

Bioclimatic mapping as a new method to assess effects of climatic change

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Abstract. Rigorous mapping of climatic patterns outstands as one of the mayor issues concerning climatic change. This paper investigates the extent of the bioclimatic approach to develop a rigorous cartographic methodology to express climatic diversity patterns. Michoacan, Mexico was chosen to represent a region of complex geo-ecological layout where the Nearctic and Neotropical biogeographical realms converge. Bioclimatic indices were computed and their spatial expression was processed in a Geographic Information System. Ground verification was performed at 93 sites across the province. In addition, from 2010 until 2012, more than 2000 kilometers of roads were surveyed to gather data on isobioclimate boundaries. In total, one macrobioclimate, two bioclimates, four thermotypes, five ombrotypes and 14 isobioclimates were distinguished in Michoacan. The Tropical pluvisesonal bioclimate was the predominant bioclimate, covering 56.17% of the province. The Tropical xeric covers 43.82% and the Tropical pluvial is practically negligible, covering 0.01% of the entire province. The relevance of the outcome is discussed in light of its potential use for assessing likely effects of climatic change.

Key words: bioclimate cartography; ecodiversity; ecosystem mapping; isobioclimates; Michoacan, Mexico.

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INTRODUCTION

Today, climate studies represent a major scientific theme, given the undeniable effects of climate change (IPCC 2013). Three main approaches prevail for the study of climate impacts on ecosystems, as follows: (1) a meteorological approach that focuses on monitoring climate over long periods of time with outcomes on small geographical scales (Easterling et al. 2000); (2) an environmental approach targeted at the meso-scale level to document present and future effects on biodiversity (Rivas-Martínez et al. 2011*b*); and (3) an ecological approach, largely used to depict

exceptions to general meso-climatic rules, which often are restricted to large scales or specific localities (Nogues-Bravo and Rahbek 2011, Pennisi 2012). Regardless of the approach, a rigorous cartographic representation of climatic patterns is of extreme relevance to all. Tools such as remote sensing and geographic information systems have played a fundamental role in these cartographic endeavors (Van-Lynden and Mantel 2001). Notwithstanding, providing a geographic representation of climatic patterns remains a challenge; especially at the meso-scale, where climate-vegetation relationships are crucial to the possible pursuit of sustainable production activ-

ities and the provision of ecosystem services such as water, agriculture, horticulture and forestry.

Previous climate classification proposals have proved to be of limited applicability to provide sound cartographic expression. Outstanding examples of these proposals include: Thornthwaite (1948), which is widely used in North America; Holdridge (1967), which is predominant in Central and South America; and García (1973), which is the most common in Mexico.

Bioclimatology is an emerging approach focused at understanding, depicting and portraying the climate-vegetation relationship at the meso-scale. According to Rivas-Martínez et al. (2011*b*), bioclimatology is structured in three organization levels, namely: macrobioclimates (Polar, Boreal, Temperate, Mediterranean and Tropical), bioclimates (28 in total) and large number of combinations of bioclimate types (thermotypes and ombrotypes). Thermotypes may be regarded as a gradient of temperature, whereas ombrotypes display a gradient of precipitation, which combined depict climatic niches so called as isobioclimates. Bioclimatology is furthermore based upon raw data for precipitation and temperature during the most extreme (dry, wet, warm or cold) months. The data are transformed into indices to provide a classification system, which depicts patterns along gradients (Rivas-Martínez 2005, Rivas-Martínez et al. 2011*b*). This approach has been rigorously applied in Temperate, Mediterranean and Boreal ecosystems (Del Río 2005, Peinado et al. 2008, Cress et al. 2009, Gonzalo 2010), and has recently been applied to a limited number of examples in tropical areas (e.g., Navarro (1997) for Bolivia; Costa et al. (2007) for Venezuela).

Cartographic expression of climatic patterns is especially important in regions harboring large native forest land cover, because of the role they play in mitigating climate changes. In this regard, Remote Sensing (RS) and Geographic Information Systems (GIS) have served to store, analyze, and cartographically display large amounts of data. Climatic data have also been analyzed through RS and GIS, so that changes in temporal and spatial climatic patterns and trends can be explored (Del Río and Penas 2006). A detailed review of the research on this subject has been done by Foody (2008). Nonetheless, sound, replicable cartographic expression of bioclimatic

outcomes at the meso-scale is still in its infancy. One encouraging exception at a meso-scale level was conducted by Del Río and Penas (2006) who carried out a thorough bioclimatic analysis and were able to predict likely climatic changes in Spain. These authors, however, focused in portraying cartographically all levels of bioclimatic classification rather than providing spatial representation of isobioclimates as surrogates of geo-ecological complexity.

In theory, vegetation, expressed in land cover types, ought to be regarded as the response variable of climatic patterns (Whittaker 1967). Mapping land cover types has gained large popularity due to the advance in remote sensing data availability and analytical tools (Chuvieco 2008). Cartography of climatic types has often been subordinated to land cover types or intermingled with atmospheric data obtained at climatic stations and further interpolated (e.g., García 1973, Rivas-Martínez et al. 2011*a*). Sound climate mapping, however, turns scientifically challenging at regions with contrasting ecological configuration; as it is the case of Michoacan province in Mexico—which covers an area approximately the size of Costa Rica—harbors representative temperate and tropical native ecosystems (Velázquez et al. 2003, Velázquez et al. 2009, Sarukhán et al. 2009, Velázquez et al. 2010, Skutsch et al. 2013), and is comprised of a peculiar geomorphological configurations (Bocco et al. 2001).

Rigorous studies aimed at providing reliable spatially explicit climatic baseline are fundamental to assess the extent of ecological impact of global changes. Along this line, the aim of this paper is to develop a methodological cartographic approach to express bioclimates as surrogates of ecological diversity at a mesoscale, in order to enhance predictions of land cover types within a geo-ecologically tropical region. The results are compared to conventional climatic zoning approaches and discussed in the light of their outreach as baseline definition for climatic change.

MATERIAL AND METHODS

Study site

The province of Michoacan is located west of Mexico City and covers 58,599 km², which

accounts for 3% of the country's surface area (INEGI 2011). The study area is located within the following coordinates: 20°24' latitude North to 17°55' latitude North; and 100°04' longitude West to 103°44' longitude West. Michoacan is mostly mountainous, and predominantly dissected by the Tepalcatepec watershed, which on the north is limited by the Transversal Neovolcanic (formed in the Quaternary period), and on the south by the Sierra Madre del Sur (formed in the Tertiary period) (Israde 2005). Because its elevation ranges from sea level to 3840 meters (Antaramián-Harutunian and Correa-Pérez 2003), the climate varies drastically along either elevational or coastal-to-inland gradients (García 1973). Soils are also diverse, with Leptosol, Regosol, Luvisol, Acrisol, Andosol, Vertisol and Feozem types being dominant (Cabrera et al. 2005).

In addition to the complex physical layout, Nearctic and Neotropical biogeographic realms converge in Michoacan (Rzedowski 1991), leading to unusually high biodiversity (Challenger 1998, Ramamoorthy et al. 1998, Villaseñor 2005, Velázquez et al. 2003, Velázquez et al. 2009, Velázquez et al. 2010). Indeed, 80% of the tree families and 50% of the tree genera reported for Mexico occur in Michoacan (Velázquez et al. 2009). At the species level, Villaseñor and Ibarra-Manríquez (1998) reported 3,600 species of trees for Mexico while Cué-Bär et al. (2006) estimated some 845 species of trees occurring in Michoacan. Furthermore, it is estimated that over 40% of the tree species are endemic to Michoacan, of which over 45% are listed as threatened (Villaseñor 2004, Cué-Bär et al. 2006, Velázquez et al. 2009). As a result, seven out of the eight tree-dominated ecosystems of Mexico occur in Michoacan, namely: coniferous forest, oak forest, mountain cloud forest, tropical dry forest, spiny forest, tropical deciduous forest, and tropical perennial forest (Carranza 2005, Rzedowski 2006). Additional information of biogeographical zoning and land cover types occurring in all Mexico can be found at: <http://www.conabio.gob.mx/informacion/gis/>

Bioclimatic cartographic expression

Our main source of data was the Digital Climatic Atlas of Mexico (DCAM). The Atlas was built primarily from climatic data reflecting

the monthly and annual averages for precipitation and temperature from 1902 through 2011 (which data was obtained from the National Meteorological System, or SMN for the Spanish acronym), together with other climatic data such as evapotranspiration and mean annual temperatures (Fernández-Eguiarte et al. 2011).

The climatic data of DCAM were calculated according to the methodology used in ANUS-PLIN (Hutchinson 2004), the same tool that was used for the global climate data in WorldClim (<http://www.worldclim.org>) (Hijmans et al. 2005). The surface climate data were calculated by finding the difference between the climate data for Mexico and the corresponding surface values from WorldClim for the same geographical position. DCAM subjected the resulting surface climate data to quality control and data outside two standard deviations above or below the mean were eliminated. With the remaining differences, spatial interpolation was performed using Inverse Distance Weighted Interpolation (Shepard 1968). The final layer was then calculated as the sum of all the surface climate data, plus the WorldClim data, plus the interpolated surface of the differences. From this final layer, raster layers were established, with pixels approximately 1 km² in size. More details and the raw data can be found in Fernández-Eguiarte et al. (2011).

The following bioclimatic indices (based on Rivas-Martínez et al. 2011b) were computed. Their calculation and an explanation of their properties are thoroughly explained at Rivas-Martínez et al. (2011b).

Io: Ombrothermic Index. $Io = (Pp/Tp)10$. This index is the result of Pp (the yearly positive precipitation in mm) divided by Tp (the yearly positive temperature).

Pp: Yearly Positive Precipitation. In mm, the total average precipitation of those months whose average temperature is higher than 0°C.

Tp: Yearly Positive Temperature. In tenths of degrees Celsius, the sum of the monthly average temperature of those months whose average temperature is higher than 0°C.

Iod₂: Ombrothermic index of the dryest bimonth. $Iod_2 = (Ppd_2/Tpd_2)$. This index

is the result of Ppd_2 (the total precipitation of the two driest months contained within the driest quarter of the year) divided by Tpd_2 (the total temperature of the two driest months contained within the driest quarter of the year).

Pi: Mean annual precipitation.

To calculate bioclimatic indices representing a long period of time, the I_o , Iod_2 and P_i , were computed for all years within the period 1902 through 2011. This gave I_o (Eq. 1), Iod_2 (Eq. 2) and P_i (Eq. 3), which were then computed as follows:

$$I_o = \sum_{i=1}^{110} \frac{I_{oi}}{110} \quad (1)$$

$$Iod_2 = \sum_{i=1}^{110} \frac{Iod_{2i}}{110} \quad (2)$$

$$P_i = \sum_{i=1}^{110} \frac{P_{ii}}{110} \quad (3)$$

where 110 is the period of 1902 to 2011; i is the index in each year.

It: Thermicity Index. $It = (T + m + M)10$; where T = mean annual temperature for the whole period of analysis (1902–2011). “ M ” is the maximum average temperature of the coldest month, whereas “ m ” is the minimum average temperature of the coldest month. To compute “ M ” and “ m ”, a data base with the coldest month of every year throughout 1902–2011 was comprised, and then it was split into two subsets. One comprised all months with values above the mode and the other subset all temperature values below the mode. The first subset served as input to compute “ M ”, whereas the second subset was used to calculate “ m ”. m = mean temperature value of the readings below the mean temperature of the coldest month throughout the period (1902–2011). M = mean temperature value of the readings above the mean temperature of the coldest month throughout the period (1902–2011).

We used these indices for each pixel to identify

preliminary outcomes, namely: macrobioclimate, bioclimate, thermotype and ombrotype. This process implied fitting every pixel, based upon its index value, into a classification scheme already developed by Rivas-Martínez et al. (2011b). For instance, a given pixel with I_t value of 201.79 falls as Supratropical Thermotype, and the same pixel with a I_o value of 14.46 falls as Hyperhumid Ombrotype. This classification procedure was done pixel by pixel with the aid of the GIS. Further details of the classification scheme for all ombrotypes and thermotypes threshold values are available at: http://www.globalbioclimatics.org/book/bioc/global_bioclimatics_2.htm#2b. Pixels containing unique combinations of thermo and ombro types within the same (macro)bioclimate were clustered and referred as isobioclimates. These isobioclimates were used to depict spatial bioclimatic patterns for the entire province of Michoacan in a raster format. Finally, the raster dataset was converted to polygon features. The scale of Bioclimatic Diversity Map of Michoacan was 1:250,000, with a minimum mapping unit of 100 hectares. The map projection was Lambert Conformal Conic, Datum WGS 1984. All these calculations, the map algebra and the cartographic representation were made using ArcGIS V9.3. It is worth-mentioning that spatial resolution of the original data remains the same as the output map produced for Michoacan province.

Ground verification was performed throughout the entire province between 2010 and 2012. A total of 93 sites covering all isobioclimates were surveyed. In addition, over 2000 km of road were used to gather data on isobioclimate boundaries.

The verification procedure was based on Macías (2009), who described land cover types-isobioclimates relationship for the whole Pacific coast of Mexico. Fieldwork took place during tree flourishing periods, in other words, during the transition from winter to spring for tropical dry forest; and during the transition from autumn to winter for temperate and tropical sub-humid forests. In these periods we distinguished clear structural and physiognomic contrasts. At every site, we focused our efforts on a well conserved, representative forest patches. In addition, all tree species were noted or collected for further identification at the Instituto de Ecología-Bajío herbarium in Pátzcuaro if the species was not

identified on site. If a cluster of tree species found at a given site did not fit with the landcover type-isobioclimate relationship reported by Macías (2009), then the climatic data was reviewed and recalculated to cross-check data reliability. If data were reliable, the isobioclimate obtained was regarded as appropriate, else Macías's isobioclimate proposal was used as ground truth. To reduce subjectivity, a minimum of 8 sampling sites per isobioclimate were surveyed in order to cover all climatic variability. Detailed vegetation studies at the community level and the relationship with isobioclimates is part of ongoing research and falls outside the scope of the present paper.

All 96 sites surveyed were crossed with all isobioclimate types to construct a confusion matrix (sensu Díaz-Gallegos et al. 2010). Map accuracy was then measured as a weighted proportion of the isobioclimate versus the number of field sites comprising those tree species related to a specific climatic condition, according to the following algorithm proposed by Card (1982) (Eq. 4).

$$p_i = \pi_j n_{ij} / n_{+j} \quad (4)$$

where π_j is the proportion of the isobioclimate j on the map, n_{ij} is the number of sites actually comprising tree species that correspond to the isobioclimate i , but appearing on the map as category j , n_{+j} is the marginal addition, and was computed by the following:

$$n_{+j} = \sum_{i=1}^q n_{ij}. \quad (5)$$

Our study aimed to reach 90% coherence between field sites and isobioclimate types, as previously reported for neighboring areas (Giménez and Ramírez 2004, Peinado et al. 2010a, Peinado et al. 2010b, Giménez and González 2011).

Bioclimate-land cover relationship

The land cover data base produced during 2008 by the "Instituto Nacional de Estadística y Geografía" (INEGI for the Spanish acronym) (INEGI 2010) was used as main input to perform analysis between bioclimate and land cover types. This data base was made through landsat images interpretation taken from spring and autumn 2007 and spring 2008. Ground truth of

the interpretation was conducted in autumn 2007 and spring-summer 2008. Michoacan harbors 15 natural land cover types, grouped in six land cover types (sensu Velázquez et al. 2010). The final scale of land cover data base was of 1:250,000, with a minimum mapping unit of 100 hectares and more than 2,200 polygons of natural vegetation. The land cover data base reclassified was crossed with the isobioclimatic map here obtained, using ArcGIS V 9.3. The results were summarized on graphics that indicate relationship among bioclimatic and natural land cover types expressed in percentage (anthropogenic land covers were not taken into consideration for this analysis).

Bioclimate-other climatic classifications relationship

In Mexico, climatic types have been defined based upon Köppen, adapted to local conditions by García (1973) (Table 2 in www.ciga.unam.mx/index.php?option=com_content&view=article&id=66:articulo-1&catid=13:investigacion&Itemid=265). This approach prevails so much that is the only one used by any academic and governmental institution. Its cartographic representation was developed by García (op cit.) and made digitally available at a scale 1:1,000,000 by "Comisión Nacional para el Conocimiento y Uso de la Biodiversidad" (CONABIO for the Spanish acronym) (CONABIO 2008). García's Mexican climatic map includes was used as input to be crossed with the bioclimatic data base using ArcGIS V9.3. The results were summarized on graphics that indicate relationship among bioclimatic and natural land cover types (anthropogenic land covers were not taken into consideration for this analysis).

Climatic diversity analyses

Bioclimate-land cover-other climatic classifications relationships were analyses in terms of their diversity of types harbored. For that purpose, Shannon-Wiener (Magurran 1988) diversity index was computed after map crossing took place. Shannon-Wiener's index was calculated as follows:

$$H' = -\sum p_i \ln p_i \quad (6)$$

where p_i = proportional abundance of hectares of each climate-land cover relationship type into Michoacan province.

Table 1. Isobioclimates cartographically depicted in the Province of Michoacan, Mexico as shown in Fig. 1. The combination of macrobioclimate (that is Tropical for all province of Michoacan, Mexico), bioclimate, thermo and ombro types is expressed in isobioclimates (cells), which in turn describe temperature and humidity gradients. Data outside the parenthesis correspond to percentage of the entire province covered by each isobioclimate. Data in the parenthesis represent the actual area (in hectares) of each isobioclimate.

Bioclimates	Thermotypes	Ombrotypes				
		Hyper-humid	Humid	Subhumid	Dry	Semiarid
Pluvial	Supratropical	0.004 (215)	0.006 (351)	...	...	...
Pluviseasonal	Infratropical	...	0.05 (2,918)	1.81 (106,197)	...	...
	Thermotropical	...	0.92 (54,188)	19.68 (1,153,109)	...	...
	Mesotropical	...	11.00 (644,727)	21.25 (1,244,855)	...	...
Xeric	Supratropical	0.04 (2,493)	1.40 (82,314)	...	...	...
	Infratropical	...	...	...	24.31 (1,424,337)	2.69 (156,976)
	Thermotropical	...	...	...	13.47 (789,485)	...
	Mesotropical	...	...	...	3.37 (197,735)	...

Note: The ellipses used in cells indicate no relationship.

We used Shannon-Wiener’s index to test the hypothesis that García’s Mexican climatic map comprised equal land cover diversity as the map obtained by the bioclimatic approach. For that purpose, Hutcheson’s algorithm (1970) was followed:

$$H_p = \frac{(N \log N) - (\sum f_i \log f_i)}{N} \quad (7)$$

where: f_i = frequency (hectares) registered for climate-land cover relationship type i .

The variance weighted diversity index was calculated according to

$$\text{var} = \frac{[\sum f_i \log^2 f_i - (\sum f_i \log f_i)^2 / N]}{N^2} \quad (8)$$

The difference between variances from both approaches was computed as

$$D_{\text{var}} = \sqrt{\text{Var}_{\text{García}} + \text{Var}_{\text{Bioclimates}}} \quad (9)$$

Subsequently, the t value was obtained and compared to the t value in tables to assess the probability to accept or reject the hypothesis.

RESULTS

Bioclimatic mapping

In total, following the bioclimatic approach, one macrobioclimate, three bioclimates, four thermotypes, five ombrotypes and 14 isobioclimates were distinguished in Michoacan. The macrobioclimate is Tropical. At the bioclimate level, the Tropical pluviseasonal predominates, covering 56.17% of the province; whereas the

Tropical xeric covers 43.82% and the Tropical pluvial is negligible, covering only 0.01% of the entire province (Table 1).

The 14 isobioclimates depict the climatic diversity occurring in Michoacan as a result of humidity and temperature gradients obtained from thermotypes and ombrotypes (Fig. 1). As expected, isobioclimates were not evenly distributed; rather, their chorological pattern is heterogeneous and complex. The Tropical pluviseasonal mesotropical subhumid and Tropical pluviseasonal thermotropical subhumid predominate, covering nearly of 41% of the entire province. Their climatic expression is remarkable, for its contrasts to the Tropical xeric infratropical dry and Tropical xeric thermotropical dry, which cover nearly of 38% of the surface of the province.

The Tropical pluviseasonal mesotropical humid bioclimate, covering almost 11% of the province, is reflected in intermingling Nearctic and Neotropical taxa. To exemplify this further, two major native ecosystems occurred within this isobioclimate: mountain cloud forest and tropical perennial forest (locally called Bosque Mesófilo and Bosque Tropical Perennifolio *sensu* Rzedowski [2006]). Fig. 1 depicts those isobioclimates that play an important role in the transitional conditions between the Nearctic and Neotropical biogeographical realms. The Tropical pluviseasonal thermotropical subhumid and the Tropical xeric thermotropical dry are considered ecotones. By comparison, the Tropical pluviseasonal thermotropical humid and Tropical xeric infratrop-

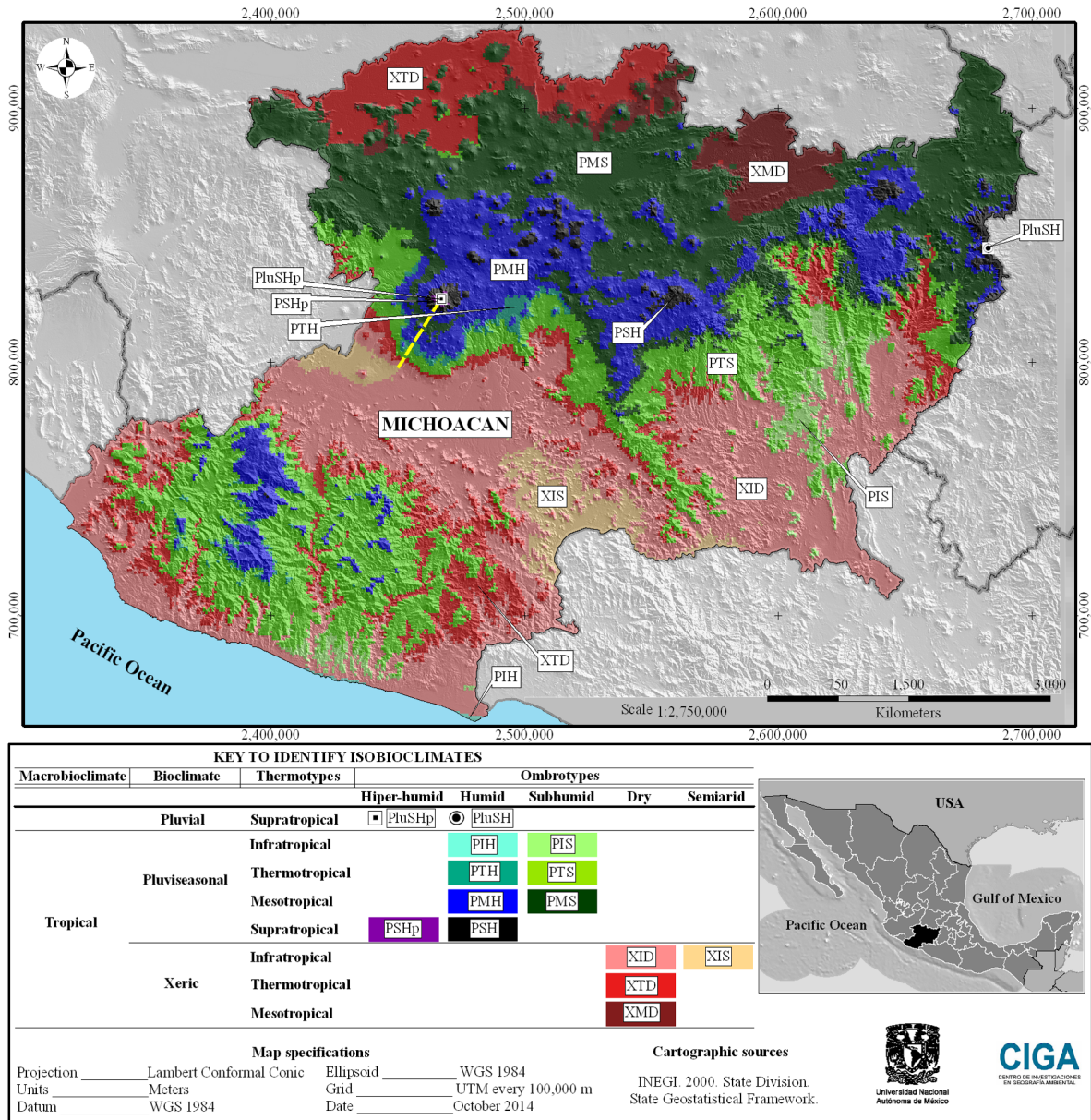


Fig. 1. Bioclimatic diversity as surrogate of the geo-ecological complexity harbored in the province of Michoacan, Mexico. The yellow dashed line on the map indicates a transect of circa 32 km from Tancitaro summit to Apatzingán. Within this transect, 10 isobioclimates occur. The original map at scale 1:250,000 for visualization and printing purposes can be seen and downloaded at: www.ciga.unam.mx/index.php?option=com_content&view=article&id=66:articulo-1&catid=13:investigacion&Itemid=265

ical dry isobioclimates best represent the Nearctic and Neotropical realms, respectively.

The rest of the isobioclimates cover small, isolated portions of the province. Yet these are representative of unique climatic conditions such as the Tropical pluvial supratropical hyper-

humid zone, the Tropical pluvial supratropical humid zone, the Tropical pluviseasonal supratropical hyper-humid and the Tropical pluviseasonal supratropical humid zones. These four contain elements that may be regarded as relicts of the last glaciations, with Cupressaceae and

Coniferaceae as the predominant tree families (Rzedowski 1991, Villaseñor and Ibarra-Manríquez 1998, Villaseñor 2004, Villaseñor 2005). In turn, the Tropical xeric infratropical semiarid, representing the most extreme tropical dry conditions, is dominated by the Cactaceae, Bursaraceae and Leguminoseae families. These small, isolated isobioclimates are particularly relevant for containing outstanding numbers of endemic species (Rzedowski 1991, Villaseñor and Ibarra-Manríquez 1998, Villaseñor 2004, Villaseñor 2005, Rzedowski 2006).

As result of the map accuracy assessment carried out via confusion matrix, the estimated percentage obtained was of 87.7, which was regarded as satisfactory for the scale and complexity of conditions prevailing in the study area.

Bioclimatic-land cover and other classification relationships

Land cover analysis showed that tropical deciduous and temperate forests prevail significantly covering about the same proportion (47.94% and 47.29%, respectively). Tropical perennial forest follows in coverage with significantly less proportion covered (4.31%). Grassland, hydrophyllous vegetation and scrubland are less relevant in coverage (0.23%, 0.14% and 0.09%, respectively). Actual figures of relationships found between bioclimates versus land cover and climatic zoning sensu García (1973) are at: Table 2 in www.ciga.unam.mx/index.php?option=com_content&view=article&id=66:articulo-1&catid=13:investigacion&Itemid=265.

These six land cover types distribute differently among isobioclimates and climates (sensu García 1973). To exemplify this further, Tropical pluviseasonal thermotropical subhumid (PTS) and warm subhumid (Aw1) harbored most of the proportion of land cover types, namely: namely temperate, tropical deciduous and tropical perennial forests. Proportions among climatic classes contrasted significantly, so that tropical deciduous forest prevails in PTS (18.23%), whereas temperate forest in Aw1 (13.68%). The whole contrast among land cover types found in climatic classes from both climatic approaches is illustrated in Fig. 2. Shannon's diversity index described best the dissimilarities of land cover types found among climatic classes; so that

bioclimates ($H' = 1.03$) are significantly less diverse ($t = 305.53$; $P < 0.05$) than climates ($H' = 1.13$; sensu García). Based upon Shannon evenness index, bioclimates also proved to be less homogeneous ($H_p = 0.65$) than climates classes ($H_p = 0.73$; sensu García).

DISCUSSION

Sound climatic zoning of complex geo-ecological regions, such as Michoacan province, is challenging. In this regard, the bioclimatic approach (sensu Rivas-Martínez et al. (2011b)) has proved to be a useful tool in two ways. On the one hand, the approach has helped to express climatic patterns along gradients; on the other, it substantially facilitates the chorological expression of these climatic patterns. Description of climatic patterns along gradients has been done elsewhere in Mexico (Giménez and González 2011) as well as in other temperate and tropical biogeographical realms (Navarro 1997, Costa et al. 2007, Cress et al. 2009). As opposed to other climatic classification schemes widely used in Mexico, such as the Köppen classification modified by Enriqueta García (García 1973), or other ones used in Central America (Holdridge 1967), the bioclimatic approach computes its index threshold based on stressful periods where the native vegetation is directly affected. Consequently, native vegetation is regarded as the response variable of the mesoclimatic patterns distributed along gradients. Taking into account that two major mountain ranges cross Michoacan (namely: the Transversal Neovolcanic Belt [a recent Quaternary formation running from east to west, at elevations from 300 to 3800 m above sea level], and the Southern Sierra Madre [a Tertiary formation running from south to east, at elevations from sea level to 3000]), climates could be expected to follow clear, uniform altitudinal gradients. Yet this is not in fact the case since land forms in these mountain ranges are substantially accidental, with complex valleys, extended piedmonts, and large plateaus (Bocco et al. 2001). In addition, precipitation and evapotranspiration are also largely influenced by the windward slope effect, since rain comes from the Pacific, and the Southern Sierra Madre serves as a barrier. This is clearly reflected in the extreme dry and hot conditions that prevail in between

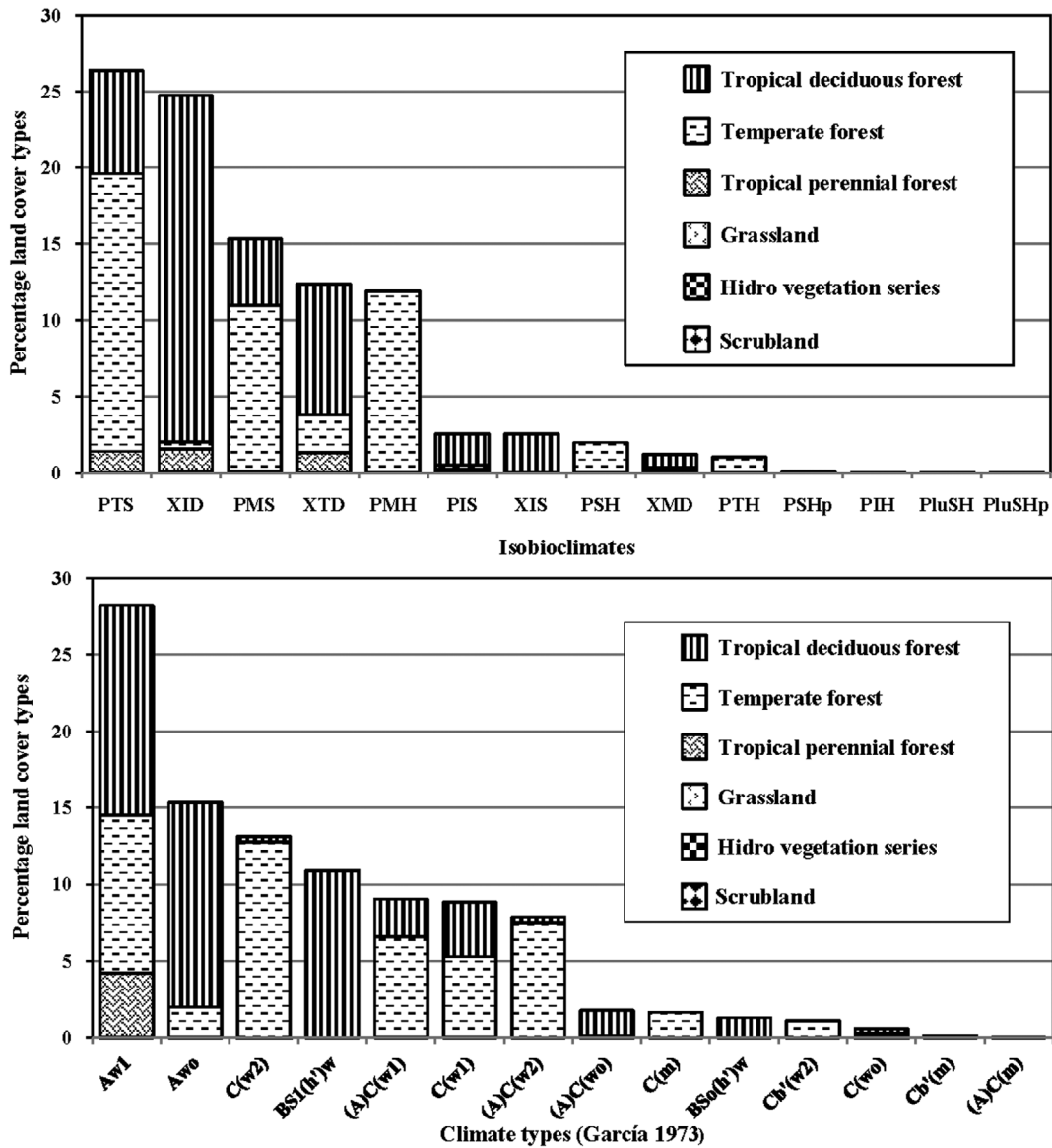


Fig. 2. Percentages of land cover types present in two climatic types (Isobioclimates and Climate types [García 1973]). The abbreviations of isobioclimates are as in Fig. 1. The meaning of abbreviations of Climate types (García 1973) can be seen in Table 3 at: www.ciga.unam.mx/index.php?option=com_content&view=article&id=66:articulo-1&catid=13:investigacion&Itemid=265

these two ranges, so much so that this region is locally known as “Tierra Caliente” (the hot land). In other words, the anticipated climatic zoning, significantly influenced as it is by mountain ranges, turns out to follow a rather whimsical pattern that had not been cartographically portrayed by previous climatic approaches. At the micro-scale level (1:50,000), other meteorological

data such as evapotranspiration may become relevant to refine climatic zoning (Rietkerk et al. 2011). At the meso-scale, however, these data do not play a major role in climatic patterns.

The transition between isobioclimates is based on humidity and temperature thresholds that occur during specific stressful situations. In turn,

isobioclimates are considered climatic diversity indicators for such regions as Michoacan; where species diversity and endemism are exceptionally high, isobioclimates may be considered as a surrogate that describes ecological complexity. The last assertion is supported by the evenness index value calculated, showing that there was a better relationship between isobioclimates and specific land cover types that showed for other climatic classifications. It is worth mentioning that contrasting ecological transitions—depicted by the number of isobioclimates—occur in many areas within Michoacan. To illustrate this further, a transect of approximately 32 km from Tancítaro summit to Apatzingán plain was delineated, as is indicated by a yellow dashed line on the map. Within this transect, 10 isobioclimates occur, representing perhaps the shortest, most contrasting ecological mosaic in Mexico.

This paper aimed at assessing the ability of the bioclimatic approach to depict the complexity of the province of Michoacan. We also applied this research to bioclimatic outputs to create a rigorous cartographic methodology to express climatic diversity at the meso-scale. Both objectives were successfully accomplished. A number of drawbacks to the traditional bioclimatic approach were identified during this research. For instance, data from meteorological stations are insufficient to pursue a sound cartographic representation of isobioclimates. To overcome this limitation, geo-statistical methods are necessary when translating point data into polygon data.

It is well-worth mentioning that Macrobioclimates, Bioclimates, Thermotypes and Ombrotypes may each have a cartographic representation. In this paper, nonetheless, our focus was on the isobioclimates, because they are a clear surrogate of geo-ecological complexity.

The cartographic expression of climatic patterns has been, is and will continue to represent a challenge for various reasons (Van-Lynden and Mantel 2001). Climate data obtained at specific points (i.e., traditional meteorological stations) needs to be interpolated into polygons in order to be properly mapped. In order to do so with statistical rigor, a number of assumptions must be fulfilled. For example, meteorological stations must represent the surrounding homogeneous conditions, the distance between them should be

sufficient to constitute a network, and the number of stations must be a function of the heterogeneity of the area (Cress et al. 2009). Current data management tools and analytical methods have, in part, helped to overcome these limitations. RS, GIS and geostatistics have enabled access to, and the analysis of, data in a raster format (Shepard 1968, Fernández-Eguiarte et al. 2011).

The relevance of the map presented in Fig. 1 is fourfold. First, it is a baseline database for modeling former potential distribution patterns of forested land cover types. Second, it serves as a reference to depict present land-use cover change analyses. Third, the map is a source of data for analyzing possible relationships among isobioclimates and specific land uses, which may need to either expand or shrink in order to fulfill production demands. Finally, the map presented in Fig. 1 may be regarded as a baseline to predict effects of climatic changes.

Michoacan province exports the largest number of avocado, lemon, mango and other fruits to North America, and depends heavily on permanent tree fruit production. A delicate balance must be achieved between production to meet these export demands and the maintenance of native ecosystem functions, which provide the services for most productive activities. Cultural/natural tradeoffs must be made in order to sustainably satisfy socio-economic and conservation needs (Velázquez et al. 2009). The results presented in this paper may serve as input to help reorient policy makers and other stakeholders involved in this endeavor.

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