Ecosystems and Diversity of the Sierra Madre Occidental

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Abstract—*The Sierra Madre Occidental (SMO) is the largest continuous ignimbrite plate on Earth. Despite its high biological and cultural diversity and enormous environmental and economical importance, it is yet not well known. We describe the vegetation and present a preliminary regionalization based on physiographic, climatic, and floristic criteria. A confluence of three main ecoregions in the area corresponds with three ecosystems: Temperate Sierras (Madrean), Semi-Arid Highlands (Madrean Xerophylous) and Tropical Dry Forests (Tropical). The Madrean region harbors five major vegetation types: pine forests, mixed conifer forests, pine-oak forests, oak forests and temperate mesophytic forests. The Madrean Xerophylous region has oak or pine-oak woodlands and evergreen juniper scrub with transitions toward the grassland and xerophylous scrub areas of the Mexican high plateau. The Tropical ecosystem, not discussed here, includes tropical deciduous forests and subtropical scrub. Besides fragmentation and deforestation resulting from anthropogenic activities, other dramatic changes are occurring in the SMO, including damage caused by bark beetles (Dendroctonus) in extensive areas, particularly in drought-stressed forests, as well as the expansion of chaparral and Dodoneaea scrub at the expense of temperate forest and woodlands. Comments on how these effects are being addressed are made.*

Introduction

The Sierra Madre Occidental (SMO) or Western Sierra Madre is the longest mountain range in Mexico and the largest continuous ignimbrite plate on Earth. It has a surface of 251,648 km^2 (not including the Madrean Archipelago), about the size of the State of Wyoming and even larger than the United Kingdom. Elevations range from 300 to 3340 m. With a rugged physiography of highland plateaus and deeply cut canyons, it extends more than 1160 km from near the United States-Mexico border (30° 35'N) to northern Jalisco (21°00'N) in western Mexico. It is linked to the Rocky Mountains through the Sky Islands in the north and connected with the Trans-volcanic Belt to the south. It is a boundary area for hundreds of species that reach their northern or southern range limits; it also contains a high proportion of endemic elements. The SMO is the source of environmental services for a large area in northwestern and north-central Mexico, includes about two thirds of the standing timber in Mexico, and boasts some of the richest diversity of habitats and species anywhere in North America.

The prominence of the SMO in the biological diversity of Mexico has been addressed by Bye (1995), González-Elizondo (1997), Felger and Wilson (1995), Felger and others (1997), and Van Devender and Reina (2005), among others. Two areas have been recognized by the International Union for the Conservation of Nature (IUCN) as megacenters of plant diversity: northern Sierra Madre Occidental and the Madrean Archipelago (Felger and others 1997) and the Upper Mezquital River region (González-Elizondo 1997). Its high diversity has been noted by Spellenberg and others (1996) who found 823 plant species for the Cascada de Basaseachi National Park. Felger and others (1997) estimated 4000 species of vascular plants for the northern portion of the range, Martin and others (1998) reported more than 2800 species for the Rio Mayo region, and Vázquez-García and others (2004) listed 2081 species for the Huichol region in the south.

A study on bats (Torres-Morales and others 2010) revealed that species richness of the SMO in northwestern Durango (including temperate and tropical areas) is comparable to that of the tropical rain forests of southeastern Mexico as a result of the great diversity of habitats in relatively small areas. This exceptional diversity is mirrored by three physiognomically dominant Madrean genera: Pinus, with 24 species (46% of the Mexican total), Quercus with 54 species (34%) and Arbutus with 7 species (100%) (González-Elizondo and others, in review). Many new Madrean taxa have been described from the region during the last 10 years, including one genus (González-Elizondo and others 2002) and more than 20 additional species, suggesting that numerous undescribed taxa are still to be found. The recent discovery of a second population for *Pinus maximartinezii* (González-Elizondo and others 2011) after almost 5 decades since its description reveals the probability of deep gaps in knowledge of biodiversity in the SMO.

Studies on SMO ecosystems and its surrounding areas started in the 1940s and continue to date (Spellenberg and others 1998; Van Devender and others 2003; Martínez-Yrízar and others 2010; and papers cited above). However, the Sierra Madre Occidental is far from being biologically and ecologically well known. We present here an outline of the main Madrean vegetation types and a preliminary delimitation of ecoregions of the SMO based on physiographic, climatic, and floristic criteria. Vegetation was mapped using ArcGis 9.3 based

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on the vegetation and land use map data in vector format Series III of INEGI (2002), with adaptations based on field and literature data. This delimitation helps to understand how organisms are distributed in the SMO; as important, it should be a baseline for future studies on taxonomy, biogeography, and ecology.

Results and Discussion

Ecoregions

Three main ecoregions converge in the SMO: Temperate Sierras, Semi-Arid Highlands, and Tropical Dry Forests (CEC 1997). We refer to them as Madrean, Madrean Xerophylous, and Tropical in the study area.

M—Madrean region occurs on the higher areas of the sierra, following the Continental "backbone," including highland ridges and a highland plateaus (fig. 1 M). It is almost 200 km wide in some places, its climates are temperate and semi-cold, and its prevalent communities are temperate forests in which several conifers and oaks are dominant elements.

MX—Madrean Xerophylous region occupies the eastern foothills and northern and eastern branches of the cordillera (fig. 1 MX), with semidry temperate or semidry semicold climates. Oak or pine-oak woodlands and evergreen scrub are the dominant vegetation.

T—Tropical region enters the SMO through the tributary ravines on the steep western flanks that drop to the narrow Pacific coastal plain (fig. 1 T). Climates are warm, semi-warm, and dry-warm, with a prevalence of tropical deciduous forests and subtropical scrub.

Two subregions are recognized based on physiographic and floristic criteria within the Madrean region:

M—Madrean *sensu stricto* on the highland ridges and the highland plateau.

MT—Madrean-Tropical on the upper western slopes in which the climates are still temperate but moister and warmer that on the interior of the range. This subregion is recognized by the presence of conifer and oak species with strong affinities to the south, as *Pinus oocarpa*, *P. douglasiana*, *P. devoniana*, *P. luzmariae*, *P. maximinoi*, *P. praetermissa*, *P. yecorensis*, *Quercus candicans*, *Q. scytophylla*, *Q. subspathulata*, and *Juniperus flaccida*, among others.

The Madrean sensu stricto region can be further divided into Northern, Central and Southern ranges (fig. 1):

M1—The Northern range includes eastern Sonora and western Chihuahua south to the Urique barranca (between 27° and 28° N). With a mean elevation of 2350 m, it has colder and more continental climates than the rest of the SMO. Besides the species shared with the Madrean Archipelago to the north (e.g. *Juniperus scopulorum*, *Quercus gambelii*), *Pinus yecorensis* and *Vaccinium chihuahuense* are characteristic of the zone.

M2—The Central range extends from southwestern Chihuahua to southern Durango and eastern Sinaloa, ending with the Quebrada del río Mezquital (22°50'-23°25' N). With a mean elevation is 2650 m, it includes peaks above 3200 m. Many species and a genus (Megacorax) are restricted here.

M3—The Southern range includes the area from the Río Mezquital to northern Jalisco. It is a rugged zone with deep and wide canyons through which the tropical and xerophylous zones converge. Many species are restricted to the area, e.g., *Pinus maximartinezii*. An example of the diversity and distribution of plant species by regions is given with *Arbutus* and *Agave* (table 1).

Because barriers to distribution across the tropical region are low, most tropical elements are distributed on a SE to NW continuum along the western foothills of the SMO from northern Nayarit and Jalisco to Sonora and Chihuahua. Nevertheless, some elements are evolving more locally, such as *Agave*, which show differential distributions with some species restricted to the subregions here proposed (table 1). As for *Arbutus*, the SMO harbors the highest diversity worldwide, with seven Madrean species. *Arbutus arizonica* is widely distributed and but other species are restricted to some subregions.

Vegetation

The Madrean, Madrean Xerophylous and Tropical regions include characteristic ecosystems and vegetation. The Madrean region harbors five major types: pine forests, mixed conifer forests, pine-oak forests, oak forests, and temperate mesophytic forests as well as communities of primary and secondary chaparral and montane meadow vegetation. Madrean Xerophylous includes oak or pine-oak woodland and evergreen juniper scrub with transitions toward the grassland and xerophylous scrub of the Mexican high plateau and to the subtropical scrub at the southern area of the Madrean Archipelago subregion. A map (fig. 2) illustrates the Madrean and Madrean Xerophylous vegetation types. The Tropical region has a prevalence of tropical deciduous forests and subtropical scrub, with small spots of tropical subdeciduos forest. These three, with no Madrean affinities, are not treated here. They would occupy the ravines on the western and southern flanks of the sierra in the map.

The classification of the vegetation follows Rzedowski (1978), a system of basic and excluding categories that is (1) easy to subcategorize and adapt to more specific situations; (2) comparable with other systems worldwide; and (3) relatively easy to map. The system combines physiognomic, floristic and ecological criteria.

Pine Forests

Between 1600 and 3320 m, these forests cover 12% of the surface area in diverse combinations of *Pinus*. They occur in several environmental conditions, with combinations of mainly *P. arizonica*, *P. engelmannii*, and *P. chihuahuana* on the northern and central zones of the range; *P. durangensis* or *P. teocote* from central Chihuahua to the south; and *P. leiophylla* and *P. strobiformis* in humid sites. *P. cooperi* is monodominant in valleys with deep soils, while the weeping pine (*P. lumholtzii*) dominates thin, acidic, poor soils. On the western slopes (region MT), *P. oocarpa*, *P. yecorensis*, *P. douglasiana*, *P. herrerae*, *P. devoniana,* and *P. maximinoi* dominate in subhumid places, *P. lumholtzii* or *P. luzmariae* on poor soils.

Mixed Conifer Forests

Fir and pine-fir forests cover less than 0.3% of the surface area mainly in small patches between 1900 and 3300 m in humid ravines and slopes in the north. The physiognomic dominants are Douglas-fir (*Pseudotsuga menziesii*) and species of *Abies* and *Picea* associated with *Pinus* and sometimes *Quercus*. *Pseudotsuga* predominates, but there are also small areas of *Abies durangensis* and *Picea chihuahuana*, and even smaller areas of *Abies concolor*, *A. neodurangensis*, and *Picea engelmannii* var. *mexicana*.

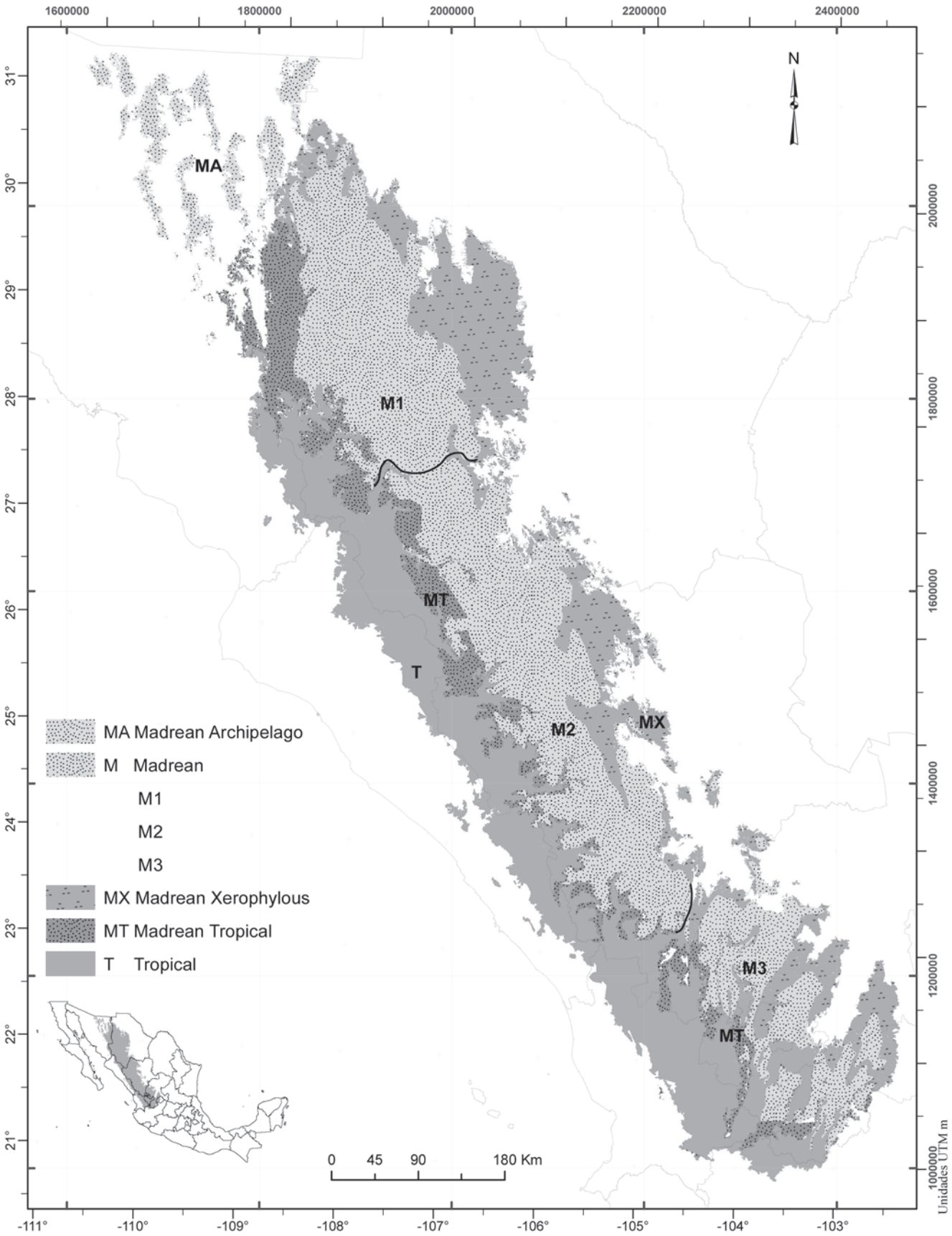

Figure 1—Regions and subregions of the Sierra Madre Occidental. MA = Madrean Archipelago; M = Madrean; MX = Madrean Xerophylous; MT = Madrean with tropical affinities; T = Tropical; M1 = North; M2 = Center; M3 = South.

Table 1--Species of *Agave* and *Arbutus* in the Sierra Madre Occidental.

MA = Madrean Archipelago; M = Madrean; MX = Madrean Xerophylous; MT = Madrean with tropical affinities; T = Tropical; 1 = North; 2 = Center; 3 = South

Species	MA	M1	M2	M3	MX1	MX2	MX3	MT1	MT2	MT3	T1	T2	T3
Arbutus arizonica (A. Gray) Sarg.	1	1	1	1									
A. bicolor S. González, M. González et P.D. Sorensen		1	1	1									
A. madrensis S. González			1	1									
A. mollis HBK.				1									
A. occidentalis McVaugh & Rosatti			1	1									
A. tessellata P.D. Sorensen								1	1	1			
A. tessellata P.D. Sorensen f. *repens*			1										
A. xalapensis HBK. var. *texana* (Buckley) A. Gray		1											
A. xalapensis HBK. var. *xalapensis*								1	1	1			
A. xalapensis HBK. f. *glandulosa* M. Martens & Galeotti													
Agave angustifolia Haw. var. *angustifolia*								1	1	1			
A. angustifolia Haw. var. *rubescens* (Salm-Dyck) Gentry									1	1			
A. applanata Lem. ex Jacobi						1							
A. attenuata Salm-Dyck subsp. *pedunculifera* (Trel.) B. Ullrich									1	1			
A. bovicornuta Gentry								1	1				
A. chrysoglossa I.M. Johnst.											1		
A. durangensis Gentry						1			1	1			
A. filifera Salm-Dyck subsp. *microceps* Kimnach										1			1
A. filifera Salm-Dyck subsp. *multifilifera* (Gentry) B. Ullrich								1	1				
A. filifera Salm-Dyck subsp. *schidigera* (Lem.) B. Ullrich		1	1	1									
A. flexispina Trel.						1							
A. geminiflora (Tagl.) Ker-Gawler										1			
A. guadalajarana Gentry										1			
A. impressa Gentry												1	1
A. inaequidens K. Koch subsp. *barrancensis* Gentry									1				
A. jaiboli Gentry								1					
A. maximiliana Baker var. *katharinae* (A. Berger) Gentry			1						1	1			
A. maximiliana Baker var. *maximiliana*			1	1					1	1			
A. nayaritensis Gentry									1	1			1
A. ocahui Gentry var. *ocahui*								1					
A. ocahui Gentry var. *longifolia* Gentry								1	1	1			
A. palmeri Engelm.					1								
Agave parryi Engelm. var. *huachucensis* (Baker) Little	1												
A. parryi Engelm. subsp. *neomexicana* (Wooton & Standley) B. Ullrich					1	1							

Table 1—Continued.

A. parryi Engelm. var. *parryi*					1	1							
A. parryi Engelm. var. *truncata* Gentry						1							
A. parviflora Torr. subsp. *densiflora* G. Starr & T.R.Van Devender		1											
A. parviflora Torr. subsp. *flexiflora*	1												
A. parviflora Torr. subsp. *parviflora*	1												
A. pintilla S. González, M. González y L. Reséndiz						1							
A. polianthiflora Gentry					1			1					
A. potrerana Trel.					1								
A. rhodacantha Trel.											1	1	1
A. rzedowskiana P. Carrillo, R. Vega & R. Delgad.									1	1			
A. salmiana Otto ex Salm-Dyck subsp. *crassispina* (Trel.) Gentry													
A. schottii Engelm.	1				1								
A. shrevei Gentry subsp. *magna* Gentry								1	1				
A. shrevei Gentry subsp. *matapensis* Gentry											1		
A. shrevei Gentry subsp. *shrevei*								1	1				
A. striata Zucc. subsp. *falcata* (Engelm.) Gentry						1							
A. vilmoriniana Berger											1	1	1
A. wocomahi Gentry		1	1					1	1				
Agave sp. nov. 1									1				

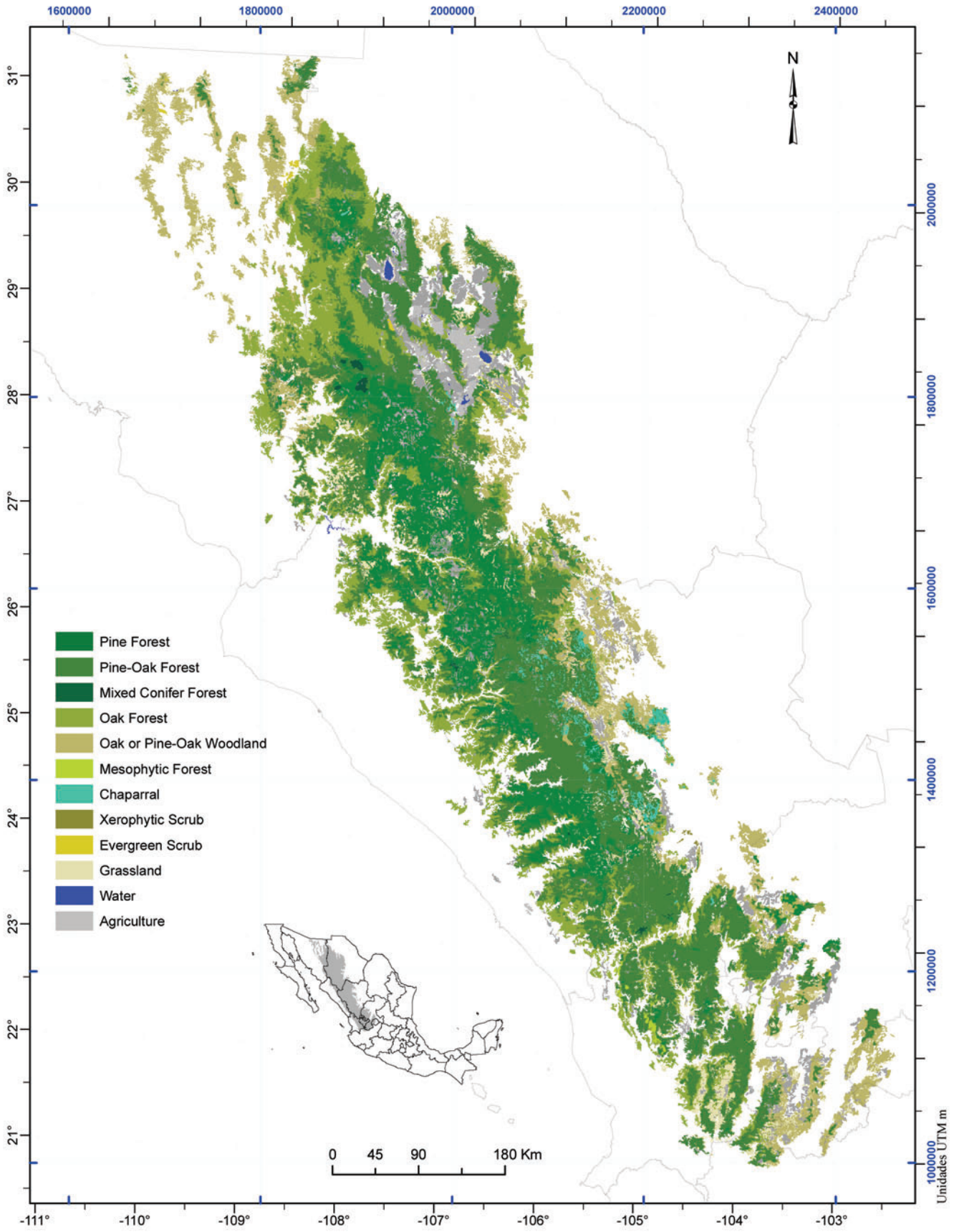

Figure 2—Vegetation of the Sierra Madre Occidental.

Pine-Oak Forests

Covering about 30% of the surface, from 1250 to 3200 m, pine-oak forests occur with a wide array of species combinations depending on elevation, physiography, and climate: *Pinus arizonica*, *P. engelmannii*, and *P. chihuahuana* with *Quercus rugosa* and/or *Q. gambelii* in the northern portions of the SMO; *P. durangensis*, *P. teocote*, and *P. cooperi* with *Q. sideroxyla*, *Q. crassifolia*, *Q. rugosa*, *Arbutus bicolor*, *A. madrensis*, and *A. arizonica* in relatively dry places; or *A. tessellata* in warmer areas. Diverse species of *Quercus* may combine with *P. engelmannii*, *P. chihuahuana*, and *A. arizonica* in semi-dry temperate areas. On thin soil or outcrops of very unsheltered bedrock, forests of *P. lumholtzii* with *Q. radiata* and a xeric phase of *Q. crassifolia* are prominent. Manzanita (*Arctostaphylos pungens*), *Juniperus deppeana*, and *J. durangensis* are among the common shrubs. On the western slopes (MT), *P. oocarpa* is associated with *P. devoniana*, *P. douglasiana*, *Q. viminea*, and *Q. gentryi*, among others. *Pinus herrerae* dominates on ridges and slopes while on lower areas *P. luzmariae* is on mesas and hillsides frequently with *P. lumholtzii* and *Q. radiata*. Between 1800–2300 m, *Q. jonesii* mixes with *P. lumholtzii*, *Q. resinosa*, *Q. crassifolia*, and *Q. viminea*. *Q. resinosa* mixes with *Q. praineana* and *P. oocarpa* on lower elevations in Durango, Jalisco, and Zacatecas.

Oak Forests

These forests are communities with a dominance of *Quercus* species but with very different composition, structure, and ecological affinities. They cover almost 14% of the surface area of the SMO, from 340 m on low hills in the middle of tropical deciduous forest, to 2900 m in semi-cold climates. Communities dominated by *Quercus* in dry temperate climates are described under the oak woodlands. Among the main associations are *Q. sideroxyla* and *Q. rugosa*, up to 2900 m and *Q. fulva*, *Q. mcvaughii* or *Q. scytophylla* below. *Q. laeta* has a broad ecological tolerance, occurring on the western and southern flanks of the SMO. In the Madrean Tropical subregion there are mesophytic oak forests with *Q. candicans*, *Q. crassifolia*, *Q. diversifolia*, *Q. scytophylla*, and *Clethra* spp; at lower elevations, *Q. subspathulata* enters the subregion. Other oak forests on the western flanks are those of *Q. viminea* or *Q. alamosensis* to the north and *Q. diversifolia* and *Q. gentryi*. *Q. albocincta* occurs at lower elevations. In the south, low forests of robles (*Q. magnoliifolia*, *Q. resinosa*) sometimes with *Q. eduardii* or *Q. viminea*, are found in many areas being substituted by Dodonaea scrub.

Mesophytic Forests

These forest communities are rich in their diversity and structure. They occupy small areas, covering about 0.14% of the surface area on the western flank of the sierra, between 1000 and 2350 m. Among their characteristic elements are *Magnolia pacifica* subsp. *tarahumara*, *Ostrya virginiana*, *Tilia americana* var. *mexicana*, *Cedrela odorata*, *Styrax ramirezii*, several *Lauraceae* such as *Persea liebmannii*, *P. podadenia*, *Nectandra* spp. and *Litsea* spp and oaks like *Q. candicans*, *Q. crassifolia*, *Q. castanea*, *Q. rugosa*, Q. scytophylla, and *Q. splendens*. Other species are *Arbutus xalapensis*, *Garrya laurifolia*, Cornus disciflora, *C. excelsa*, *Clethra* spp, Prunus spp, *Peltostigma pteleoides*, *Ilex quercetorum*, *I. toluccana*, *Cleyera integrifolia*, and *Brahea aculeata*. Often pines and other conifers are present including *Pinus maximinoi*, *P. devoniana*, *P. douglasiana*, *P. herrerae*, *P. strobiformis*, *P. durangensis*, *Abies neodurangensis* or *Pseudotsuga menziesii*. Other communities, such as the Madrean montane meadow that occurs in small spots between 2300 and 3100 m, include a high proportion of endemic species.

Oak or Pine-Oak Woodlands

These woodlands cover more than 13% of the surface along the eastern foothills and isolated outlying ranges of the SMO at 1450-2500 m. Physiognomic dominants are pinyon (*Pinus cembroides*) and/or several species of *Quercus* of xerophylous affinities.

In northern Sonora and Chihuahua, blue oak (*Q. oblongifolia*), Emory oak (*Q. emoryi*), or Arizona oak (*Q. arizonica*) are often monodominant or associated with *Pinus cembroides*, *P. chihuahuana*, *Arbutus arizonica*, *Q. grisea*, and *Q. chihuahuensis*. *Quercus hypoleucoides* occurs in the uplands and to the west is *Q. viminea*. Common associations on the eastern foothills of the sierra are those of *P. cembroides* and *Q. grisea* or *Q. eduardii*. At the transition with higher elevation forests, *Pinus chihuahuensis*, *P. engelmannii*, and *Q. durifolia* are common. Táscate (*Juniperus deppeana*) is the common shrub; *J. coahuilensis* enters the region where lower elevation juniper scrub contacts higher elevation woodlands.

Weaknesses and Strengths of the Present Situation of the Madrean Ecosystems in the Sierra Madre Occidental

An accelerated deforestation, fragmentation of habitats, and reduction in forest densities are the most dramatic changes occurring in the last decades in the Sierra Madre Occidental. Although sustainable forest management is promoted and forest certification has become well established in many ejidos, communities, and private lands, illegal logging still persists as well as clearing of the forest for agriculture or cattle grazing. Forests and woodlands of the SMO have been becoming more open and replaced by shrubs (inland chaparral), a disturbance linked to perturbation by logging, overgrazing, and fire. Also, extreme climatic events in the lower peripheral communities are driving changes. A striking example of this was the heavy frosts of the winter of 1997 that killed extensive areas of *Acacia schaffneri* and *Opuntia* scrub on the areas flanking the eastern foothills. This was followed by an extreme drought and hot temperatures during the 1998 spring that reduced many of the oak woodlands at the eastern lower slopes.

Other changes occurring in the vegetation cover are (1) the expansion of the shrubs *Arctostaphylos pungens* and *Quercus depressipes* driven by disturbance; (2) the dwindling of oak woodlands that are being replaced by hopbush (*Dodonaea viscosa*), an invader from warmer areas; and (3) the effects of bark beetle (*Dendroctonus*) infestation that have killed extensive areas of pines and also affected fir, Douglas-fir and spruce that were likely already stressed by drought.

The implementation of sustainable management in recent years is allowing conservation of the biodiversity in some places of the sierra. CONAFOR's National Forest Commission programs on payment for environmental services (including hydrological, carbon sequestration, and conservation of biodiversity) and protection and conservation of soils, reforestation and watershed restoration involve ejidatarios, comuneros, and private owners in the processes of protection and management of ecosystems. Additionally, many communities are betting on ecotourism, as well as rural and adventure tourism, which represent an alternative to logging and provide time for the forest to recover, bringing hope to the ecosystems and people of the SMO.

Conclusions

Despite its high biological and cultural diversity, the SMO is ironically far from being well known. New records, new species, and new genera are still being discovered in areas of the Sierra Madre Occidental. Much of the biological treasures of this mountain range remain to be discovered and much more exciting exploration is yet to be done to find them.

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