Biota Neotropica 24(3): e20241648, 2024
www.scielo.br/bn

biotaneotropica
ISSN 1676-0611 (online edition)
Article

Priority areas for conservation of the vascular flora in the Sierra Madre del Sur, Mexico

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ARAGÓN-PARADA, J., MUNGUÍA-LINO, G., DE-NOVA, J.A., CARRILLO-REYES, P., RODRÍGUEZ, A., SALINAS-RODRÍGUEZ, M.M. **Priority areas for conservation of the vascular flora in the Sierra Madre del Sur, Mexico.** Biota Neotropica 24(3): e20241648. https://doi.org/10.1590/1676-0611-BN-2024-1648

Abstract: The Sierra Madre del Sur (SMS) concentrates the greatest plant diversity in Mexico (9,524 species) and 10% of the endemism. And 8.3% of its surface is covered by Natural Protected Areas (NPAs). Strategies to create NPAs are based on identifying biodiversity hotspots to preserve the maximum number of species with the least resources. Areas with high biodiversity reflect geographic patterns and evolutionary processes useful for designing NPAs. The objectives were: were 1) to identify Priority Areas for Conservation (PACs) in the SMS based on taxonomic richness, endemism, and phylogenetic diversity, and 2) to seek the geographic congruence of the identified PACs with current NPAs. In a 10 × 10 km grid cell, indices of taxonomic richness, weighted endemism, and phylogenetic diversity were calculated for a set of 9,524 species. Furthermore, consensus areas of endemism were identified for a total of 1,133 endemic species. In the SMS, 33 consensus areas of endemism were rescued, and the taxonomic richness, weighted endemism, and phylogenetic diversity were heterogeneous and 94% correlated. Similarly, 27 PACs were identified. Three NPAs completely cover four PACs, 12 PACs are partially found in three NPAs, and in 38 Areas Voluntarily Designated for Conservation (AVDCs). Finally, 12 identified PACs are not found within any NPA. In the SMS it is necessary to promote the establishment of new NPAs or AVDCs that protect with high plant diversity.
Keywords: *Endemism; Hotspots; Natural protected area; Phylogenetic diversity; Taxonomic richness.*

Áreas prioritarias para la conservación de la flora vascular en la Sierra Madre del Sur, México

Resumen: La Sierra Madre del Sur (SMS) concentra la mayor diversidad vegetal en México (9,524 species) y el 10% del endemismo y el 8.3% de su superficie está cubierta por Áreas Naturales Protegidas (ANPs). Las estrategias para crear ANPs se basan en identificar hotspots de biodiversidad con la finalidad de preservar el máximo número de especies con la menor cantidad de recursos. Las áreas con alta biodiversidad reflejan patrones geográficos y procesos evolutivos útiles para el diseño de ANPs. Los objetivos fueron: 1) identificar Areas Prioritarias para la Conservación (APCs) en la SMS con base en la riqueza taxonómica, endemismo y diversidad filogenética, y 2) buscar la congruencia geográfica para las APCs identificadas con las ANPs actuales. En una cuadrícula de celdas de 10 × 10 km, se calcularon los índices de riqueza taxonómica, endemismo ponderado y la diversidad filogenética para un conjunto de 9,524 especies. Además, se identificaron áreas de consenso de endemismo para 1,133 especies endémicas. En la SMS, se rescataron 33 áreas de consenso de endemismo y la riqueza taxonómica, el endemismo ponderado y la diversidad filogenética fueron heterogéneos y estuvieron correlacionados en un 94%. Así mismo, se identificaron 27 APCs. Tres ANPs cubren en su totalidad cuatro APCs, 12 APCs se encuentran de manera parcial en tres ANPs y en 38 áreas destinadas voluntariamente para la conservación (ADVCs). Por último, 12 APC identificadas no se encuentran dentro de alguna ANP. En la SMS es necesario fomentar la creación de nuevas ANPs o ADVCs que resguarden los sitios con alta diversidad vegetal.

Palabras clave: *Área natural protegida; Diversidad filogenética; Endemismo; Riqueza taxonómica; Hotspots.*

Introduction

One of the objectives of conservation biology is the preservation of biological diversity for the benefit of future generations (Balletto et al. 2010). For this, systematic planning for conservation has been designed, prioritizing areas of high natural value and implementing strategies to ensure their survival and maintenance (Sobral et al. 2014), by assessing species and identifying the threats to which they are subject (Dauby et al. 2017). Species diversity is unevenly distributed globally and it is concentrated in hotspots, geographic areas that feature exceptional concentrations of species with exceptional levels of endemism, and face exceptional degrees of threat (Myers 1988, Myers 1990). These areas are associated with loss of primary vegetation and human population density, leading to increased threats at the genetic, species, and ecosystem levels (Myers et al. 2000, Sechrest et al. 2002). At present, global extinction rates are up to a thousand times higher than those indicated by the fossil record, mainly in these areas of exceptional biodiversity (Isaac et al. 2007, Dirzo et al. 2014, Pievani 2014, Ceballos et al. 2020). Conservation of priority areas for these hotspots, is therefore essential because they are home to a high number of species and their evolutionary history (Balletto et al. 2010).

Biodiversity conservation is mainly based on taxonomic diversity (e.g. number of species), ignoring the differences between species and their evolutionary relationships (Sobral et al. 2014, Rodrigues et al. 2011). Currently, conservation programs include metrics related to the evolutionary history of organisms (Buerki et al. 2015), such as phylogenetic diversity which is a metric summing the branch lengths of a set of species or lineages within a phylogenetic tree (Faith 1992, Winter et al. 2012, Figueroa et al. 2021). Evolutionarily Distinct and Globally Endangered (EDGE) uses the evolutionary distinctiveness index and the species distinctiveness risk, the latter is based on International Union for Conservation of Nature (IUCN) assessments to prioritize species for conservation (Isaac et al. 2007). Similarly, phylogenetic diversity is useful for evaluating protected areas and proposing new areas for conservation (Rodrigues et al. 2005, Lu et al. 2018; Sosa et al. 2018). Species evolutionary history is a comprehensive and complementary measure to taxonomic richness because it reflects lineage diversity. Being phylogenetic diversity more informative than taxonomic richness alone (Sechrest et al. 2002). Planning natural protected areas should consider specific richness, endemism, and phylogenetic diversity (Godoy-Bürki et al. 2014).

Endemic species are restricted to limited geographic areas (Noguera-Urbano 2017, Thornhill et al. 2017). Their occurrence has been used to highlight PACs, called biodiversity hotspots, which are geographically diverse areas where at least 1,500 endemic species occur (Myers et al. 2000). On our planet, hotspots are consistent with transition zones between two or more biogeographic regions, where biotas overlap and result in biotic interaction with their elements (Myers et al. 2000; Tribsch 2004, Kreft and Jetz 2010, Aagesen et al. 2012). Mesoamerica is one of the largest hotspots, stretching from central Mexico to Panama and containing approximately 23,000 plant species, 12,000 of restricted to that area only in Mexico (Myers et al. 2000, Ulloa-Ulloa et al. 2017). However, about 80% of the original vegetation has been converted to agriculture, and 300 species of endemic flora and fauna are threatened (Olson et al. 2001, Harvey et al. 2008).

In Mexico, the biogeographic provinces that form part of Mesoamerica are Mexican Pacific Coast, Transmexican Volcanic Axis, Balsas Depression, Yucatan Peninsula, Sierra Madre Occidental, Sierra Madre Oriental, Sierra Madre del Sur, Chiapas Highlands and Veracruz (Morrone 2017, 2020). About 70% of the species and more than 50% of the endemism of the vascular flora of the country are concentrated in these areas (Villaseñor 2016, Téllez et al. 2020. Espejo-Serna et al. 2021). The Sierra Madre del Sur (SMS) has the highest plant diversity with more than 7,016 vascular plant species and 1,133 endemics species (Espinosa et al. 2016, Villaseñor 2016, Aragón-Parada et al. 2021). The SMS covers an area of approximately 1,200 km, from Cabo Corrientes in Jalisco to the Isthmus of Tehuantepec in Oaxaca, including parts of the states of Colima, Guerrero, Jalisco, Michoacán, Oaxaca, Puebla, and Veracruz. It is considered an area of high ecosystem diversity and low levels of fragmentation (Ventura-Aquino et al. 2008, Espinosa et al. 2016). In this province, the highest taxonomic richness, endemism, and phylogenetic diversity are found in Cerro Teotepec-Filo de Caballos, Mixteca, Orizaba, Sierra de Coalcomán, Sierra Juárez, Sierra de Manantlán, Sierra de El Tuito and Sierra Sur harbor (Aragón-Parada et al. 2021, 2023).

There are 225 Natural Protected Areas (NPAs) in Mexico managed by the National Commission of Natural Protected Areas (CONANP), representing 46% of the country's surface area (González-Ocampo et al. 2014, Jiménez-Sierra et al. 2014, CONANP 2024). Although 13 priority terrestrial regions for conservation have been identified in the SMS (Arriaga-Cabrera et al. 2000) only seven NPAs have been designated: The Sierra de Manantlán Biosphere Reserve in Jalisco and Colima, four national parks (Omiltemi State Park and Juan Álvarez National Park in Guerrero, Benito Juárez National Park in Oaxaca, and Cuenca del Río Blanco National Park in Puebla and Veracruz), a portion of the Valle de Tehuacán-Cuicatlán Biosphere Reserve in Puebla and Oaxaca, and a fragment of the Zona Protectora Forestal Cuenca Alimentadora del Distrito Nacional de Riego 043 Natural Resources Protection Area in Jalisco (CONANP, 2024). There are also 72 Areas Voluntarily Designated for Conservation (AVDCs), which are public, private, or social property, certified by the Secretariat of Environment and Natural Resources of México (SEMARNAT) as areas destined for conservation due to the interest of their owners (Monterrubio-Solís 2019, Luis-Santiago 2021). Together they cover less than 5% of the surface area of the SMS (Ordoñez-Díaz & Flores-Villa 1995). However, no attempt has been made to integrate information on richness, areas congruent with the distribution of as many endemic species as possible, and phylogenetic diversity, reflecting geographical patterns and evolutionary processes, to propose Priority Areas for Conservation. Our main objectives were 1) to identify Priority Areas for Conservation (PACs) in the SMS based on taxonomic richness, endemism, and phylogenetic diversity, and 2) to seek the geographic congruence of the identified PACs with current NPAs. Our results could contribute to the design of conservation strategies for vascular plants in the region.

Materials and Methods

1. Study area

The SMS is composed of three subprovinces: The Sierra Madre del Sur Occidental (SOC), Sierra Madre del Sur Central (SCE), and Sierra Madre del Sur Oriental (SOR) (Morrone 2017) (Figure 1). It is located 1,200 km southwest, parallel to the Pacific Ocean in southwestern Mexico, from Cabo Corrientes in Jalisco to the Isthmus of Tehuantepec in Oaxaca, spanning the state borders of Puebla and Veracruz (Santiago-Alvarado et al. 2016, Morrone 2017). Their geology and physiography are the most complex of the mountain systems of Mexico (Santa María-Díaz et al. 2016). Two rivers interrupt its continuity; the Armería River on the borders of Colima, Jalisco, and Michoacán, and the Balsas River on the borders of Guerrero and Michoacán (Espinosa et al. 2016). Its elevation varies from 300 to 3,730 m (Aragón-Parada et al. 2021). It has warm humid and warm sub-humid (A), temperate humid and temperate sub-humid (C), and dry (B) climates (Espinosa et al. 2016). Although the SMS is located within the Intertropical Convergence Zone, its climate is nontropical; it has seasonal variations from rainy and hot to dry and cold. Precipitation is also determined by elevation. Higher precipitation occurs at higher elevations on the windward side. Meanwhile, leeward air leads to higher temperatures and a significant decrease in precipitation, due to the Föehn effect (Hernández-Cerda et al. 2016).

2. Taxonomic and spatial dataset

Geographic coordinates of SMS vascular plants were obtained from previous studies (Rodríguez et al. 2018, Sosa et al. 2018, Téllez et al. 2020, Aragón-Parada et al. 2021, Aragon-Parada et al. 2023), Global Biodiversity Information Facility (www.gbif.org), and the Orchidaceae database provided by the Asociación Mexicana de Orquideología. In addition, specimens from different herbaria in Mexico (ENCB,

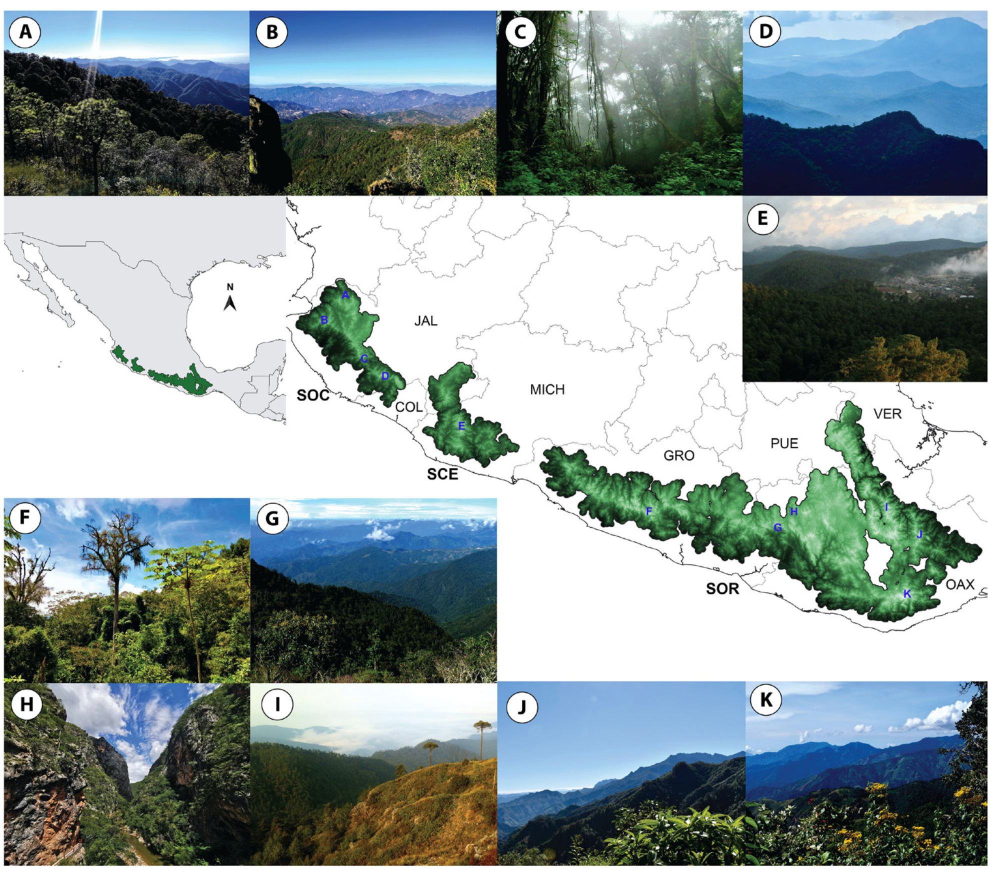

Figure 1. Areas with high vascular plant diversity in the Sierra Madre del Sur (SMS). SOC: Sierra Madre del Sur Occidental, (A) San Sebastián del Oeste, (B) Sierra El Cuale, (C) Sierra de Cacoma, (D) Sierra de Manantlán. SCE: Sierra Madre del Sur Central, (E) Sierra de Coalcomán. SOR: Sierra Madre del Sur Oriental, (F) Cerro Teotepec, (G) Boquerón de Tonalá, (H) Sierra Juárez, (I) Triqui-Mixteca, (J) Sierra Sur, (K) Sierra Mixe. COL: Colima, GRO: Guerrero, JAL: Jalisco, MICH: Michoacán, OAX: Oaxaca, PUE: Puebla, VER: Veracruz. Photographs A-B by A. Nuño, C by P. Carrillo-Reyes, D, G, H, I, J, K by J. Aragón-Parada, E by A. Castro, and F by M. Anguiano.

FCME, GUADA, HUAP, HUMO, IBUG, IEB, MEXU, OAX, SERO, UAGC, UAMIZ, and ZEA) and images of digitized specimens from foreign collections (BH, CAS, F, K, MO, and NY) were consulted (Thiers 2021). In QGIS 2.16.3 (QGIS Development Team 2015), geographic inconsistencies were checked and corrected. We quantified 91,322 records corresponding to 9,524 species of ferns and allies, gymnosperms, and angiosperms (Aragón-Parada et al. 2021, Aragón-Parada et al. 2023).

3. Phylogenetic hypothesis

The phylogenetic diversity of vascular plants in the SMS was calculated from the phylogeny proposed by Aragón-Parada et al. (2023) based on the megatree in V.PhyloMaker (Jin & Qian 2019), which combines GBOTB for seed plants (Smith & Brown 2018) and the pteridophytes clade of in the Zanne et al. (2014) phylogeny, with updates, corrections and expansions, as indicated in Jin and Qian (2019). The final GBOTB. extended.tre contains 3,476 species present in our list of the SMS pruned in V.PhyloMaker. The 6,048 species missing from the backbone megatree were successfully bound using scenario 3, which adds species as polytomies within their parental clades and assigns branch lengths using BLADJ (Webb et al. 2008).

4. Diversity indexes and areas of endemism

A set of 91,322 geographic data corresponding to 9,524 vascular plant species was considered to estimate the taxonomic richness (TR), weighted endemism (WE), and phylogenetic diversity (PD) indices using Biodiverse v.3.1 (Laffan et al. 2010, Laffan et al. 2013). The Areas of Endemism (EA) were estimated with 7,242 records. This corresponds to 1,133 species endemics to the SMS. A cell size of 10 × 10 km was used. This is based on the Area of Species Occupancy (ASO) proposed by the IUCN (Bland et al. 2017, Keith 2018). We used NDM/VNDM v3.0 to identify areas of endemism, with 1,000 runs maintaining overlapping subsets if 98% of their species were unique (Szumik et al. 2006). In addition, consensus areas (CAs) with 25% similarity were calculated using the strict rule (Rodriguez et al. 2018). CAs were analyzed based on their species and the criteria of Goloboff (2011) and Rodriguez et al. (2018). Finally, we used QGIS v2.16.3 (QGIS Development Team 2015) to visualize the results.

5. Priority areas for conservation

The TR, WE, PD, and CAs indices were overlapped to identify PACs of vascular plants in the SMS. Those cells or sets of cells where all indices coincided were saved as PACs. For the description of each area, the following criteria were considered: name, state, municipality, surface, type of vegetation, number of endemic species, and natural protected area, if present. Finally, the PACs were compared with the federal and state NPAs and AVDCs (CONANP 2022).

Results

1. Diversity indices and areas of endemism

The TR, WE, and PD are heterogeneous in the SMS and are correlated at (R = 0.94%, $p < 0.001$; Figure 2A-C). Two cells are located in the SOR subprovince in Veracruz presented the highest RT values

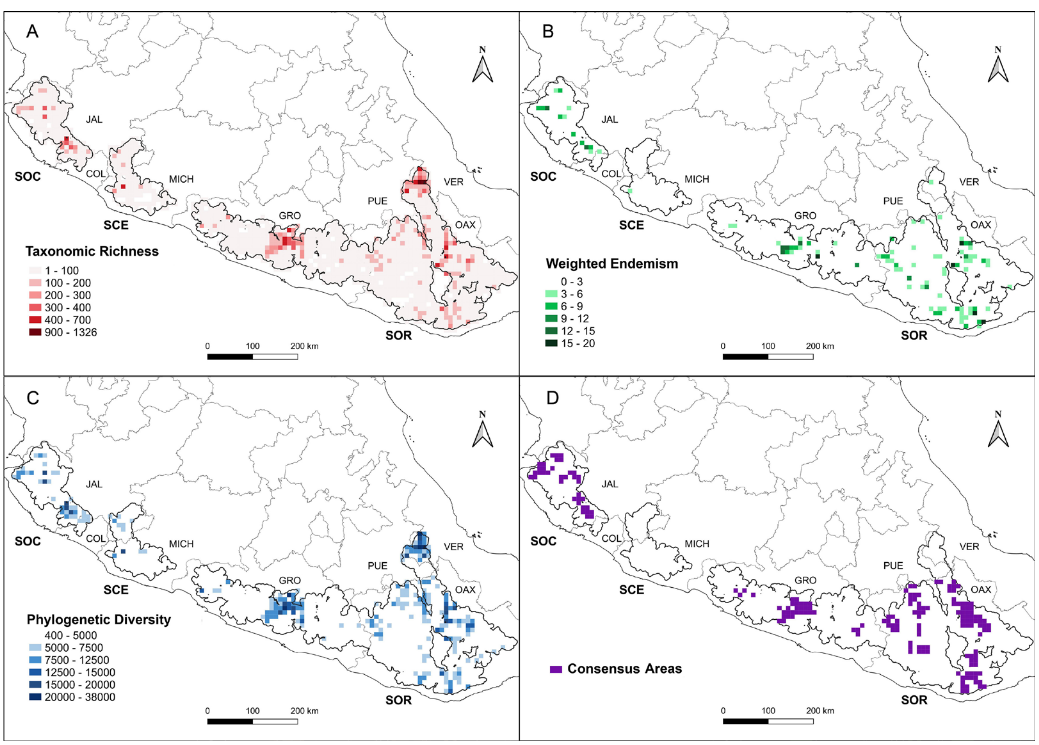

Figure 2. Spatial distribution of the vascular flora of the Sierra Madre del Sur (SMS). A) Taxonomic Richness, B) Weighted Endemism, C) Phylogenetic Diversity, and D) Consensus Areas. SOC: Subprovince Sierra Madre del Sur Occidental. SCE: Subprovince Sierra Madre del Sur Central. SOR: Subprovince Sierra Madre del Sur Oriental. COL: Colima, GRO: Guerrero, JAL: Jalisco, MICH: Michoacán, OAX: Oaxaca, PUE: Puebla, VER: Veracruz.

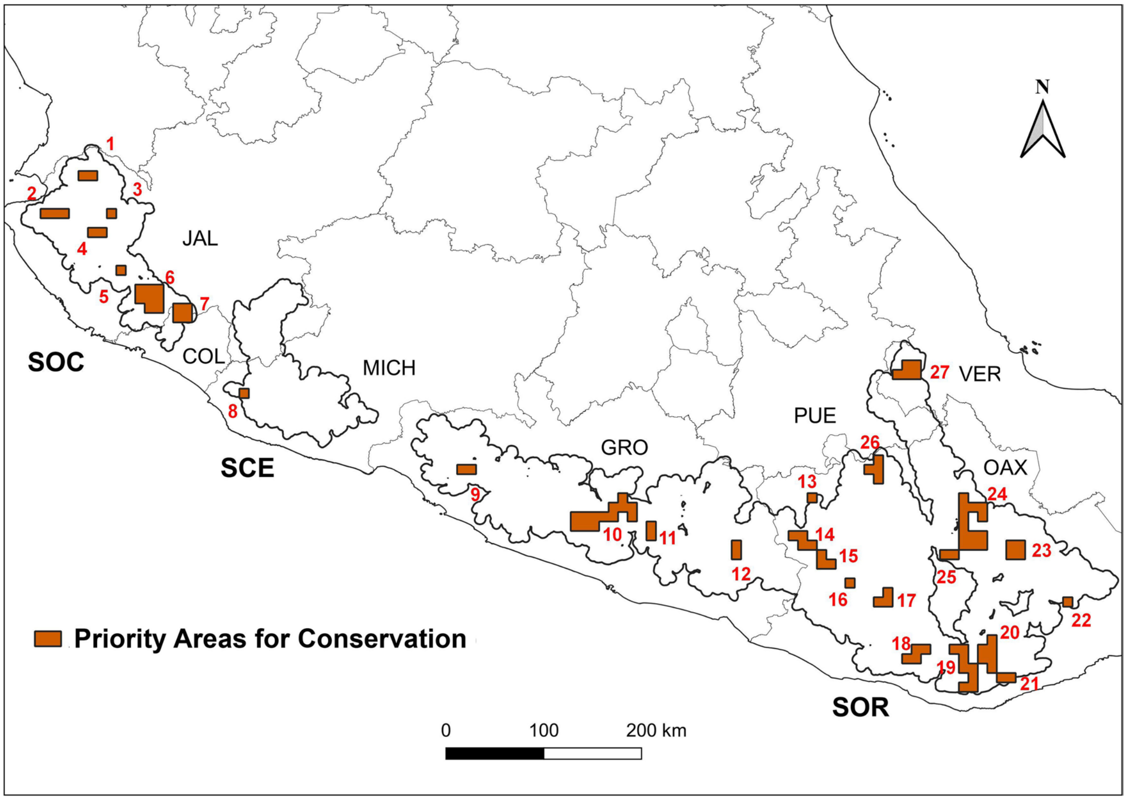

Figure 3. PACs of the vascular flora of the Sierra Madre del Sur (SMS). The numbers correspond to the names of the PACs in Table 1. SOC: Sierra Madre del Sur Occidental Subprovince. SCE: Subprovince Sierra Madre del Sur Central. SOR: Subprovince Sierra Madre del Sur Oriental. COL: Colima, GRO: Guerrero, JAL: Jalisco, MICH: Michoacán, OAX: Oaxaca, PUE: Puebla, VER: Veracruz.

(900 to 1,326 spp.). Eleven cells record values of 400 to 700 species (Figure 2A), one in the SOC in Jalisco, another in the SCE in Michoacán, and nine in the SOR including three in Guerrero, three in Oaxaca, two in Veracruz, and one in Puebla. Seven cells have the highest values of WE (15 to 20). Six cells are located in the SOR subprovince, four in Oaxaca, two in Guerrero, and one in the SOC in Jalisco (Figure 2B). The highest PD is recorded in five cells (20,000 to 38,000). All of them are in the SOR subprovince, with three cells in Veracruz and two in Guerrero. Likewise, there are 16 cells with values between 15,000 to 20,000, five located in the SOC in Jalisco, one in the SCE in Michoacán, and 11 in the SOR, four cells in Oaxaca, three in Guerrero, three in Veracruz, and one in Puebla (Figure 2C). The NDM/VNDM analysis recovers 33 CAs from 107 areas of endemism. Endemism area scores range from 2.0 to 11.53. Nine CAs are in the SOC in Jalisco and 24 in the SOR, of which four occur in Guerrero and 20 in Oaxaca (Figure 2D).

2. Priority areas for conservation

In the SMS, 27 vascular flora PACs are identified. These covered an area of 9,695 km^2 (8.3%) (Figure 3, Appendix I). These PACs contain 6,310 species (62% of the total in the SMS), of which 832 species are endemic (73.4% of the total endemism in the SMS). Seven PACs are located in the SOC subprovince in Jalisco and Colima: 1) San Sebastián del Oeste, 2) Sierra de El Tuito, 3) Cerro de La Campana-Jacales, 4) La Cuesta-Bosque de Maple, 5) Sierra de Cacoma, 6) Sierra de Manantlán, and 7) Cerro Grande. The SCE subprovince, in Michoacán, includes one: 8) El Moro. In the SOR subprovince, 19 PACs are located in Guerrero, Oaxaca, Puebla and Veracruz and correspond to: 9) Vallecitos de Zaragoza-El Balcón, 10) Cerro Teotepec-Filo de Caballos, 11) Cerro del Alquitrán-Rincón de la Vía, 12) Malinaltepec, 13) Boquerón de Tonalá, 14) Tecomaxtlahuaca-Juxtlahuaca, 15) Putla de Guerrero-Yucuiti, 16) Itundujia-Yosondúa, 17) Textitlán, 18) Lachao-Coatlán, 19) Tamazulapan-Pluma Hidalgo, 20) Cerro Quiexoba, 21) Xanica-La Constancia, 22) Cerro de Las Flores, 23) Cerro Zempoaltepetl, 24) Sierra Juárez-Chinantla, 25) Sierra de San Felipe-Corral de Piedra, 26) Cerro Verde, and 27) Córdoba-Orizaba. Of these, 15 overlap in whole or in part within a federal or state or as part of an AVDC, and 12 areas do not overlap within any NPA (Figure 4, Appendix II).

Discussion

1. Diversity indexes and areas of endemism

The cells with the highest values of TR, WE, and PD are consistent, and they mostly agree with the results of the CAs analysis (Figure 2). In total, 27 areas are identified with a congruent geographic distribution of TR, WE, PD, and the CAs, which we propose as PACs for the vascular flora in the SMS (Figure 3). These areas are supported by previous studies that analyzed flora diversity and its biogeographic patterns at regional (Contreras Medina 2016, Aragón-Parada et al. 2023), national (Rodríguez et al. 2018, Sosa et al. 2018, Téllez et al. 2020), and continental scales

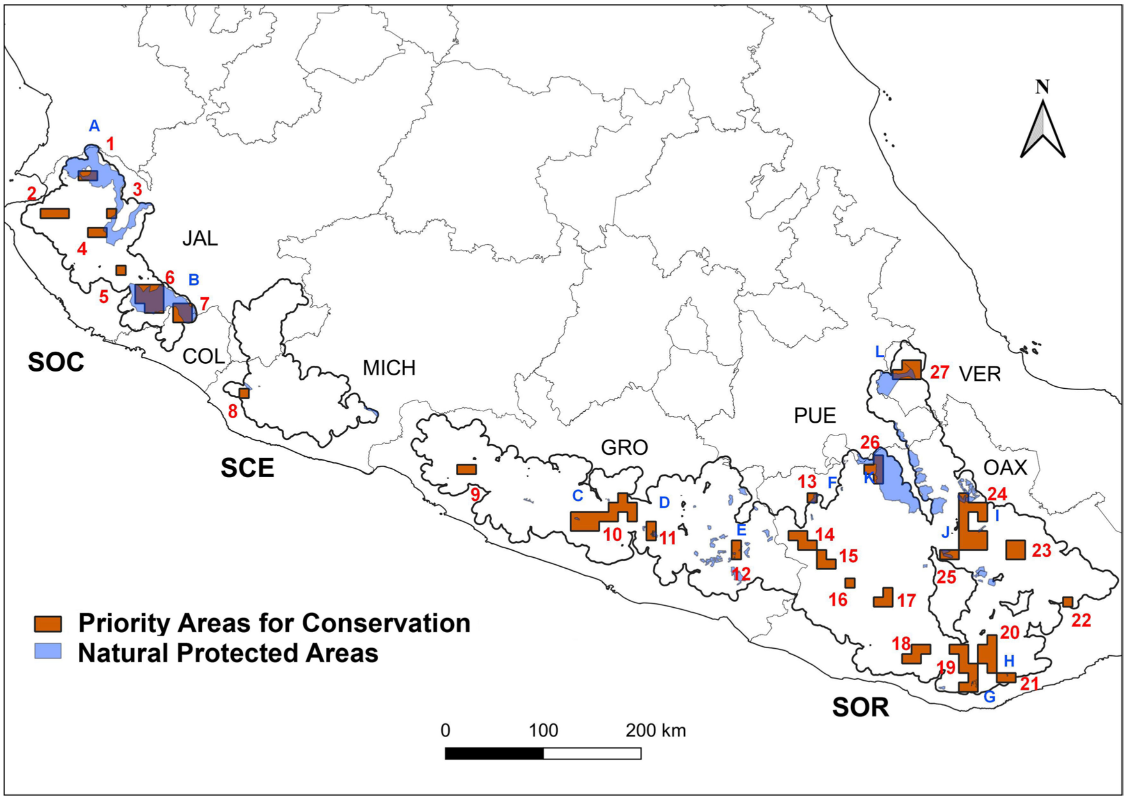

Figure 4. PACs of the vascular flora of the Sierra Madre del Sur (SMS) and Natural Protected Areas (NPAs). Numbers and letters correspond to PACs and NPAs/AVDCs in Table 1. SOC: Subprovince Sierra Madre del Sur Occidental. SCE: Subprovince Sierra Madre del Sur Central. SOR: Subprovince Sierra Madre del Sur Oriental. COL: Colima, GRO: Guerrero, JAL: Jalisco, MICH: Michoacán, OAX: Oaxaca, PUE: Puebla, VER: Veracruz.

(North America) (Mishler et al. 2020). Areas with high TR and PD are supported by Sosa and Lorea (2017) who describe areas of richness and endemism of geophytic plants in the mountainous regions of Mesoamerica. Similarly, Rodríguez et al. (2018) obtained nine CAs of selected groups of angiosperms in Mexico, of which seven are presented in the SMS. Likewise, in this biogeographic province, Munguía-Lino et al. (2016) found a CA for the tribe Tigridieae (Iridaceae). The Sierra de Manantlán in Jalisco, the Sierra Norte and Mixteca in Oaxaca, and Córdoba-Orizaba in Veracruz are highlighted as areas with high taxonomic richness (300 to 1,326 spp.). These areas are consistent with those obtained by García-Mendoza et al. (1994), Suárez-Mota & Villaseñor (2011), Rivera-Hernández (2015), and Téllez et al. (2020). Furthermore, the cells rescued here with high values in the metrics analyzed have been identified as sites that shelter early divergent lineages (paleoendemism), as is the case of the Gulf of Mexico slope in the northeastern region, as well as lineages of recent diversification (neoendemism), in the central and western areas of the SMS (Aragón-Parada et al. 2023).

The PACs Córdoba-Orizaba, Cerro Teotepec-Filo de Caballos, Cerro Quiexhoba, Sierra Juárez-Chinantla, and Sierra de Manantlán are supported by the results of Sosa et al. (2018), Mishler et al. (2020), and Aragón-Parada et al. (2023), who identified areas with exceptional plant diversity for the vascular flora of Mexico. Finally, 19 PACs are reported for the first time as sites that include CAs with high levels of TR, WE, and PD: Cerro de La Campana-Jacales, La Cuesta-Bosque de Maple, San Sebastián del Oeste, Sierra de El Tuito and Sierra de Cacoma in Jalisco; El Moro in Michoacán; Cerro del Alquitrán-Rincón de la Vía, Malinaltepec and Vallecitos de Zaragoza-El Balcón in Guerreo; as well as, Cerro de Las Flores, Cerro Zempoaltepetl, Itundujia-Yosondúa, Lachao-Coatlán, Putla de Guerrero-Yucuiti, Sierra de San Felipe-Corral de Piedra, Tamazulapan-Pluma Hidalgo, Tecomaxtlahuaca-Juxtlahuaca, Textitlán, and Xanica-La Constancia, in Oaxaca.

The hight taxonomic richness and endemism in the SMS has been highlighted by previous studies in specific vascular plant groups in the SMS with a relevant richness and endemism, such as the genus *Quercus* (Fagaceae) (Valencia-Ávalos & Morales-Saldaña 2016), and *Sedum* (Crassulaceae) (Aragón-Parada et al. 2019). Likewise, other studies at the local level in the SMS support our results, such as in Guerrero, where Martínez-Gordillo et al. (2016) studied the genus *Salvia* in the Sierra Madre del Sur of Guerrero, Lozada-Pérez et al. (2016) that recorded the floristic diversity of Malinaltepec and Jiménez-Rodríguez et al. (2016) that listed the vascular flora of the municipality of Leonardo Bravo. In Oaxaca, Suárez-Mota & Villaseñor (2011) analyzed the diversity of endemic Asteraceae in the state, Ayala-Hernández & Solano-Camacho (2016) studied the flora of the mountain mesophyll forests of the Sierra Triqui-Mixteca, and Solano et al. (2016) listed the family Orchidaceae in the Sierra Sur of Oaxaca.

Regarding the accuracy of the taxonomic sampling and the presence of geographical gaps for the SMS, our dataset includes all data available reported in previous studies, open databases, as well as field trips carried out during this work. The recorded species richness agrees with those reported for states such as Guerrero, Jalisco, Michoacán, and Oaxaca in other studies (e.g. Hernández-López 1995, Cué-Bär et al. 2006, García-Mendoza & Meave 2011, Villaseñor & Ortiz 2014, Villaseñor, 2016, Cuevas-Guzmán et al. 2021). The SMS has great socio-economic disparities and is one of the poorest regions in Mexico. Factors such as monocultures, illegal logging, mining, and, above all, organized crime have led to insecurity for botanical expeditions in certain areas, such as the central zone of the state of Michoacán, the southeast of Jalisco, and the east of the state of Guerrero. As a result, there are several areas that are underrepresented in floristic inventories, and unfortunately, this will not change until the security situation in the country improves.

2. Priority areas for conservation

Based on the spatial distribution of the vascular flora in the SMS, we propose 27 PACs (Figure 2; Appendix I, Appendix II). In the year 2000, the National Commission for the Knowledge and Use of Biodiversity (CONABIO) identified 13 terrestrial priority regions for biodiversity conservation in the SMS (Arriaga-Cabrera et al. 2000, Arriaga-Cabrera et al. 2009). However, there have been few actions aimed at proposing protection zones for its flora and fauna. In total, there are 13 federal or state NPAs and 72 AVDCs in the SMS (Mohar-Acedo et al. 2013, González-Ocampo et al. 2014, Jiménez-Sierra et al. 2014, Monterrubio-Solís 2019, Luis-Santiago 2021, CONANP 2022). Only three NPAs fully cover four of the PACs identified here (Figure 4). Three other NPAs partially cover five PACs, and 38 AVDCs are found within seven PACs. Notably, 12 PACs identified here are not located within any NPA or AVDC (Figure 4; Appendix I).

In the SOC, in Colima and Jalisco, the NPAs Área de Protección de Recursos Naturales Zona Protectora Forestal Cuenca Alimentadora del Distrito Nacional de Riego 043 and Reserva de la Biosfera Sierra de Manantlán cover three identified PACs: San Sebastián del Oeste, Sierra de Manantlán, and Cerro Grande. These NPAs serve to preserve and protect a high plant diversity as previously indicated by Vázquez et al. (1995) and Cuevas-Guzmán et al. (2021). However, the PAC Sierra de El Tuito, La Cuesta-Bosque de Maple, Cerro de la Campa-Jacales, and Sierra de Cacoma deserve attention for their protection, since they do not contain any NPAs. Moreover, these areas are supported by the results of Morales-Arias et al. (2016), Acosta-Pérez (2021), Aragón-Parada et al. (2021), and Padilla-del Muro (2022), who pointed out the high diversity of species, endemisms, and plant communities in an elevation gradient ranging from 500 to 2,500 m.

In the SCE of Jalisco and Michoacán, the PCA El Moro is close to, but is not part of, the NPA El Barrancón de las Guacamayas, so conservation and protection efforts are needed. The SCE subprovince is one of the areas with less botanical exploration, due to social conflicts in the region (Aragón-Parada et al. 2019, Aragón-Parada et al. 2021). Therefore, new areas can be evaluated for conservation once their total diversity is known.

The SOR is the largest subprovince, and it is located in the states of Guerrero, Oaxaca, Puebla, and Veracruz. Here, 18 of the 27 PACs identified in the SMS are protected, regardless of whether they match any NPA or AVDC. This subprovince includes 11 NPA and 72 AVDCs (Monterrubio-Solís 2019, Luis-Santiago 2021, CONANP 2022). In Guerrero, there are two NPAs, General Juan Álvarez National Park and Omiltemi State Ecological Park, as well as 21 AVDCs (Luna-Vega & Llorente-Bousquets 1994, Hernández-Bello & Hernández-Moreno 2016, CONANP 2022). In the PAC Cerro del Alquitrán-Rincón de la Vía and Malinaltepec, the AVDC plays an important role in the conservation of the flora, although they occupy less than 20% of the identified areas and protect 27 endemic species. The Cerro Teotepec-Filo de Caballos PAC is one of the largest areas with 1,235 km^2. This area includes the Omiltemi State Ecological Park and the Cañada del Iris Conservation Area (Luna-Vega & Llorente-Bousquets 1994, CONANP 2022). Together, these NPAs cover less than 5% of the SOR in Guerrero and protect 66 endemic species. Finally, the Vallecitos de Zaragoza-El Balcón PAC is not found in any NPA or AVDC, so its analysis and inclusion in any is necessary.

In Oaxaca, there are five NPAs and 47 AVDCs (Monterrubio-Solís 2019, Luis-Santiago & Duran 2020, CONANP 2022). Six of the 14 PACs identified in Oaxaca are located within an NPA. The PAC identified here are supported by the findings of Solano-Gómez et al. (2008), Meave et al. (2012), and Suárez-Mota et al. (2018), who recognized several PACs of the flora of Oaxaca. Only the PAC Boquerón de Tonalá is completely inside the protected area: Boquerón de Tonalá (CONANP 2022). The Sierra de San Felipe-Corral de Piedra and Cerro Verde PAC are partially located within the NPAs; Benito Juárez National Park, Tehuacán-Cuicatlán Biosphere Reserve, and La Cruz-Corral de Piedra AVDC (SEMARNAT 2013, 2016, Luis-Santiago & Duran 2020). In the PAC of Tamazulapan-Pluma Hidalgo, Xanica-La Constancia, and Sierra Juárez-Chinantla, 30 AVDCs together cover less than 2% of the identified areas (CONANP 2022). In addition, eight PAs are not located in any protected area in the state (Supplementary material). Therefore, the PACs identified here should be analyzed and integrated into any NPA or AVDC. Finally, the PAC Córdoba-Orizaba is identified in Veracruz, which is partially submerged in the Cañón de Río Blanco National Park NPA (Rivera-Hernández 2015).

It has been argued that hotspots are geographical regions that are a reservoir of biodiversity and are highly vulnerable because of destruction. The study of the distribution of biodiversity and its spatial phylogenetic diversity reveals the complexity and importance of certain areas of hotspots, which facilitates the use, management, and conservation of regional resources of their species and ecosystems. Here, twenty-seven PACs are identified in the SMS based on TR, WE, PD, and CAs, which could be used as a reference to design planning strategies and focus conservation efforts for vascular plants. Fifteen PACs are covered, in whole or in part, by NPAs or AVDCs. Twelve PACs are not under any conservation regime. They should be proposed for evaluation and inclusion in an NPA or AVDC. Due to the surface area covered by NPAs and AVDCs (8.3%), it is necessary to design and create new NPAs in the SMS, as the current ones are not sufficient to protect and conserve floristic diversity. The ejido and communities-guarded AVDCs are alternatives that represent a valuable effort to maintain genetic, taxonomic, and ecosystem diversity and stability. Finally, taxonomic diversity, endemism, and the evolutionary history of taxa yield to design of more robust strategies to conserve sites with high biological diversity.

Supplementary Material

The following online material is available for this article:

Appendix I - Priority Areas for Conservation (PACs), Natural Protected Areas (NPAs), Areas Voluntarily Designated for Conservation (AVDCs).

Appendix II - Priority Areas for Conservation of vascular plants in the Sierra Madre del Sur. Mexico, SOC: Sierra Madre del Sur Occidental, SCE: Sierra Madre del Sur Central, SOR: Sierra Madre del Sur Oriental. Priority Areas for Conservation (PACs), Natural Protected Areas (NPAs), Areas Voluntarily Designated for Conservation (AVDCs).

Acknowledgments

We are grateful to the staff of the IBUG herbarium for the information provided, to the Asociación Mexicana de Orquideología for the database of the family Orchidaceae, to M. Anguiano and A. Castro for the provision of photographs, to M. Cupido for revising the manuscript. Finally, the senior author thanks the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT) for the Doctoral and Postdoctoral Scholarship (CVU: 778553) and Rufford Small Grants Foundation (37522-1 grant) to the first author.

Author Contributions

Juvenal Aragón-Parada: conceived and designed the study, conducted field trips and herbaria revisions, generated a database from the field and digital information, data analysis and results interpretation, and manuscript preparation.

Guadalupe Munguía-Lino: concept, design, and development of the research, data analysis, results interpretation, and manuscript preparation.

José Arturo De-Nova: advised and guided the research, data analysis, results interpretation, and manuscript preparation.

Pablo Carrillo-Reyes: provided species records, participated in field trips, and collected data.

Aarón Rodríguez: provided species records.

María Magdalena Salinas-Rodríguez: conceived and designed the study. All authors revised and critically contributed to the drafts and gave final approval for publication.

Conflicts of Interest

The authors declare that they have no conflicting interests.

Data Availability

Geographical database and phylogenetic framework are available on Zenodo digital repository <https://doi.org/10.5281/zenodo.11074373>.

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Received: 26/04/2024

Accepted: 07/08/2024

Published online: 13/09/2024