrigues *et al,* 2014) and Rio Grande do Norte (Fig. 4), in conditions of subhumid-dry tropophyllo bioclimatic regime.

Figure 3. Interior of the Mata Atlântica forest in Mata do Buraquinho (João Pessoa) in the coastal zone of Paraíba. July 2015. Photo by R. Cámara.

Figure 4. Vegetation of the Agreste in an area of inselbergs (Araruna Municipality) and 'savannization' of forest for livestock grazing. July 2020. Photo by B. Israel de Souza.

The Cerrado de Tabuleiro (Rizzini, 1992) is a plant formation related to the Cerrado biome which mainly occurs in the central/western region of Brazil (Cole, 1986; Furley y Ratter, 1988; Riou, 1995) but which also develops on the geomorphic formation of the Tabuleiro, formed by silts and sands from the Barreiras Formation (Pliocene) (Silva *et al.,* 2015) on the coast of northeast Brazil (Freire *et al.,* 2011). This plant formation presents species typical of the Cerrado; although found in subhumid-dry mesophyllo regime bioclimatic conditions, the substrate of sands and silts of the Barreiras Formation favours situations of edaphic xericity, enabling this formation to develop instead of the Mata Atlântica (Paladini, 2016). Collapse erosion has occurred over this geologic formation, caused by major storms and very fast subsurface circulation through erosion pipes, called *voçorocas*, with species from the Mata Atlântica situated at the bottom due to the concentrated humidity (Paladini, 2016) (Fig. 5).

Figure 5. Cerrado de Tabulerio in Conde Municipality (Paraíba coast). January 2020. Photo by B. Israel de Souza.

Until the 1960s there was very little agricultural use due to the acid and nutrient-poor soils where it is located. The vegetation was therefore largely preserved. That situation changed starting in the 1970s, due to the National Alcohol Programme (Pró-Alcool) and the federal government's incentives for fuel production using plant biomass derived from sugarcane to reduce dependence on petroleum imports (Moreira and Targino, 1997; Paladini, 2016).

There is a disjunction in the subhumid-dry tropophyllo bioclimatic regime found in two specific points of the state: northeast of the city of Campina Grande in Areia municipality in the Borborema highlands. Between 600 and 750 m, in windward conditions that permit rain with an average of up to 1,200 mm/year, where a humid and subhumid tropical forest is distributed, regionally known in this part of Brazil as Brejo de Altitude (Tabarelli and Santos, 2004; Ab'Saber, 2003).

The Caatinga is the dominant plant formation in the interior of Paraíba state in the Planalto da Borborema and the Sertão. It presents three different structures according to the bioclimatic regime and humidity conditions. In semiarid tropophyllo regime bioclimatic conditions thorny forest formations predominate (Fig. 6). In the municipalities of São João do Tigre and Caturité, on the surface of the Cariris Velhos range between 600 and 750 m, the dominant species are *Mimosa ophthalmocentra, Capparis flexuosa, Anadenanthera colubrina, Aspidosperma pyrifolium, Ziziphus joazeiro* and *Commiphora leptophloeos* (Porto de Lima, 2012).

Figure 6. Area with preserved Caatinga forest coverage in the municipality of São João do Tigre. September 2017. Photo by B. Israel de Souza,

In situations of greater anthropic disruption or more xericity in semiarid xerophyllo biocomiatic regime high and closed scrub formations develop. The inventories done in Coxixola municipality show that the dominant species are *Croton sonderianus* and *Myracrodruon urundeuva*.

In the Cariri range, close to the municipality of São Domingos do Cariri, there is a more xeric region with an arid xerophyllo bioclimatic regime and open bush and low thorny deciduous formations (Porto de Lima, 2012), with *Poincianella pyramidalis* and numerous cacti such as *Pilosocereus catingicola*, *Pilosocereus polygonus* (xique-xique) and bromeliaceae (*Bromelia laciniosa*) densely covering the ground.

In the work developed by Souza *et al.* (2015) in the municipality of São Domingos do Cariri, in a landscape notable for the few individuals and the low diversity of plant species, *Poincianella pyramidalis* was one of those that stood out with respect to the others, a common feature in this part of Paraíba, according to Barbosa *et al.* (2007). Alongside *Croton sonderianus* and *Aspidosperma pyrifolium*, *Poincianella pyramidalis* presents as dominant in most of the phyto-sociological survey work done in the Caatinga (Sampaio, 1996).

Unlike the situation we have in the Paraíba highlands and in the Sertão, the data from the Serra do Paulo, southwest of the Paraíba River basin in the Cariri, show the importance of mountainous areas in the Caatinga biome. In these situations, there is generally a higher average amount of rain and lower temperatures compared to areas at lower altitude, which favours the presence of more vegetation with greater diversity (Sampaio, 2010), known as Matas Serranas, which correspond to a subhumid-dry eurythermophilous bioclimatic regime. Furthermore, the abrupt topography of some hillsides hampers the presence of more human usage in various localities; this is therefore a decisive factor in the presence of vegetation coverage that is still relatively preserved (Fig. 7).

In the case of the region of Areia municipality and its surroundings, there is a disjunction of the Mata Atlântica in the state's interior, in humid mountains, known as Brejos de Altitude. They were largely substituted in the past, not just by sugarcane to produce cachaça and rapadura (unrefined whole cane sugar), but also by coffee cultivation and, starting in the second half of the 20th century, by cattle pastureland (Moreira and Targino, 1997).

Figure 7. Interior of the State Park of Mata do Pau-Ferro (Areia municipality), with Brejos de Altitude vegetation. Photo by Joel Maciel Pereira Cordeiro, September de 2017.

4. Results

Three bioclimatic maps were obtained using the aforementioned methodology, based on the continuous Worldclim databases. First, a map of the current bioclimatic situation, which enabled us to reference the bioclimatic regimes identified with the current plant formations, based on our field experience in the study area (Fig. 8). We used it to produce Tables 2 and 3, which show the extent of the bioclimatic regime types and the plant formations described in the previous section.

In Paraíba state it is possible to identify the thermophilous regime, located in places without thermal limitations and with a low annual thermal range. The eurythermophilous regime is occasionally found, with significant thermal variation during the course of the year and in each month, though without any vegetation stagnation due to thermal causes. In the resulting map of Paraíba state, 4 of the 27 types of bioclimatic regimes were obtained: mesophyllo, tropophyllo, xerophyllo and eurythermal tropophyllo. Figure 8 and Table 2 shows the large area (28,246 km^2) occupied by the xerophyllo (semiarid and arid) bioclimatic regime in western and central Paraíba. Based on the combination with the ombrotypes of Thornthwaite (1956), we obtain the 9 subtypes that appear in Figure 8.

This means that the potentially most extensive plant formation at present in Paraíba state (Table 3) would be Scrub Caatinga (26,612 km^2) and Thorny Forest Caatinga (14,760 km^2). The Caatinga as a whole is the biome most represented in the state (43,006 km^2), followed by Agreste (9,620 km^2) and Mata Atlântica (2,394 km^2).

Second, a map was produced to show the bioclimatic conditions for the Last Glacial Maximum (40 ky). Based on the bioclimatic results, we were able to project the extent of the plant formations at that time, which are shown in Figure 9 and Tables 2 and 3.

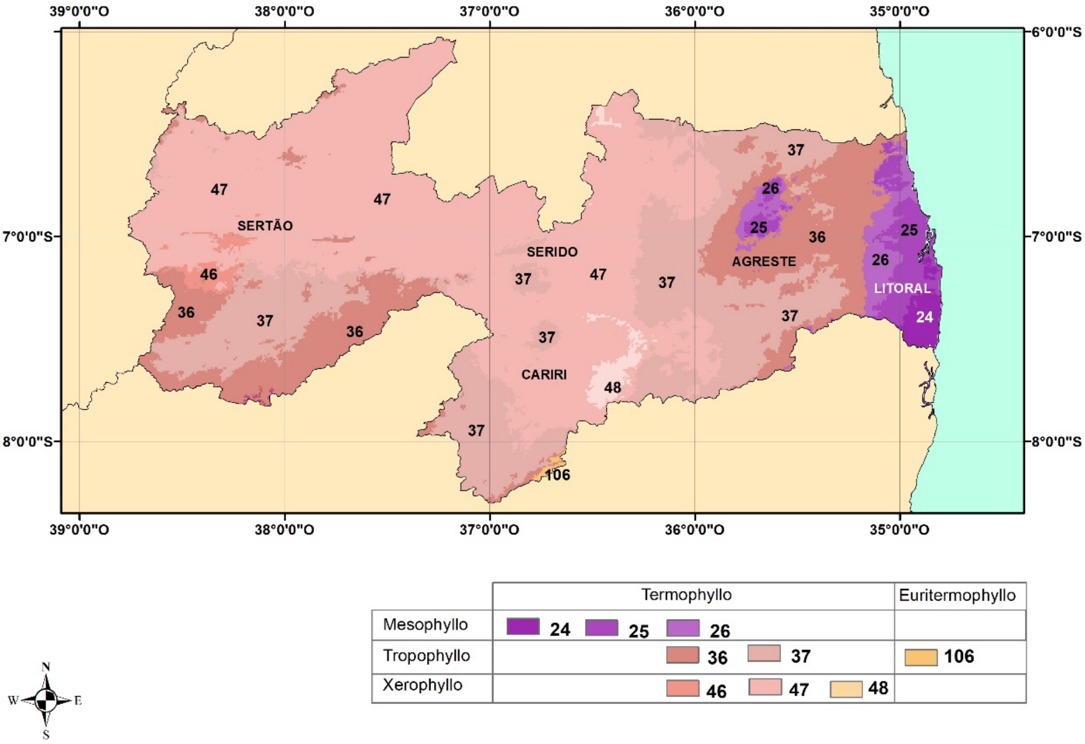

Figure 8. Map of the current situation of the bioclimatic regimes of Paraíba state: inferior humid (24), humid-subhumid (25) and subhumid-dry (26) mesophyllo; subhumid-dry (36) and semiarid (37) tropophyllo; subhumid-dry (46), semiarid (47) and arid (48) xerophyllo; subhumid-dry eurithermophyllo tropophyllo (106). Source: own production.

Table 2. Area in km² of the bioclimatic regime types in Paraíba state at the Last Glacial Maximum, at present (2021) and for the RCP 8.5 scenario of the CCMS 4.0 climate change model.

Bioclimatic regime subtype	Last Glacial Maximum	2021	CCMS4.0 2070 RCP8.5
Ombrophyllo	4698.57	2.56	0.00
Mesophyllo	7611.26	3801.62	0.00
Tropophyllo	17008.40	24402.13	7139.76
Xerophyllo	7504.96	28246.36	46740.72
Hyperxerophyllo	0.00	0.00	2649.72
Eurythermal mesophyllo	1785.88	11.93	0.00
Eurythermal tropophyllo	19495.88	72.42	0.00
Eurythermal xerophyllo	3231.60	0.00	0.00

Table 3. Area in km² of potential plant formations in Paraíba state at the Last Glacial Maximum, at present (2021) and for the RCP 8.5 scenario of the CCMS 4.0 climate change model.

	Last Glacial Maximum	2021	CCMS4.0 2070 RCP8.5
Mata Atlântica	9801.09	2394.97	0.00
Cerrado	2508.74	1430.51	0.00
Agreste	12373.61	9620.78	0.00
Thorny Forest Caatinga	4634.79	14760.05	7139.76
Scrub Caatinga	7504.96	27612.47	0.00
Shrub Caatinga	0.00	633.89	49390.44
Brejo	1785.88	11.93	0.00
Mata Serrana	19495.88	72.42	0.00
Mata Serrana Shrub	3231.60	0.00	0.00

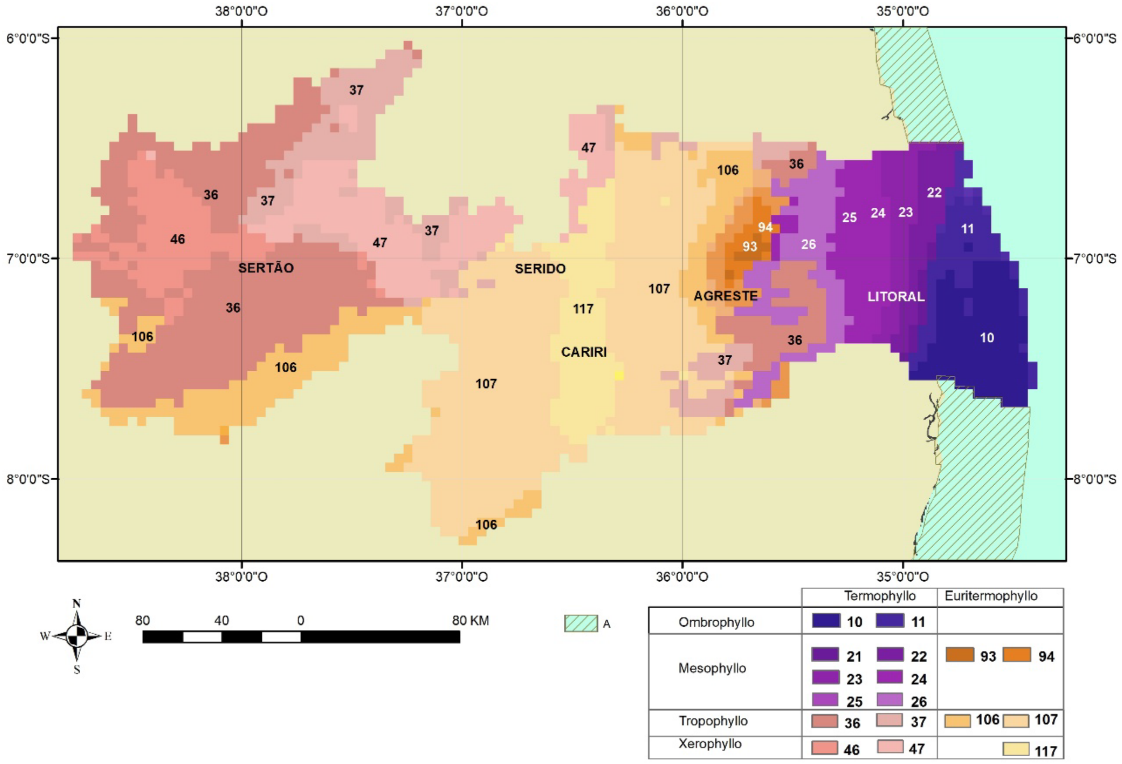

Figure 9. Map of the bioclimatic regimes of Paraíba state at the Last Glacial Maximum (40 ky) with: hyper-humid (10), superlative humid (11) ombrophyllo; superlative humid (21), superior humid (22), medium humid (23), inferior humid (24), humid-subhumid (25), subhumid-dry (26) mesophyllo; subhumid-dry (36), semiarid (37) tropophyllo; subhumid-dry (46), semiarid (47) xerophyllo; medium humid (93), inferior humid (94) eurithermophyllo mesophyllo; subhumid-dry (106), semiarid (107) eurithermophyllo tropophyllo; semiarid eurithermophyllo xerophyllo (117). Source: own production.

Compared to the current area, the Mata Atlântica area was clearly 7,406 km^2 larger, extending over the now submerged continental shelf; a hyper-humid to superlative humid ombrophyllo bioclimatic regime covered an area of 4,698 km^2 that is virtually non-existent today. This leads us to suggest that the Mata Atlântica present nowadays in humid-subhumid mesophyllo bioclimatic conditions comprises relicts of that previous situation. The rising sea level since the Last Glacial Maximum and the receding coast (Tabuleiro cliffs on the Paraíba coast) (Peulvast *et al.*, 2004) left the Mata Atlântica restricted to its current positions. The area covered by eurythermal bioclimatic conditions is also more important, from eurythermal mesophyllo to xerophyllo, with 24,513 km^2 versus the current 83 km^2, mainly distributed in the Cariri, in areas nowadays occupied by the Caatinga.

The tropophyllo and xerophyllo bioclimatic conditions resembling the current ones, with Caatinga, are limited to the Sertão, with situations similar to those found today.

Finally, a third map was produced, showing the situation of the state projected to the year 2070 in the RCP 8.5 scenario according to the CMSS 4.0 coupled climate change model (Fig. 10). In this situation the ombrophyllo, mesophyllo and eurythermophilous bioclimatic regime conditions disappear; only tropophyllo and xerophyllo bioclimatic regimes are still represented, with the hyperxerophyllo appearing in the Seridó. The more humid conditions are reduced to an arid tropophyllo regime in the mountains and in the Agreste, and semiarid along the coast, implying the disappearance of the bioclimatic conditions for all the current plant formations except the thorny forest Caatinga (7,139 km^2) in the tropophyllo conditions and the shrub Caatinga (49,390 km^2) for the rest of the state, with desert conditions in the Seridó.

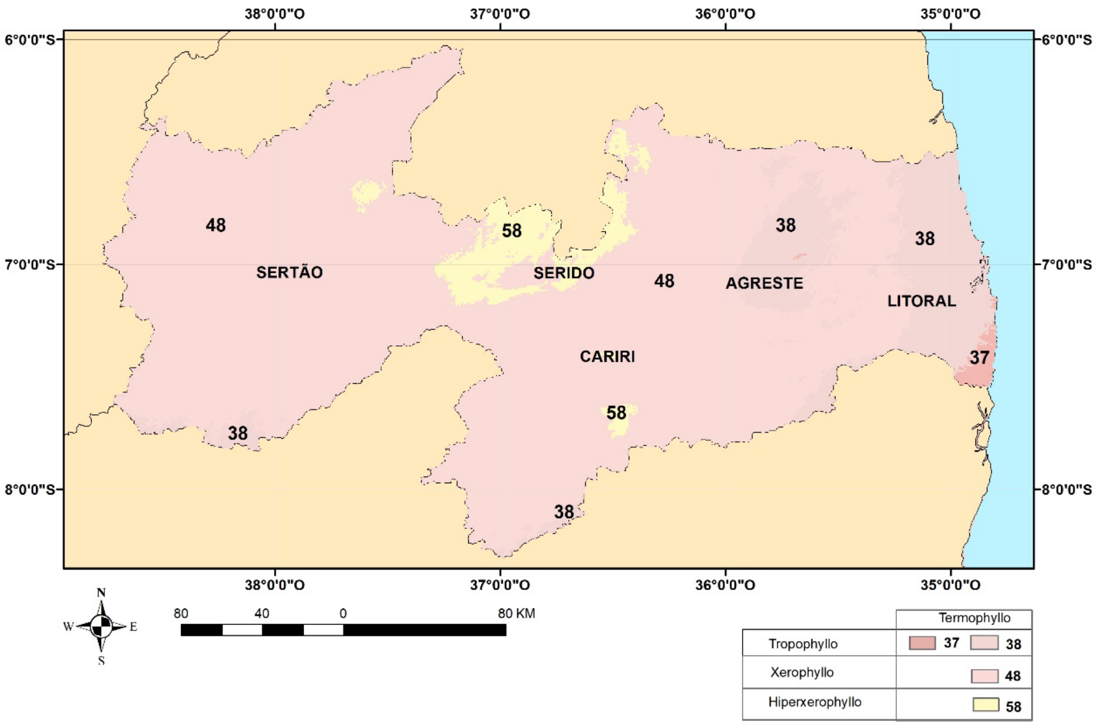

Figure 10. Map of the bioclimatic regimes in Paraíba state for the RCP 8.5 year 2070 scenario of the CMSS 4.0 model with: semiarid (37) and arid (38) tropophyllo; arid xerophyllo (48); and arid hyperxerophyllo (58). Source: own production.

5. Discussion and conclusions

The application of the methodology proposed by Cámara *et al.* (2020) allows the bioclimatic regimes to be associated to the plant formations, based on the current situation. The results of past bioclimatic situations can then be seen, such as the case of the Last Glacial Maximum, as well as future ones with the RCP 8.5 year 2070 scenario for the CMSS 4.0 model. We compared these results with existing publications for the past and for the future of Paraíba state.

For past situations we looked to the most recent one with the greatest contrast – the Last Glacial Maximum. In the respective map, what is most relevant is the exposed continental shelf, nowadays submerged (Peulvast *et al.,* 2004), and the expanded presence on it of the Mata Atlântica. Marine pollen data gathered in northeast Brazil indicate the presence of Caatinga in the interior between the periods of the Last Glacial and the early Holocene (42,000 BP to 9,400 BP), most of the time reflecting semiarid conditions. The longest and most humid period was between 18,500 and 12,800 years BP, enabling the expansion of humid forests, as indicated by the expansion of tropical forest and humid mountain forests (Ruiz Pesenda *et al.,* 2010), with a return to drier climatic conditions during the early Holocene (Behling *et al.,* 2000). It is possible that during the Last Glacial period some of the current humid forests in the mountains (Andrade-Lima, 1982; Ab'Saber, 1997) were connected, forming a larger area during the colder and more humid climatic conditions. Gu *et al.* (2017) thus hold that the Atlantic forest expanded after the Last Glacial in the lowlands along Brazil's coast, including the continental shelf still exposed during that period, before the rising post-glacial sea level flooded the continental shelf.

We considered the extreme situation for 2070 in a scenario with a very high level of greenhouse gas emissions, with radiative forcing of 8.5 W/m^2 (RCP 8.5) with rising trend, and 936 ppm of CO_2 in the atmosphere. Hausfather and Peters (2020) indicate that RCP 8.5 was based on what ended up being an overestimate of projected carbon production, as for 2070 such resources will be almost exhausted, unable to produce more greenhouse gas emissions because they will have been replaced by clean energy alternatives such as solar or wind power. They assert that this makes the RCP 8.5 scenario increasingly implausible with each year that passes. Since the Fifth IPCC Report this situation has been considered very unlikely, though still possible, because the feedbacks are not well understood (Ward *et al.,* 2012).

As seen in Table 4, the projection for 2070 of RCP 8.5 is 2ºC on average. The central aim of the Paris Agreement was to boost the global response to climate change, keeping global temperature increase in this century under 2ºC higher than preindustrial levels.

Table 4. Projections of increased global warming (°C) (Fifth IPCC Report).

	2046-2065	2081-2100
Scenario	*Avg. and probable range*	*Avg. and probable range*
RCP 2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP 4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP 6	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP 8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)

The work of Steffena *et al*. (2018) nevertheless detected a threshold in which temperatures can increase between 4 and 5ºC over preindustrial levels, taking climate system feedback mechanisms into account, which would vouch for the 2ºC situation for an RCP 8.5 in 2070. That would imply an average sea-level rise of 0.30 m for 2070 and 0.63 m for 2100 (Table 5).

Table 5. Projections of increase of average global sea level (meters) (Fifth IPCC Report).

	2046-2065	2081–2100
Scenario	*Avg. and probable range*	*Avg. and probable range*
RCP 2.6	0.24 (0.17 to 0.32)	0.40 (0.26 to 0.55)
RCP 4.5	0.26 (0.19 to 0.33)	0,47 (0,32 to 0,63)
RCP 6	0.25 (0.18 to 0.32)	0.48 (0.33 to 0.63)
RCP 8.5	0.30 (0.22 to 0.38)	0.63 (0.45 to 0.82)

Based on the inventories and the results of the bioclimatic variables, we can establish a relationship between the bioclimatic regimes and the distribution of plant formations, identifying spatial distribution patterns of those formations and the respective species according to those bioclimatic variables, within the framework of each bioclimatic regime type or subtype (with the ombroclimate) – average temperature, annual precipitation, potential evapotranspiration and hydric vegetation stagnation (in the case of Paraíba) – as well as the indexes for real and potential bioclimatic intensity derived from the bioclimatic balances (BBs) of Montero de Burgos and González Rebollar (1974). It is thus an effective method to relate the distribution of plant formations and bioclimatic regime types; we can therefore make forward and backward projections, showing variation of the distribution of plant formations according to the bioclimatic regimes in the considered situations.

This paper shows the possibility of recognizing the presence of relict plant formations in the current conditions, such as the case of the Mata Atlântica, and explains the presence of species requiring less humidity within that formation. On the other hand, the 2070 projection warns that the xerification process may take place if the barrier of a 2ºC increase in the planet's average temperature compared to the preindustrial era is surpassed, leading to disappearance of the bioclimatic conditions that would enable conservation of the Mata Atlântica itself or the dry thorny forests of the Caatinga, with shrub forms expanding in the Sertão and in the Cariri down to the coast or even desert conditions in the Seridó.

Beyond this potential bioclimatic framework, the processes involved in the use of plant resources and soils have over time replaced the original coverage of flora, producing extensive degradation and establishing a situation, with respect to the Caatinga, which may be leading a large part of Paraíba to worrisome levels of desertification.

Acknowledgments

The knowledge about these plant formations derives from our field experience in joint research projects between the University of Seville and the Federal University of Paraíba (main campus in João Pessoa). These projects have resulted in research articles, two master degree theses and two doctoral theses. Based on the fieldwork, it was possible to profile the extent of the plant formations and comprehensively map them with the bioclimatic regimes obtained for the state of Paraíba: *Recursos y manejo del territorio y del agua en la cuenca hidrografica del rio Paraiba: disponibilidad y uso para el desarrollo de las comunidades locales*. Programa de Cooperación Internacional (Acciones Integradas), Ministerio de Educación y Ciencia-AECID. D/024312/09 (2010-2012) y *Conservación y valorización socio-ambiental de los recursos naturales del litoral de Paraiba.* Programa de Cooperación Internacional (acciones integradas), Ministerio de Educación y Ciencia-AECID. A/017075/08 (2008-2009)

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