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METHODS IN VEGETATION SCIENCE

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Merged phytosociological and geographical approach for multiple scale vegetation mapping as a baseline for public environmental policy in Mexico

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Abstract

Questions: What is the potential use of maps derived from a merged geographical and phytosociological approach to support the design of public environmental policies? Do these approaches and data sources deliver complementary land-cover/vegetation maps?

Objective: The present article documents a joint phytosociological and geographical approach to improve vegetation cartography in temperate-tropical transitional ecosystems.

Location: The research was conducted at national (Mexico) and state (Michoacán) scales. Mexico and Michoacán have been recognized as regions of high eco-geographical complexity, where temperate-tropical conditions intermingle, creating large eco-socio-cultural mosaics.

Methods: Data from 268 field verification sites and 223 relevés surveyed during the last two decades and recent land cover sources were used as the main inputs. The results were further validated by three workshops with local botanists and field verification during 2021.

Results: At the national level, Mexico's forests, shrubs, herbs, and non-vascular major formation classes were hierarchically split by dominant life forms and prevailing climatic affiliations. At the state level, these major formation classes split into 19 subformations, of which 15 were forest communities.

Conclusions: We discuss the scientific challenge of transitioning from land cover into vegetation maps and (dis)similarities of approaches reviewing concepts and analytical (quanti)qualitative instruments. The paper contrasts the present output with the experiences of other countries such as Canada, the United States, Bolivia, and Colombia. Finally, the results are discussed in light of their relevance for constructing public environmental policies, such as land use planning, establishment of protected

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areas, allocation of incentives for sustainable environmental services, and long-term conservation practices.

KEYWORDS

environmental policy, geographical and phytosociological approaches, land cover/vegetation classification, Mexico, Michoacán, vegetation mapping, vegetation survey

1 | INTRODUCTION

The study of vegetation, whether natural or cultural, and from local to global scales, is essential for understanding ecological processes, setting management actions, and conducting sustainable land use planning (FGDC, 2008; Matteucci & Colma, 1982). Thus, the rigorous representation of vegetation on maps goes from being an object of academic relevance to being an input of scientific, social, economic, and cultural relevance. Vegetation maps are fundamental instruments used to support management decisions, environmental policy design, and to assess the human ecological footprint. Therefore, the quality of the content of a vegetation map is a matter of scientific priority (Küchler, 1951, 1967; Pedrotti, 2004; Pereira et al., 2010; Velázquez et al., 2010, 2016).

Traditional phytosociological classification and ordination techniques have not been sufficient to produce vegetation clusters as core inputs for vegetation mapping (Faber-Langendoen et al., 2018). Brockmann-Jerosch and Rübel (1912) introduced the term phytosociological cartography, meaning spatially explicit plot-based vegetation inventories that were thoroughly analyzed and organized hierarchically. Phytosociology is a complex process that involves observing and interpreting the behavior of the plant species of a site, site communities, and their relationship with the environment. In practical terms, phytosociology requires representing the spatial and temporal phenomena related to the flora and vegetation expressed in units with specific phytogeographic fields (Pedrotti, 2004, 2013).

Databases of species inventories (since the beginning of the twentieth century) and land cover (since the beginning of the 1980s) are abundant and most are publicly available. Key well-known examples are the efforts made in Europe, where, in the absence of a joint approach, plot-based data are available for multipurpose objectives (e.g., http://www.givd.info/ID/EU-DE-020). Examples of available databases worldwide are also available, such as the sPlot initiative (https://www.idiv.de/en/sdiv/working_groups/wg_pool/splot/splot_database.html).

Geographic land cover cartography has developed significantly along with advances in remote sensing and geographic information systems (Mas et al., 2017; Taylor & Johnston, 1995). During the last four decades, both have revolutionized ways of carrying out land-cover cartography. Currently, aerial photography has been effectively replaced by satellite images with increasing temporal, spatial, and spectral resolutions. The geographic approach refers to the spatial segmentation of land-cover types distinguished from spectral values (ONU, 2001). Progress in cloud computing and machine-learning algorithms have led to large volumes of data being produced and land cover maps have been created at an unprecedented pace (Kraak & Ormeling, 2003; Shelestov et al., 2017). Most land cover maps included in the scientific literature of the last two decades have been based on a geographic approach using spectral information. Depending on the scale, ground-truthing used to validate cartographic classes is minimal (Alexander & Millington, 2000). The scientific challenge at hand is the transition of land cover data into vegetation maps.

A detailed procedure of combining phytosociological and land cover databases has not been developed, nor has this approach been fully considered to improve the quality of vegetation maps to be used for environmental agencies or policymakers (De Cáceres et al., 2015; Pedrotti, 2004, 2013; Velázquez et al., 2010). There are several reasons for this. First, the information is generated from different disciplinary backgrounds so that species inventories are obtained by botanists/phytosociologists (Mueller-Dombois & Ellenberg, 1974), while land cover databases are generated primarily by foresters, agronomist, and geographers. Second, environmental agencies study vegetation for understanding long-term (centuries at least) evolutionary and ecological processes so that species distinction is crucial for drawing conclusions, while policymakers study land cover for social and economic purposes of short-term relevance (decades at most). Some examples of maps constructed with phytosociological and land cover databases with geographic accuracy are found for temperate ecosystems (Biondi et al., 2011; Hesjedal, 1975; Pedrotti, 2013; Raynolds et al., 2005; Zak & Cabido, 2002). In contrast, transitional tropical/temperate ecosystems generally lack accurate examples of detailed vegetation cartography (Pérez-Valladares et al., 2019).

The present article documents a joint phytosociological and geographical approach to improve vegetation cartography in temperate-tropical transitional ecosystems. To be broadly applicable, the study was conducted at two scales. At the national level, it encompassed the entire country of Mexico, and at the regional level, it focused on the tree-dominated communities of the state of Michoacán. No vegetation map has yet been produced for the state of Michoacán despite encompassing both temperate and tropical conditions and harboring outstanding geophysical, socio-cultural, and biological diversity (Cué-Bär et al., 2006; Sarukhán et al., 2015). We discuss the potential for replication of our approach and the relevance of landcover/vegetation hierarchical maps for supporting environmental agencies/policymakers. Multiscale hierarchical land cover/vegetation mapping is seen as a fundamental input for environmental policy design at the federal, state, and municipal levels of governance.

2 | METHODS

2.1 | Land cover map (geographical approach) at national level

Every 5 years, the National Institute of Statistics and Geography (INEGI) produces a land cover database on land use/cover for Mexico. The first database (1976) was produced by aerial photograph interpretation, while the last series scale 1:250,000 (2016) used Landsat and Spot images as the main input sources. INEGI (2016) delivers a vector set of land use/cover, the so-called USV-sVI, series VI. This vector set (2016) comprised 182 cartographic classes and a dictionary with an explanation of the spectral attributes as well as the most common genera and species found within each cartographic class. Using the vector database and the description of each class, along with a literature review of cartographic classes in transitional tropical/temperate zones, we reclassified the 182 classes into hierarchically nested land cover types. To distinguish nested land cover types depicted by cartographic classes at each level, we followed the method of land cover and vegetation hierarchical attributes as described by Velázquez et al., (2016). The levels and scale of the representation are given below.

2.1.1 | Level zero (Natural land cover/Cultural land cover)

The database associated with the vector layer of Mexico's USV-sIV was reorganized into two classes (cultural land cover/natural land cover [Velázquez et al., 2016]) and spatially represented at a scale of 1:10,000,000 (Table 1). All land use/cover types classified and described as human settlements, agricultural fields, and areas for livestock grazing, dams, forest plantations, orchard plantations, and polygons with less than five percent coverage of native plant species were grouped as cultural land cover types at this level (INEGI, 2016). The remaining cartographic classes were grouped into a single cartographic class, denoted as the natural land cover type. This was done using ArcMap Geographic Information System (GIS) 10.5 and, to be consistent with the scale, areas smaller than 1,600 km^2 (<4 mm^2 on the map) were merged into the class of the largest adjacent polygon.

2.1.2 | Level I (Biome)

Each cartographic class clustered as natural land cover type from the vector layer of Mexico's USV-sIV (2016) were reclassified into four classes of land cover types, distinguishing clearly visible physiognomic attributes, namely forest (tree-dominated), scrubland (shrub-dominated), herbaceous (grass-dominated), and non-vascular (Velázquez et al., 2016). To distinguish this attribute, we zoomed into a scale of 1:4,000,000; polygons smaller than 256 km^2 (<4 mm^2 on the map) were merged into the adjacent polygon with the largest territorial extension, acquiring the category assigned to the latter. This was performed using ArcMap GIS 10.5.

2.1.3 | Level II (Large formation)

To produce this level, a map overlay mass was constructed using the four biomes obtained in the level I and the climatic vector map of Mexico obtained from http://www.conabio.gob.mx/informacion/metadata/gis/clima1mgw.xml?_httpcache=yes&_xsl=/db/metadata/xsl/fgdc_html.xsl&_indent=no.

The climatic map was first simplified into four major prevailing conditions: humid, dry, temperate, and tropical. The overlapping

TABLE 1 Hierarchical levels used for the development of the legend of the vegetation map at scale 1:100.000

HIERARCHICAL LEVELS	DESIGNATION	CRITERIA	ELEMENTS, CHARACTERISTICS, DOMINANT CHARACTERISTICS
Level I	Biome	Physiognomic dominant life-form	Tree, shrub, herb, and non-vascular plant.
Level II	Large formation	Dominant climate	Temperate humid and dry, tropical humid and dry, and cold.
Level III	Formation	Phenology	Deciduous, semi-deciduous, perennial, and semi-perennial.
Level IV	Sub-formation	Thorns	Spiny, spineless, and semi-spineless.
		Leaf morphology	Aciculifoliate, clustered, angustifoliate, cespitose, scale-like, latifoliate, linear leaves, megaphilia, microphila, and others.
		Succulence	Crasicaule, crassifolia, and non-succulent.
Level V	Syntaxonomical scheme	Floristic	Dominant taxa per forest community.
Cultural covers	Idem		Crops, plantations, human settlements, and communication routes.
Water bodies	Idem		Lakes and dams.

of the two vector databases depicted 19 classes, hereafter referred to as large formations. Cartographically, the scale of analysis was 1:1,000,000; polygons smaller than 16 km^2 (<4 mm^2 on the map) were merged into the adjacent polygon with the largest territorial extension, acquiring the category assigned to the latter.

2.1.4 | Level III at state level (Formation)

The political boundaries of the State of Michoacán were used to select the large formations depicted in Level II of the analyses. The State of Michoacán harbors 12 of the 19 large formations occurring in Mexico. The additional criteria at this level were the dominant phenology and structural vegetation attributes, so that formations were depicted for the entire state of Michoacán. These were spatially represented on a scale of 1:250,000. The minimum mapping area was 1 km^2 (4 mm on the map). Thus, polygons smaller than 100 ha were merged into the adjacent polygon with the largest territorial extension, acquiring the category assigned to the latter. The above procedure was performed using ArcMap GIS 10.5. At the formation level, ground validation was performed to confirm the polygons characterized by mixtures of tropical/temperate climates with deciduous and semi-deciduous species. From the phytosociological viewpoint, formations may be regarded as a proxy to define the levels of Class else Order, although vegetation surveys were conducted to distinguish dominant species and indicator species. The three levels, I, II, and III, were ground-validated using 268 sites, and information was provided by “Comisión Nacional Forestal” (hereafter CONAFOR).

2.1.5 | Level IV (Sub-formation)

To produce this level, we used a method based on the comparison between a map and remotely sensed input data to detect discrepancies between derived map classes and spectral responses. First, the spatial resolution of an existing map produced by visual interpretation of SPOT imagery (2017) at the sub-formation level was improved. To achieve this, we carried out segmentation of the SPOT images to obtain groups of spectrally homogeneous and spatially continuous pixels (segments) (scale 1:100,000). In the following step, each segment received the majority land cover category from the map through GIS overlay operations. Segments were also characterized from the images by computing the average response in different spectral bands (Mas & Gonzalez, 2015). For each category, the density function was calculated from the spectral responses. This indicates the probability of each segment belonging to a specific land cover class. Multivariate trimming was then applied to depict segments with spectral band responses regarded as outliers. The categories of these dubious segments were resolved by visual interpretation. Finally, an accuracy assessment was performed using contrasting spectral-based classification and map categories. The final input was assessed to have 80% map accuracy. More details on the remote sensing procedure can be found in Mas et al., (2017).

2.2 | Level V Vegetation survey (phytosociological approach)

From 1995 to 2017, 223 vegetation sampling units were surveyed in forest communities in the State of Michoacán following the Braun-Blanquet approach, as described by Velázquez et al., (2016). In each vegetation sampling unit, we conducted a complete species inventory of all vascular plants and estimated the coverage of each species. Exemplars of all plant species were collected to validate the identifications in the herbarium. Vegetation plot data were analyzed using a two-way indicator species analysis to define the hierarchical phytosociological arrangement of all forest communities occurring in the state of Michoacán (Grandin, 2006). A thorough phytosociological description of the associations, databases with species coverage, syntaxonomical array, phytosociological nomenclature, and location of the relevés can be found in Velázquez and Cleef (1993), Almeida et al., (1994), Velazquez et al., (2000), Galán de Mera et al., (2002), Rivas-Martinez (2004), Galán de Mera et al., (2006), Peinado et al., (2008), Pérez-Vega et al., (2010), Medina-García (2016), Takaki et al., (2019), Medina-García et al., (2020a), and Medina-Garcia et al., (2020b).

2.3 | Vegetation classification framework

Using the database of vegetation communities and the validated land cover map at the sub-formation level, we followed the framework provided by Velázquez et al., (2016) to develop a hierarchical and standardized classification system that spans vegetation of all physiognomies from forest to scrublands to herbaceous plants. At level V, land cover and vegetation databases were combined (Velazquez et al., 2016). Four levels of aggregation resulted in establishing a link between the criteria of the purely geographical approach for the definition of classes of land cover (levels I to III) and an intermediate level between the detailed land cover and phytosociological approach (levels IV and V). The actual syntaxonomical array at the class, order, and alliance levels was compiled into a synoptic syntaxonomical scheme.

2.4 | Vegetation-land cover integration

The integration of databases from the phytosociological (vegetation databases) and geographic (land cover map) approaches was conducted to obtain the final vegetation map (1:100,000 scale). At this level, vegetation attributes such as physiognomy, climatic conditions, phenology, dominant leaf type, and dominant genera and species were considered. Integration was performed by overlaying the polygons of the verified land cover database with the plot-based data allocated to forest communities and labeled according to the hierarchical and standardized classification system. The new vector map used as the main input was crucial for delineating polygons, which were not distinguished in the previous level. Vegetation map validation came from existing databases such as those from CONAFOR and those from relevés conducted by the authors of the present contribution, adding a total of 481 verification points (Gopar-Merino & Velazquez, 2016).

The outputs obtained from the methods described in sections II.1, II.2, II.3, and II.4, were further validated by three workshops with local botanists, conducted between 2009 and 2016. At these, we shared the preliminary vegetation map without labels and asked experts to label polygons. The labels of the experts were then compared to the labels attached to polygons according to our method and discrepancies verified in the field, following methods described by Pérez-Valladares et al., (2019). To keep outcomes up to date, two-month field verification in the whole state of Michoacán took place in 2021.

3 | RESULTS

3.1 | Land cover maps

3.1.1 | Natural/Cultural land cover (scale 1:10,000,000)

The spatial analysis of Mexico showed that, in 2016, natural land cover types occupied 71.35% (1,398,587 km^2) of the country. These types included polygons comprising both largely undisturbed and anthropogenically disturbed vegetation because the scale used did not permit disturbance processes to be clearly associated with the successional stages of vegetation. Cultural land cover types accounted for 27.91% (547,061 km^2) and water bodies accounted for 0.74% (14,541 km^2) of the country. Almost 30% of the cultural land cover types may be regarded as areas where native vegetation has been replaced irreversibly. The spatial distributions of these classes are shown in Figure 1.

3.1.2 | Growth form (level I: biome land cover [scale 1:1,000,000 to 4,000,000])

Of the six land cover types covering Mexico at this level, those of forest type are the most represented in the country, with 35% (687,299 km^2) of the land surface. Cultural land cover is the second most important class, with 28% (547,061 km^2) of the national cover, and scrublands is the third largest, with 26% (518,633 km^2). Herbaceous, water bodies, and non-vascular covers are the least extensive, with approximately 9% (178,565 km^2), 1% (14,541 km^2), and 1% (14,090 km^2), respectively. Cultural land cover increased slightly as the higher resolution allowed delineation of areas not depicted at the coarser scale. The spatial distributions of these biomes are shown in Figure 2.

3.1.3 | Climatic affiliation (level II: biome plus large formation [scale 1:500,000 to 1,000,000])

In Mexico, dry tropical biomes are the most predominant, accounting for 44% of the territory. This is followed by dry temperate, humid tropical, humid temperate, and cold (29%, 24%, 4%, and 0.005%, respectively). Although the combination of biomes and large formations yielded 19 possible combinations for Mexico (without considering cultural land cover and water bodies), the most important combinations were dry tropical shrubs covering 19% (366,279 km^2) of the country, followed by humid tropical forests with 13% (262,692 km^2), and dry tropical forests with 10% (194,831 km^2). The spatial distributions of these 21 classes are shown in Figure 3.

3.1.4 | Phenology (Levels III and IV: biome plus large formation plus formation plus subformation [scale 1:100,000 to 1:250,000])

At the state level, Michoacán comprised four phenological types: deciduous vegetation covering 25.05% of the state surface, followed by sub-deciduous vegetation with 17.38%, evergreen vegetation with 12.42%, and sub-evergreen vegetation with 5.89%. The combination of biomes, large formations, and phenological attributes yielded eight different classes of formations (excluding cultural land cover and water bodies). These formations were split into 15 sub-formation classes, of which 13 were forest communities, one scrubland, and a cluster of grasslands and hygrophilous vegetation types. The specific statistical contributions and spatial distributions of these classes are shown in Table 3 and Figures 4 and 5.

3.2 | Phytosociology

3.2.1 | Floristic (Level V: biome large formation plus formation plus sub-formation plus syntaxonomical array) [scale 1:100,000 to 1:250,000]

The results obtained by clustering analysis allowed us to distinguish two distinctive groups (Table 2). One referred to taxa with temperate affinity (Challenger & Soberón, 2008; González-Elizondo et al., 2012; González-Medrano, 2003), which was typical of temperate or semi-cold sub-humid climates (as described by García, 1964). This group included four classes, six orders, and twelve alliances. The other group harbored syntaxa of tropical affinity, characteristic of tropical dry, humid, and sub-tropical climates. This group included two classes, three orders, and four alliances (Table 2).

Owing to the minimum cartographic area (16 hectares on the ground, or 2 × 2 mm in the map), scrublands and herblands were mapped as two different classes without splitting them any further. A detailed description of the characteristic species that define each syntaxonomical group, the phytosociological description

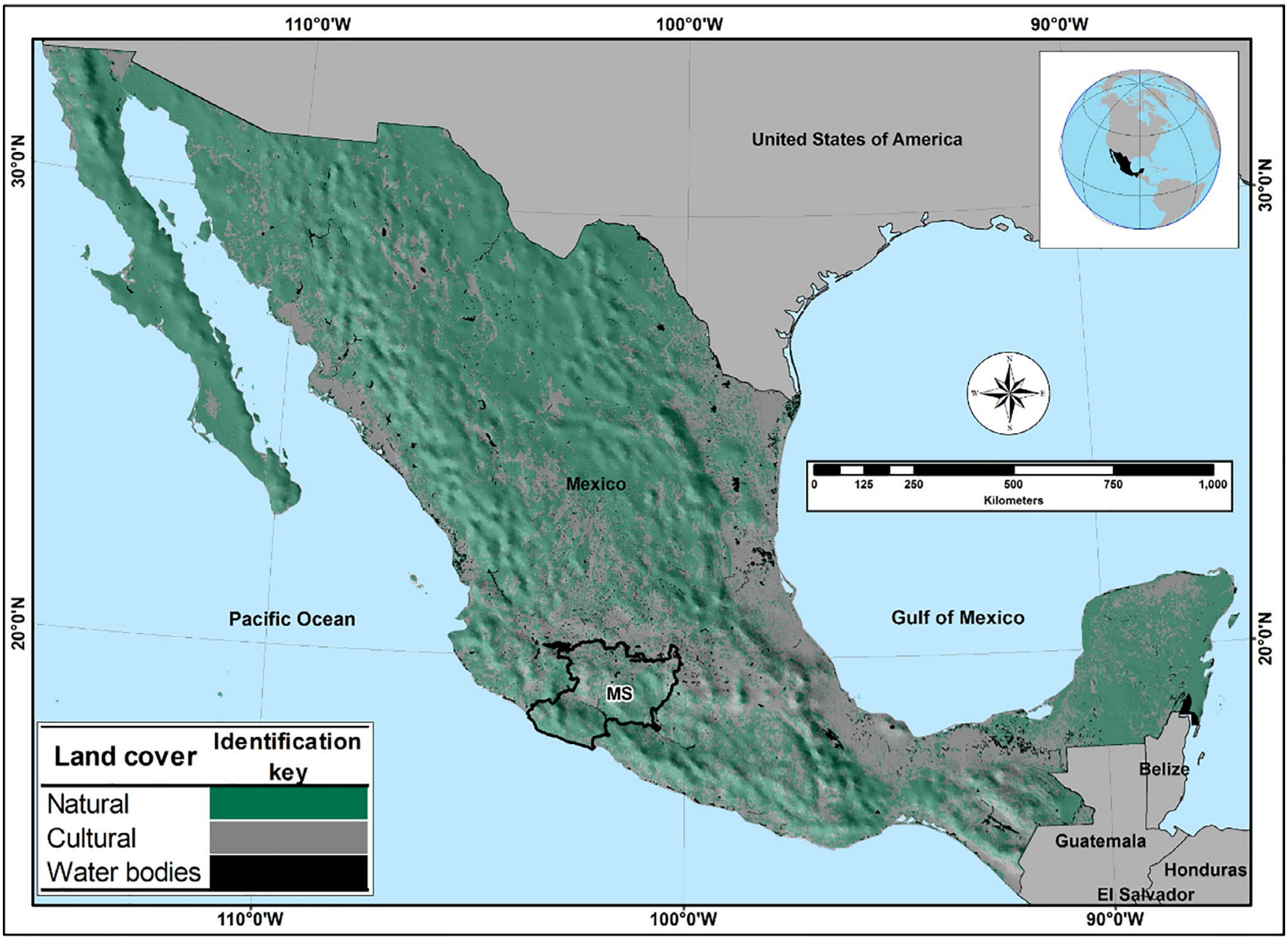

FIGURE 1 Natural and Cultural land cover types of Mexico in 2016. Natural land cover comprises polygons under different degree of disturbance. Cultural land cover represents areas where disturbance of native vegetation has been above the threshold of resilience so that recovery seems irreversible. MS stands for the state of Michoacán depicted by the black line.

and nomenclature, along with its ecological and geographical context (scale 1:100,000), can be found in the references provided in Table 2.

Within the hierarchical and standardized classification system, 15 sub-formations were depicted (Table 3). Further matching with phytosociological and syntaxonomical arrays permitted splitting into 17 vegetation cartographic classes. These include 15 forest types, one scrubland, one herbland, and other hygrophilous vegetation types. Water bodies and cultural land cover types made up the 19 cartographic classes that we were able to depict spatially.

Dry tropical deciduous broadleaved forest of the alliance of *Lysilomo divaricatae–Cordion elaeagnoidis* was the largest class, covering 16.23% of the whole state. Humid temperate evergreen needle-leaved and broadleaved forest of the alliance of *Pinion montezumae*–leiophyllae followed, covering 12.05% of the state. Humid tropical sub-deciduous needle-leaved and broadleaved forests of the order *Pino oocarpae–Quercetalia magnoliifoliae* was the third most important class, covering 11.81% of the state (Figure 4).

In contrast, the dry tropical sub-deciduous megaphyllous forest of the *Rhizophorion mangle* alliance was the least represented, covering only 0.01% of the state surface. The humid tropical sub-deciduous needle-leaved and broadleaved forest of the alliance of *Oreopanaco xalapensis–Quercion conspersae* also was rather limited, covering 0.84% of the state surface. Regarding forests with temperate affinities, dry sub-evergreen linearifolia and broadleaved forest of the order *Alnetalia acuminati–jorullensae* was the least represented, covering 0.02% of the whole state surface. These two forest types are regarded locally as cloud forests. Another temperate forest type rather limited in distribution was the humid evergreen aciculifoliate and needle-leaved of the class of *Pino hartwegii-Abietetea reilgiosae* which was also restricted to 0.37% of the state surface (Table 3; Figures 4 and 5).

It is relevant to state that the present chronological syntaxonomical pattern does not distinguish between disturbance and secondary vegetation types. For spatially explicit disturbance patterns and eventual stages of ecological transitions, as well as for splitting secondary vegetation types, larger scales must be used.

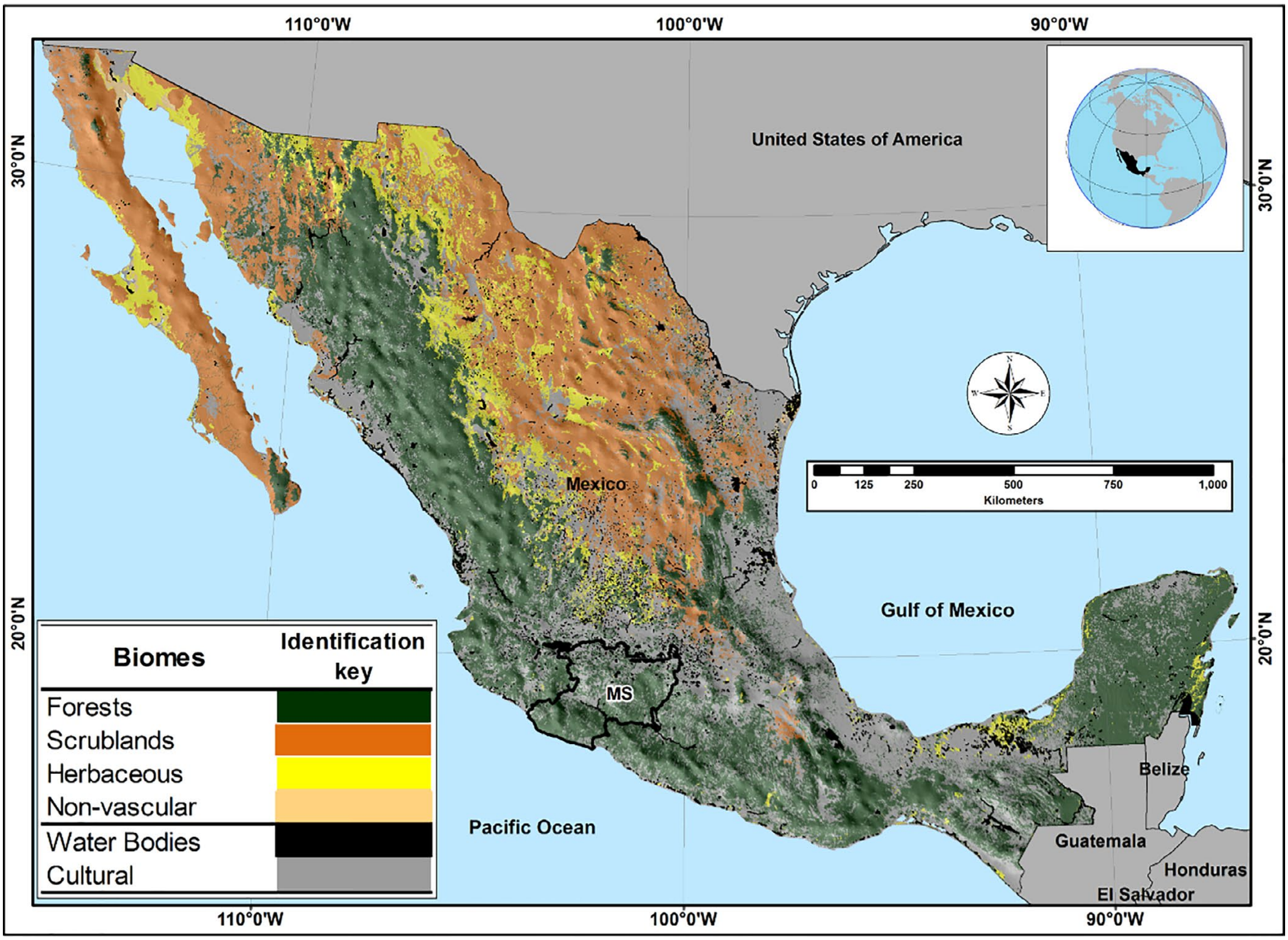

FIGURE 2 Geographic distribution of the Biomes of Mexico in 2016. Recommended scale for this level of vegetation complexity: 1:1,000,000 to 4,000,000. MS stands for the state of Michoacán depicted by the black line.

4 | DISCUSSION AND CONCLUSIONS

4.1 | The procedure for vegetation mapping

The procedure for vegetation mapping in this study represents a critical route where the two prevalent approaches (phytosociological and geographic) were integrated through standardized hierarchical rules that resulted in a coherent syntaxonomical array (Table 2), legend (Table 3), and scale (Figure 5). Our results represent the first attempt to provide a spatially explicit model of forest communities in one of the five most tree-species-rich states of Mexico (Cué-Bär et al., 2006). Firs, pines, oaks, alders, feather bush trees, copal trees, plum trees, macuilillos, and mangroves were the most common taxonomic groups comprising the gradient of forest communities in Michoacán. The results of merging both approaches were novel in regions with high ecogeographic complexity.

Previous studies on vegetation mapping have made significant advances (Biondi et al., 2011; Briones & Villareal, 2001; Cartujano et al., 2002; De Cáceres et al., 2015; Lewis, 1998; Pedrotti, 2013; Raynolds et al., 2005; Zak & Cabido, 2002). Nonetheless, examples of joint cartographic efforts in transitional biogeographic realms where vegetation mosaics are complex are yet to be fully documented (Gopar-Merino et al., 2015; Pérez-Valladares et al., 2019). Phytosociological groups, independent of their level (class, order, alliance, association), are the result of a detailed 1:1 scale floristic analysis, and their arrangement following well-longstanding rules for definition, naming, and hierarchically organization (Schaminée et al., 2009). Land cover mapping also follows criteria for standards in cartography (Bostock et al., 2013). Phytosociological groups do not always cover a sufficient area for cartographic representation as independent units. Land cover classes, despite the high resolution of available satellite images (e.g., GeoEye-1 Sentinel-2), do not display floristic attributes. Two unprecedented examples are as follows: (1) Global Biodiversity Information Facility (https://www.gbif.org/dataset/d7dddbf4-2cf0-4f39-9b2a-bb099caae36c) and (2) Global Index for Vegetation Database (https://www.givd.info/ID/EU-DE-020). These efforts are inadequate in certain regions and countries, such as Madagascar, Bolivia, Perú, Colombia, Brazil, and Mexico.

At a national scale, the Canada-US initiative of the "Federal Geographic Data Committee" is an exemplar because of the

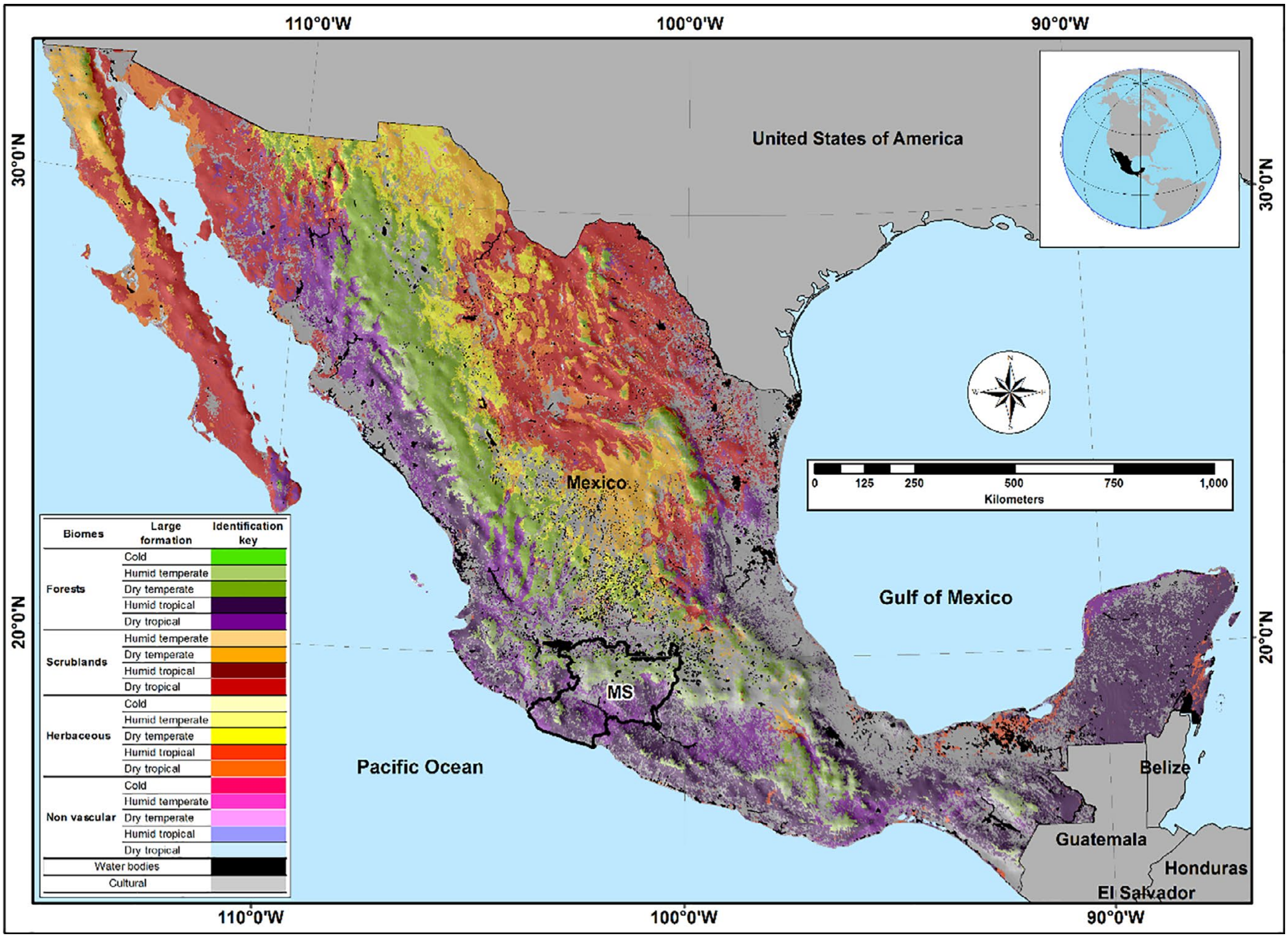

FIGURE 3 Geographic distribution of the Large formations of Mexico in 2016. Recommended scale for this level of vegetation complexity: 1:500,000 to 1,000,000. MS stands for the state of Michoacán depicted by the black line.

hierarchical classification of vegetation and its relationship with the Earth land coverage databases (Faber-Langendoen et al., 2014). The generation of a single global classification system is limited by the complexity inherent in each region. For example, Navarro and Maldonado (2002) and Navarro and Ferreira (2004) for Bolivia and Rangel-Churrio (1997) for Colombia are rich in phytosociological content but limited by land cover cartography. In contrast, in Brazil, there are many sources of land cover cartography (https://www.ibge.gov.br/), but the majority of sources lack phytosociological content. The most well-known case of vegetation cartography where the approaches are integrated is in Europe, allowing Europeans to consolidate the knowledge of the vegetation in coherent and compatible databases that support a large number of European environmental policies (Evans, 2012; Pedrotti, 2004).

Often, the lack of a methodological example represents a limitation in linking the advances of two disciplinary fields looking at the same study objects, namely, plants. Overcoming this limitation was one of the intentions of this article, in which we revealed the applicability of the method in Mexico as a transitional biogeographic region at two scales of analyses and highlighted its role as a biodiversity hotspot (Sarukhán et al., 2015).

4.2 | Contrasting approaches in vegetation and land cover cartography

Here, we applied concepts that are often assumed to be synonymous but derive from different approaches which produce contrasts in their fundamental natures. Examples of these concepts are vegetation community versus land cover types and successional vegetation stages versus secundarization (disruption) of the land cover types. Perhaps the concept of resolution happens to be most misused when referring to vegetation maps in contrast to land cover maps. Vegetation plot data are collected at a 1:1 scale covering small areas meant to be representative of wider vegetation units, while land cover data are meant to cover a large surface area, but at coarser scales. Sources of information also differ whereby botanists/phytosociologists used species per sampling unit (relevé) as the main source, while for foresters/agronomist/geographers used databases derived from remote sensing sources (e.g., aerial photographs, satellite, or drone imagery). Furthermore, data processing tools (multivariate analysis versus geographic information systems) vary significantly between the former and the latter (Xie et al., 2008). In the present study, the integration of the databases of the phytosociological

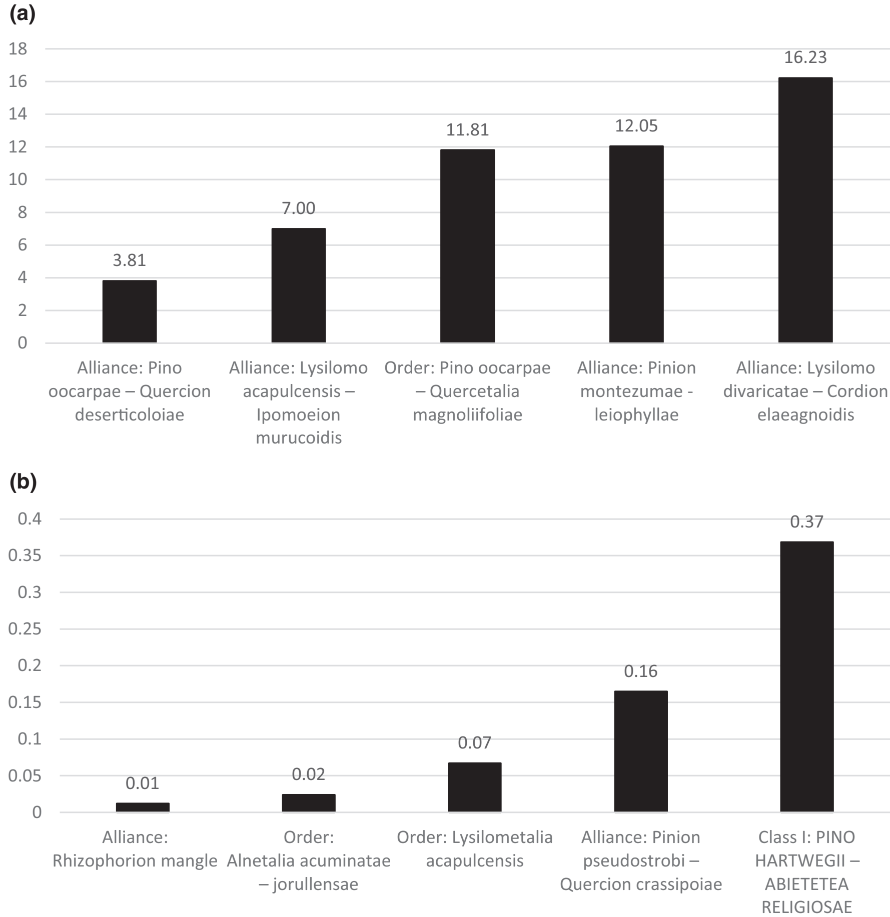

FIGURE 4 Statistics of the ten outstanding vegetation classes of the state of Michoacán. Numbers on top of the bars refer to percentage of occupied surface. Graph A is comprised of the five most represented vegetation types whereas graph B refers to the least distributed ones in the state of Michoacán.

(syntaxonomical array) and geographic (land cover map) approaches were considered as inputs to produce a logical transition from a land cover to a vegetation map (Tables 1, 2, and 3; Figure 5).

The human ecological footprint at local, regional, and global scales is critical for determining the future trends of both vegetation and land cover. Vegetation successional stages (species replacement in time as result of trigging disturbing events) differ significantly from the disruption of land cover patterns (expression of human land use on the land cover) so that both ecological and geographical processes intermingle. In these processes, scale matters because at finer scales, it is easier to show vegetation successional stages, whereas at coarse scales it is easier to map disrupted land cover patterns. Methods that clearly distinguish between the two complementary processes have yet to be demonstrated. For larger scales, drones may be a promising remote sensing tool to overcome the lack of resolution matching between vegetation plot data and remote sensing inputs.

4.3 | Highlights for the Mexican context

In Mexico, from the 1960s to the 1980s, the floristic-based approach for the development of databases for conducting vegetation cartography dominated (Miranda & Hernandez, 1963; Rzedowski, 1978). The outcomes comprised descriptions of the most prominent Mexican vegetation types and their distribution patterns were made at a very coarse scale. The results displayed limited cartographic detail and did not meet sufficiently rigorous cartographic standards to be considered as vegetation maps. Examples of these standards are the minimum mapping area, cartographic projection systems, and legend color palette. Empirical approximations of vegetation cartography are common among botanists whose research in regions reflects their knowledge of the flora and, in general, the results do not comply with a rigorous definition of a map with cartographic standards. From 1990 onwards, the geographic approach has dominated (Mas et al., 2004; Mas et al., 2016). The National Mexican Cartographic Agency (INEGI) plays a crucial role, as stated in the introduction. Nonetheless, a clear integrative methodological approach between floristic and geographic efforts has yet to be achieved.

The Michoacán landcover/vegetation map (Figure 5) revealed one outstanding outcome. There was a high degree of land coverage of a cultural nature; 38% of the entire state of Michoacán has been transformed into farmland, pastureland, forest plantations, cleared areas, secondary vegetation, and human settlements (an even higher conversion rate than nationally). This transformation was most intense in the northern and central regions, where recovery seems irreversible. Orchard plantations of avocado, peach, mango, and guava, although regarded as tree-dominated landscapes, were largely responsible for the massive transformation of native forested landscapes. A cultural footprint was also evident in the southern region of the Tepalcatepec watershed. In coastal ecosystems, a large disturbance was observed during fieldwork but was not

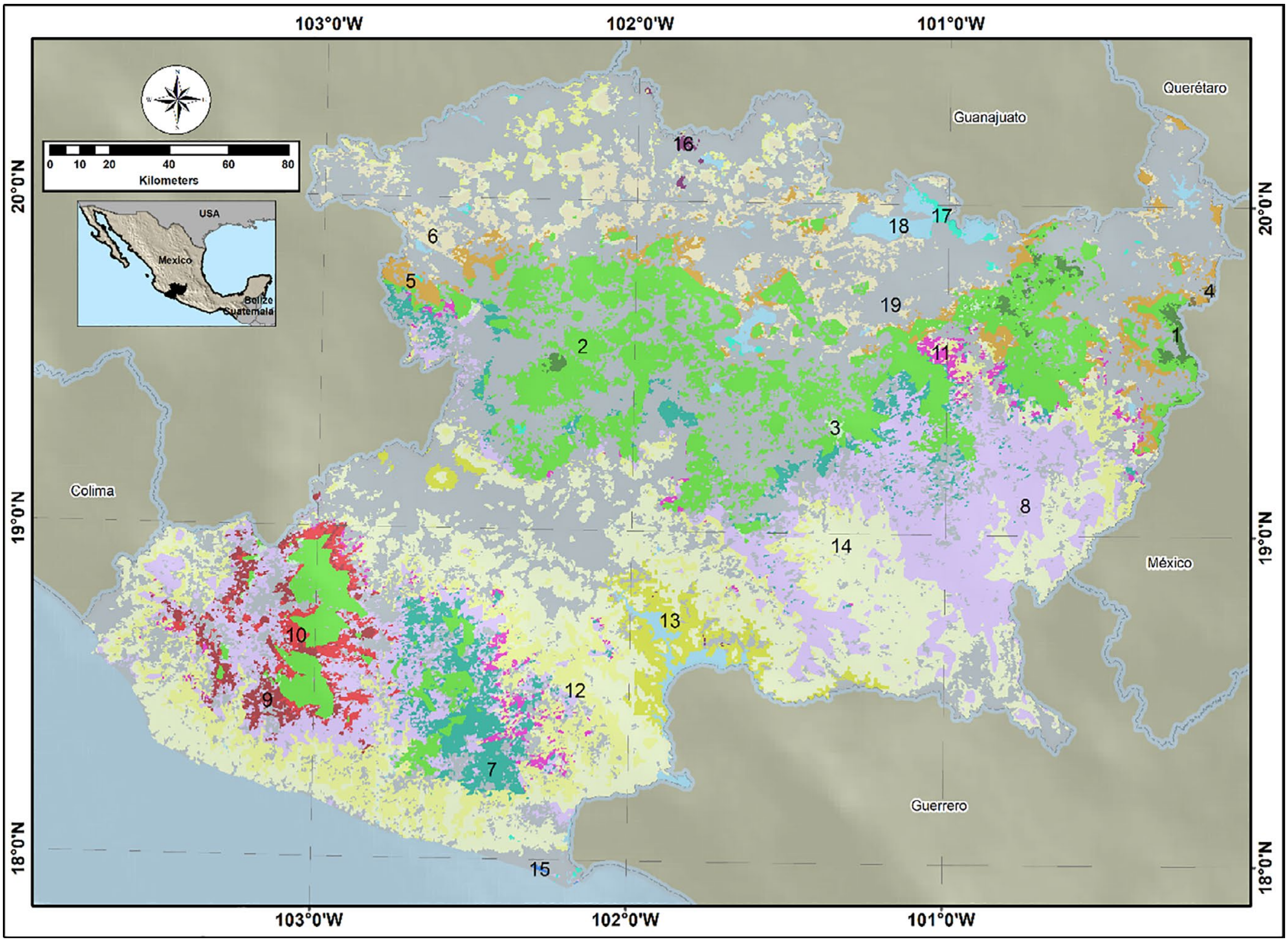

FIGURE 5 Geographic distribution of the 19 cartographic classes comprised in Michoacán in 2016. This map shows 17 vegetation units out of the 19 classes as a result of the integration of phytosociological and geographic approaches. Forest communities comprised 15 out of the 17 vegetation units. Table 3 provides thorough information on statistics and criteria used in the joint approach. At the present scale, some cartographic units depicted alliances and some other orders or even classes. Zoom in and further phytosociological surveys are needed to depict the complex syntaxonomical array comprised in the state of Michoacán.

fully apparent at the present scale of this map. At finer scales, such as 1:50,000, a large footprint was evident in the form of secondary vegetation intermingling with small parcels for seasonal rain fed agriculture, extensive livestock production, and low intensity forest community management. All these cultural practices were conducted along highways, unpaved roads, and hinterlands of towns, where the degree of disturbance was only visible at the local scale.

Forest community types with tropical affinities were slightly more prevalent and were more conserved than temperate vegetation types. Sixty percent of the total surface of the state of Michoacán seemed to be in a reasonable degree of conservation. This is noteworthy since this area harbors over 800 native tree species, and about half of these are endemic to Mexico (Cué-Bär et al., 2006). To exemplify this further, Michoacán contains 61 species of *Quercus*, 37 of *Bursera*, and 16 species of *Pinus*. This represents 12% of *Quercus*, 37% of *Bursera*, and 13% of *Pinus* species worldwide. *Quercus* and *Pinus*, moreover, are mainly regarded as having a Nearctic origin, whereas *Bursera* is undoubtedly of Neotropical affinity (Table 2 and Figure 5). *Bursera* species (copal trees) are predominantly classified as seasonally dry tropical vegetation with low dominance and scattered distribution and are therefore highly vulnerable to the climatic irregularities typical of the El Niño and La Niña phases, as well as climatic changes resulting from global warming trends.

The hierarchical expression of the legend (Tables 1, 2, and 3) clearly shows the phytosociological and geographic criteria used for each level. It is noteworthy that the map in Figure 5 may serve as a baseline for designing sound forest policies appropriate to the diversity of forest communities. This is crucial because most environmental policies in Mexico regard all forest types as homogeneous. Consequently, environmental policies disregard the particularities of type, origin, condition, distribution, and nature of species within each syntaxonomical level.

To briefly conclude, the syntaxonomical array presented in Table 2 was derived uniquely from a phytosociological approach. Conversely, the land-cover map was derived from the geographical approach. The syntaxonomical hierarchy in classes, orders, alliances, and eventually associations did not match geographic criteria. This is the reason why the cartographic classes depicted in Figure 5 do not follow geographic citeria at the same level of syntaxonomical array (see Table 3). Thus,

TABLE 2 Syntaxonomical overview at the Alliance level of the forest communities comprised and mapped in the State of Michoacán (scale 1:100,000)

SYNTAXA OF THE TEMPERATE AFFINITY	
Class I: *PINO HARTWEGII–ABIETETEA RELIGIOSAE* (Rivas-Martinez, 2004; Velazquez et al., 2000*)	
Order	**Alliance**
Vaccinio gemminiflori–Pinetalia hartwegii (Almeida et al., 1994)	*Pinion hartwegii* (Velazquez & Cleef, 1993*)
Abietalia religiosae (Velazquez & Cleef, 1993*)	*Abietion religiosae* (Velazquez & Cleef, 1993*)
Class II: *PINO MONTEZUMAE–QUERCETEA RUGOSAE* (Rivas-Martinez, 2004*)	
Order	**Alliance**
Pinetalia pseudostrobi–montezumae (Medina-García et al., 2020a*)	*Pinion montezumae–leiophyllae* (Medina-García et al., 2020a*)
	Pinion pseudostrobi–leiophyllae (Medina-García et al., 2020a*)
	Pino pseudostrobi–Quercion laurinae (Medina-García, 2020a*)
	Pino pseudostrobi–Quercion crassipedis (Takaki et al., 2019*)
Class III: *PINO OOCARPAE-QUERCETEA MAGNOLIIFOLIAE* (Medina-García, 2016*)	
Order	**Alliance**
Pino oocarpae–Quercetalia magnoliifoliae (Medina-García, 2016*)	*Pino oocarpae–Quercion glaucodis* (Takaki et al., 2019*)
	Pino oocarpae–Quercion deserticolae (Medina-García, 2016*)
	Pino oocarpae–Quercion candicantis (Medina-García, 2016*)
Class IV: *ALNETEA ACUMINATAE* (Galán de Mera & Vicente Orellana, 2006)	
Order	**Alliance**
Alnetalia acuminati–jorullensae (Takaki et al., 2019*)	*Alnetalio jorullensis–Quercion candicantis* (Medina-García, 2016*)
Alnetalia acuminatae (Galán de Mera et al., 2002)	*Oreopanaco xalapensis–Clethrion mexicanae* (Medina-García, 2016*)
	Oreopanaco xalapensis–Quercion conspersae (Takaki et al., 2019*)
SYNTAXA OF THE TROPICAL AFFINITY	
Class V: *PACHYCEREO PECTEN-ABORIGINI–LYSILOMETEA DIVARICATI* (Peinado et al., 2008)	
Order	**Alliance**
Lysilometalia acapulcensis (Medina-García et al., 2020b)	*Lysilomo acapulcensis–Ipomoeion murucoidis* (Medina-García et al., 2020b)
Cordietalia elaeagnoidis (Medina-García et al., 2020b)	*Lysilomo divaricatae–Cordion elaeagnoidis* (Medina-García et al., 2020b)
	Stenocereo quevedoni–Cordion elaeagnoidis (Medina-García et al., 2020b)
Class VI: *RHIZOPHORETEA MANGLE* (Bolós et al., 1991)	
Order	**Alliance**
Rhizophoretalia mangle (Bolós et al., 1991)	*Rhizophorion mangle* (Bolós et al., 1991)

The present proposal brakes down into six Classes; nine Orders, and sixteen Alliances. This syntaxonomical array includes three Classes; four Orders, and twelve Alliances that have been botanically described, although these remain yet to be published officially as phytosociological classes and are marked as *.

even if the scale is refined, mismatches may occur because neither approach follows the same criteria to define syntaxonomical levels and cartographic units. Finer scales will certainly facilitate an increase in the possibility of delineating smaller syntaxonomical classes. However, mosaics of syntaxonomical classes will always remain in cartographic units, regardless of the scale of geographic analysis.

4.4 | Relevance for environmental policy

Classification and vegetation mapping are closely related academic tasks that involve an interdisciplinary approach. If cartography portrays what exists in a place, the classification defines the order of approximation of the object to be mapped (Thompson, 1996). A vegetation map combines the systematic classification of land cover types and mosaics of plant communities that occur in a landscape. Currently, there is a growing demand for integrated vegetation maps to conduct research in zoology, geology, ecology, forestry, agronomy, conservation biology, climatology, and environmental agencies, as well as with policymakers (Küchler, 1967; UNEP/FAO, 1994). An integrated vegetation map constitutes the first snapshot of a region, allowing us to see the potential use of a territory. It represents a critical modeling input for potential carbon capture assessments, evaluation of the integrity and degree of conservation of the network of

TABLE 3 Hierarchical standardized land cover/vegetation of Michoacán.

BIOMES	LARGE FORMATION	FORMATION	SUB-FORMATION	SYNTAXONOMICAL SCHEME	IDENTIFICATION NUMBER	IDENTIFICATION COLOR KEY	Squared Km	%
I	II	III	IV	V				
Forests	Humid temperate	Evergreen	Aciculifoliate / Needle-leaved	**Class I: *PINO HARTWEGII–ABIETETEA RELIGIOSAE***	**1**		**216.47**	**0.37**
			Needle-leaved / Broadleaved	**Alliance: *Pinion montezumae-leiophyllae***	**2**		**7,077.59**	**12.05**
		Sub-evergreen	Megaphyllous / Broadleaved	**Alliance: *Pino pseudostrobi-Quercion crassipoiae***	**3**		**96.84**	**0.16**
	Dry temperate	Sub-evergreen	Linearifolia /Broadleaved	**Order: *Alnetalia acuminati–jorullensae***	**4**		**14.05**	**0.02**
			Needle-leaved	**Alliance: *Pinion pseudostrobi-leiophyllae***	**5**		**1,112.49**	**1.89**
			Needle-leaved /Broadleaved	**Alliance: *Pino oocarpae–Quercion deserticolae***	**6**		**2,238.27**	**3.81**
	Humid tropical	Sub-deciduous	Needle-leaved / Broadleaved	**Alliance: *Pino pseudostrobi-Quercion laurinae***	**7**		**1,700.08**	**2.89**
			Needle-leaved / Broadleaved	**Order: *Pino oocarpae-Quercetalia magnoliifoliae***	**8**		**6,936.29**	**11.81**
			Broadleaved	**Alliance: *Oreopanaco xalapensis-Clethrion mexicanae***	**9**		**562.27**	**0.96**
			Megaphyllous	**Alliance: *Alnetalio jorullensis-Quercion candicantis***	**10**		**508.99**	**0.87**
	Dry tropical	Sub-deciduous	Needle-leaved / Broadleaved	**Alliance: *Oreopanaco xalapensis–Quercion conspersae***	**11**		**490.89**	**0.84**
		Deciduous	Broadleaved	**Alliance: *Lysilomo acapulcensis–Ipomoeion murucoidis***	**12**		**4,108.47**	**7.00**
				Alliance: *Stenocereo quevedoni-Cordion elaeagnoidis*	**13**		**915.62**	**1.56**
				Alliance: *Lysilomo divaricatae-Cordion elaeagnoidis*	**14**		**9,529.02**	**16.23**
		Sub-deciduous	Megaphyllous	**Alliance: *Rhizophorion mangle***	**15**		**7.13**	**0.01**
Scrublands	Dry tropical	Deciduos	Broadleaved	**Order: *Lysilometalia acapulcensis***	**16**		**39.48**	**0.07**

(Continues)

TABLE 3 (Continued)

BIOMES	LARGE FORMATION	FORMATION	SUB-FORMATION	SYNTAXONOMICAL SCHEME	IDENTIFICATION NUMBER	IDENTIFICATION COLOR KEY	Squared Km	%
I	II	III	IV	V				
Herbaceous (grassalands and hygrophilous vegetation types)					17		120.21	0.20
Water bodies	Not applicable	Not applicable	Not applicable	Water bodies	18		817.48	1.39
Cultural cover	Not applicable	Not applicable	Not applicable	Cultural cover	19		22,238.04	37.87
TOTAL							58,513.20	100.00

On the whole, 19 cartographic classes were depicted following the present geographic and phytosociological joint approach (see Figure 5).

protected natural areas, environmental supply for environmental goods and services, potential for forest management, and other territorial planning strategies (FAO, 1995). It should be noted that for an integrated vegetation map to serve as a baseline it ought to combine top-down and bottom-up approaches to achieve scientific acceptability in accuracy and precision (De Cáceres et al., 2015; Mas et al., 2009; Velázquez et al., 2003; Velázquez et al., 2016). The present outcome may serve to bridge scientific outcomes with policymakers to develop sustainable land use planning.

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AUTHOR CONTRIBUTIONS

Alejandro Velazquez: conceived of the research framework, collected data, performed statistical analyses, wrote the paper and leaded the contribution of all authors.

Consuelo Medina García: collected data, performed botanical and statistical analyses.

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Elvira Duran: conceived of the research framework, collected data.

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Joaquín Giménez de Azcarate: collected data, performed botanical and statistical analyses.

Arnulfo Blanco: collected data, performed botanical analyses.

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DATA AVAILABILITY STATEMENT

There are not additional data supporting the present outcomes.

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