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Wild plant conservation in Mexico in the 21st century
Conservación de plantas silvestres en México en el siglo XXI

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Abstract
Twenty-one years have elapsed of the 21st Century and within the framework of the celebration of the 100th volume of *Botanical Sciences*, it is relevant to assess the progress of the research on conservation and on the activities undertaken for protecting the plants of Mexico, including the complementary *in situ* and *ex situ* approaches. By means of a systematic search of scientific articles related to the conservation of the Mexican flora on the Web of Science database, for the 2000–2021 period, we identified different scientific inputs, all showing specific objectives for undertaking conservation activities. The publications that resulted from this search were classified into six categories: (a) Regions and Ecoregions; (b) Communities or Ecosystems; (c) Taxonomic Groups; (d) Species and Populations; (e) Botanical Gardens; and (f) Seed Banks. For these categories, the results are presented under the headings "*in situ* conservation" and "*ex situ* conservation." Additionally, we assessed by a random examination, the bibliography used to support touristic development projects. The results show that, despite the wide temporal range considered in this review, and even though there is a vast number of publications related to the characterization of the Mexican biodiversity, the production of scientific work oriented to the development of plant conservation strategies and activities is still scarce. Also evident is the lack of connection and communication among researchers of different disciplines, highlighting the disciplinary or multidisciplinary activities that they undertake. Finally, ten conclusions are presented, and some future research activities are suggested for conserving the Mexican flora.
Keywords: Flora, *in situ* and *ex situ* conservation, biodiversity, plant diversity, natural resources.

Resumen
Habiendo transcurrido los primeros 21 años del Siglo XXI y en el marco de la celebración del Volumen 100 de la Revista *Botanical Sciences*, es relevante realizar una evaluación de los avances en la investigación relacionada con la conservación *in situ* y *ex situ* de la diversidad vegetal de México. Mediante una búsqueda acotada y sistemática de los artículos científicos sobre la conservación de la flora mexicana, contenidos en la base de datos Web of Science para el periodo 2000-2021, se reconocieron aportaciones científicas enfocadas específicamente en actividades de conservación. Las publicaciones se clasificaron en seis categorías: (a) Regiones o Ecoregiones, (b) Comunidades o Ecosistemas, (c) Grupos Taxonómicos, (d) Especies y Poblaciones, (e) Jardines Botánicos, y, (f) Bancos de Semillas. Considerando estas categorías, los resultados se presentan bajo los rubros "conservación *in situ*" y "conservación *ex situ*". Adicionalmente, se llevó a cabo una revisión acerca del apoyo bibliográfico que utilizan proyectos de desarrollo turístico. Los resultados mostraron que, a pesar del amplio intervalo temporal considerado en esta revisión y del abundante trabajo que existe con relación a la caracterización de la biodiversidad en México, es notable la escasa producción científica para el desarrollo de estrategias o actividades concretas de conservación de plantas. Es evidente una falta de conexión y comunicación entre investigadores de diferentes disciplinas, ya que prevalece el trabajo unidisciplinario o, en el mejor de los casos, el multidisciplinario. Finalmente, se presentan diez conclusiones y se sugieren algunas actividades futuras para trabajar en la conservación de la flora mexicana.
Palabras clave: Flora, conservación *in situ* y *ex situ*, biodiversidad, diversidad vegetal, recursos naturales.

At the Rio Summit, held in 1992 in the city of Rio de Janeiro, sustainable development was proposed as the strategy to ensure environmentally sound and long-term development. Therefore, the United Nations Convention on Biological Diversity established the following main objectives: (1) to conserve biological diversity, (2) to use its components in a sustainable way, and (3) to make a fair and equitable distribution of benefits derived from that use (United Nations 1992). Within this framework, in March 1992 the National Commission for the Knowledge and Use of Biodiversity (CONABIO) was created in Mexico, as a permanent inter-ministerial commission, with the purpose to coordinate and promote actions related to the knowledge and the sustainable use of our country's biodiversity (Sarukhán *et al.* 2009, CONABIO 2012). The work carried out by CONABIO is unprecedented in Mexico and its contributions have benefited different areas of the country and abroad.

Since then, milestones of the outmost importance have been reached in terms of integrating and analyzing information from different disciplines such as taxonomy, ecology, physiology, agronomy, geography, climatology, edaphology, and even from the social sciences to define both general and particular approaches to the biological conservation, as well as the use of technologies that are necessary to support increasingly robust conservation proposals (*e.g.*, Bojórquez-Tapia *et al.* 1995, Álvarez-Buylla *et al.* 1996, Heywood & Iriondo 2003, Heywood & Dulloo, 2005, Lascuráin *et al.* 2009, Costedoat *et al*. 2015, Brooks *et al.* 2016, Larkin *et al.* 2016, Hayano-Kanashiro *et al.* 2017, List *et al.* 2017, Pfaff *et al.* 2017).

In general, biodiversity conservation is carried out using both *in situ* and *ex situ* approaches. These two are complementary and ensure the conservation of the genetic diversity of species and their populations in the short and long terms. *In situ* conservation encompasses the maintenance and sustainable use of species and their viable populations in their natural habitats as well as the ecosystem diversity. *In situ* conservation also includes the diversity of species used in agriculture and their wild relatives as source of genetic diversity in the habitats where such diversity appeared and/or where it continues to evolve (Heywood & Dulloo 2005, Pisanty *et al.* 2009). On the other hand, *ex situ* conservation is the application of a wide variety of resources, techniques and specialized infrastructure that contribute to the recovery and survival of individuals or populations outside their habitats. A central objective of *ex situ* conservation is to reduce the extinction risk of species or populations, as well as to reintroduce populations into their natural habitats (Lascuráin *et al.* 2009). There are various methods and techniques for *ex situ* conservation, such as seeds, pollen and tissues cryopreservation, gene banks, botanical gardens, and arboreta (Lascuráin *et al.* 2009). To date, it is widely accepted that *ex situ* conservation activities can play a very relevant role and complementary to the *in situ* approach, which integrates some conservation procedures such as the recovery and reintroduction of species and ecological restoration (Heywood & Iriondo 2003, IUCN/SSC 2014, Dávila-Aranda *et al.* 2016, Heywood 2017).

In this context, the objective of this work was to gather and analyze the information available in scientific publications explicitly related to *in situ* and *ex situ* conservation of wild plants in Mexico during the 2000-2021 period, with the purpose of answering questions such as: how much has been published on the subject in the last twenty years?, what are the themes or objects of study (disciplines, plant groups, regions, species, etc.) of the publications?, what have been the approaches and methods used?, and how much is the scientific information generated on plant conservation taken into consideration in public policy instruments on environmental matters?

Methods

Compilation and review of scientific literature. To determine the main scientific contributions to plant conservation in Mexico, a systematic search was carried out in May 2021 using the Web of Science search engine for scientific papers published on the subject between 2000 and 2021. The search criteria consisted in including those papers published in scientific journals in which the database included the terms plant conservation + Mexico in their title. In addition, we also included those papers that included in their abstracts, the terms "*in situ* conservation" or "*ex situ* conservation". After checking and avoiding duplicates, 207 documents remained as the result of the search (articles, books or chapters). The final number of documents was 103 after filtering out articles that lacked information that could be clearly related to *in situ* or *ex situ* conservation activities on wild plants in Mexico.

Analysis of the consideration of scientific literature in public policy instruments in environmental themes. In order to know the use of scientific information in plant conservation in Mexico in the public policy on environmental themes, a sample of public documents associated to various tourism development projects in coastal areas of the country ruled by the authority for the years 2002, 2004, 2006, 2008 and 2010 was reviewed, specifically the documents that correspond to the Regional Environmental Impact Statements (MIA-R by its Spanish acronym). In the review of this documentation, it was determined that a MIA-R was considered to use scientific information on plant conservation if it complied to the following bibliographic sources: (i) publications on Protected Natural Areas that refer to plants (*e.g.*, the flora of the Sian Ka'an or El Triunfo Biosphere Reserve, etc.); (ii) publications that indicate or suggest in the title that they include conservation issues; (iii) references of any of the Priority Areas defined by CONABIO.

According to the main topics addressed by the publications retrieved from the bibliographic search, they were classified into six categories: (a) Regions or Ecoregions, (b) Communities or Ecosystems, (c) Taxonomic Groups, (d) Species and Populations, (e) Botanical Gardens, and (f) Seed Banks. For these categories, publications are presented under the headings "*in situ* conservation" (topics a-d) and "*ex situ* conservation" (topics e and f); additionally, the results of analysis of the tourism development projects MIA-R are described.

***In situ* conservation**

The literature review revealed that there is a scarce production of papers specifically aiming to undertake *in situ* conservation activities of the Mexican flora during the period considered in this work. The retrieved papers include data from regions or ecoregions, communities or ecosystems, taxonomic groups (*e.g.*, genera or families), as well as from species and populations (*e.g.*, endemic, threatened or endangered).

Regions or Ecoregions. Conservation studies of regions or ecoregions are focused on relatively large geographic areas, with hundreds of plant species and dozens of natural communities included. The Natural Protected Areas of Mexico (ANP by its Spanish acronym) were initially established based on aesthetic and recreational criteria, but gradually the criteria evolved to support initiatives that aim to contribute to the *in situ* conservation of the regions' or ecoregions' biodiversity. In the last 20 years, the scientific community and Mexican institutions such as the above mentioned CONABIO and the National Commission for Protected Natural Areas (CONANP by its Spanish acronym), both entities belonging to the Secretariat of Environment and Natural Resources (SEMARNAT by its Spanish acronym), became aware of the need to review the operation, size and connectivity of the country's protected areas. Currently, the Mexican territory has a total of 182 ANPs covering about 90,839,522 ha (Table 1; CONANP 2018). The monitoring of the operation in some ANP has shown the successes and the difficulties regarding the management and conservation of natural resources in regions such as the Yucatán Peninsula (García-Frapolli *et al.* 2009). In addition, other studies have focused on redesigning and delimiting the ANPs, using new criteria and additional information in order to explore alternative designs that maximize the conservation of habitats and natural resources (*e.g.*, in the Mariposa Monarca [Monarch Butterfly] Biosphere Reserve, Bojórquez-Tapia *et al*. 2003, and the Sierra de San Pedro Mártir National Park, Bojórquez-Tapia *et al.* 2004).

Moreover, some studies have aimed to identify regions of high concentration of endemic plant species in order to propose and prioritize areas for conservation, such as in the Baja California Peninsula (Riemann & Ezcurra 2007), the Sierra Madre Oriental (Salinas-Rodríguez *et al.* 2018) and the Sierra Norte of Oaxaca (Suárez-Mota *et al.* 2018). Finally, some studies have focused on evaluating the loss of species due to habitat modification and alteration by large-scale human activities, such as grazing (*e.g.*, Isla Guadalupe, León de la Luz *et al.* 2003) and agriculture (*e.g.*, Baja California, Vanderplank *et al.* 2014). In addition, spatial models of land cover and land use change have been used to estimate the impact of human activities on natural ecosystems. An example of this is the Mesoamerican Biological Corridor in Chiapas (Ramírez-Mejía *et al.* 2017) or other sites on the Costa Grande region of Guerrero state and in central Quintana Roo state (Durán-Medina *et al.* 2007).

Table 1. Protected Natural Areas of Mexico by categories.

Category	Number	Total area (ha)	% Protected
Biosphere Reserve	44	62,952,750.50	69.3
Natural Park	67	16,220,099.30	5.5
Natural Monument	5	16,269.11	0.1
Natural Resources Protection Area	8	4,503,345.22	17.6
Flora and Fauna Protection Area	40	6,996,864.17	26.5
Santuaries	18	150,193.29	0.6
Total	182	90,839,521.55	100

Communities or Ecosystems. Some studies on community or ecosystem conservation in Mexico have focused on habitat fragmentation effects on species composition and the physiognomy of the dominant vegetation (*e.g.*, Arroyo-Rodríguez & Mandujano 2006, Sánchez-Gallen *et al.* 2010). For instance, a well-documented example is the humid tropical forest of Los Tuxtlas, Veracruz which has been particularly affected by deforestation (Arroyo-Rodríguez & Mandujano 2006). Oher studies have aimed to establish specific conservation and restoration programs at the local level, by implementing sustainable management schemes for threatened ecosystems such as the cloud forest (Luna Vega *et al.* 2000, Toledo-Aceves *et al.* 2011).

Additionally, several studies have evaluated the spatial variation of the impact of climate change on biodiversity across different ecosystems or communities in Mexico (Trejo *et al.* 2011). For example, Estrada-Contreras *et al.* (2015) evaluated the effects of climate change on tropical evergreen, coniferous and mesophyllous montane (cloud) forests in the state of Veracruz; according to their results and under the conditions expected in 2050, for about 20 species of this vegetation type there will be considerable reductions in their distribution ranges and others will probably become extinct, as is the case of *Dialium guianense* (Caesalpinoideae: Fabaceae), *Calophyllum brasiliense* (Calophyllaceae), and *Brosimum alicastrum* (Moraceae), since this ecosystem will be reduced to 60 % of its current surface. Similarly, Gómez-Mendoza & Arriaga (2007) predicted the reduction of the distribution area of several species of *Quercus* (7-48 %), and *Pinus* (0.2-64 %); the most vulnerable species of the *Pinus* genus were *P. rudis, P. chihuahuana, P. oocarpa* and *P. culminicola*, and of *Quercus* were *Q. crispipilis, Q. peduncularis, Q. acutifolia,* and *Q. sideroxyla*. By contrast, Rehfeldt *et al*. (2012) predicted the expansion of the tropical deciduous forest and the xerophilous scrub to suitable climates in several regions of Mexico.

Likewise, other studies addressing climate change seek to identify geographic areas with the potential to host the largest number of species representative of a particular ecosystem, to prioritize conservation areas (*e.g.*, the mesophyllous montane (cloud) forest, López-Arce *et al.* 2019), such as the work undertaken by Worthington *et al*. (2020), in which the authors proposed to include Mexico in mangrove restoration and conservation programs at a global level. Another good example is the recent study undertaken by Tellez *et al*. (2020) that analyzes the richness of native trees in Mexico, including 2,885 species (ca. 44 % endemic to Mexico) that belong to 612 genera and 128 families listed in the IUCN Red List, in SEMARNAT's NOM-059, or in both. In addition, a total of 98 Mexican tree species are listed in CITES for their protection. Moreover, in terms of current conservation efforts, they also document that 19 % of the Mexican tree species have an *ex situ* protection in seed banks, and that most species richness peaks overlap in protected areas.

From an ethnoecological perspective, in recent years the studies undertaken on agroforestry systems have provided relevant information on the conservation of locally important plant communities. These studies focus on the complexity of original vegetation zones interspersed with cultivated areas that include management strategies for the original communities and populations, which favor the maintenance of biological and cultural diversity, while providing numerous resources and ecosystem services to rural human communities (Schroth *et al.* 2004, Perfecto & Vandermeer 2008). For instance, these systems have been studied in detail in the Tehuacán-Cuicatlán Valley, where approximately 1,600 plant species are used by humans in numerous ways (Casas *et al.* 2001, Lira *et al.* 2009a). Results of these studies leave no doubt that such traditional exploitation of original vegetation areas represents sustainable practices where conservation is possible. Also, in the Tehuacán-Cuicatlán Valley, Vallejo *et al*. (2014) analyzed the biodiversity conservation success of the agroforestry systems of the temperate zones, as well as the motivation of people to carry out these practices. In this study, 79 tree and shrub species were recorded, 86 % of which are native and represent 43 % of all trees and shrubs species recorded in natural forests. Likewise, the authors identified that motivations to conserve standing plants in these systems are associated to their use as fruit trees, firewood, shade, beauty, as well as their nature and other environmental services.

In the case of the Tehuacán-Cuicatlán Valley, it has been reported that agroforestry systems derived from columnar cactus forests conserve between 50 and 90 % of the plant species richness existing in wild systems and on average close to 93 % of the genetic diversity of wild populations of cacti species representative of the original forests (Moreno-Calles & Casas 2008). Additionally, Rendón-Sandoval *et al*. (2021), who studied these systems in Cuicatlán, at the southern end of the Tehuacán-Cuicatlán Valley, agree in that agroforestry systems can maintain biodiversity while helping to satisfy human needs, and that those that protect or sponsor a greater proportion of forest cover and species diversity can provide a broader spectrum of benefits to people; such benefits include not only those obtained directly from the use or marketing of plant products (food, medicine, etc.) but also those that are less tangible, but equally essential, such as providing shade, maintaining humidity or providing habitat for pollinators.

Taxonomic Groups. The existing publications on taxonomic groups of vascular plants are aimed at analyzing diversity patterns at different spatial scales to prioritize areas for conservation. Such is the case of the studies on Asteraceae (Redonda-Martínez *et al.* 2021), Cactaceae (Gómez-Hinostrosa & Hernández 2000, Ortega-Baes & Godínez-Alvarez 2006, Ortega-Baes *et al.* 2010, Hernández & Gómez-Hinostrosa 2011), and Cucurbitaceae (Lira *et al.* 2002), as well as those undertaken on species of the genus *Dahlia* (Asteraceae; Carrasco-Ortiz *et al.* 2019) and *Lycianthes* series Meiozonodontae (Solanaceae; Anguiano-Constante *et al.* 2018).

Species and Populations. With the purpose of evaluating the genetic status and long-term viability of threatened species, important contributions related to population genetics have been published. Several species of the genus *Agave* (Asparagaceae) have been particularly studied from this perspective, for example *A. cupreata* and *A. potatorum* (Martínez-Palacios *et al.* 2011, Aguirre-Dugua & Eguiarte 2013), and *A. angustifolia* and *A. victoriae-reginae* (Eguiarte *et al.* 2013). Other threatened or endangered species in the order Cycadales (Cycads *sensu lato*, Gymnospermae) have also been addressed, such as *Dioon angustifolium* (González-Astorga *et al.* 2005), *Zamia loddigesii* (González-Astorga *et al.* 2006), and *Microcycas calocoma* (Pinares *et al.* 2009), as well as flowering plants in the family Orchidaceae, such as *Laelia speciosa* (Ávila-Díaz & Oyama 2007). In addition, similar works have been published on species of Cactaceae, including *Mammillaria crucigera* (Solórzano & Dávila 2015) and *M. pectinifera* (Maya-García *et al.* 2017), and in the Magnoliaceae, for *Magnolia pacifica* (Muñiz-Castro *et al.* 2020), *M. decastroi*, *M. lopezobradorii*, *M. mexicana*, *M. sinacacolinii*, and *M. zoquepopolucae* (Aldaba-Núñez *et al.* 2021).

Moreover, spatial analyses using distance indices have been carried out for undertaking *in situ* management and conservation of threatened species from arid and semi-arid environments, as in the case of *Ariocarpus kotschoubeyanus* and *Mammillaria mathildae* (Cactaceae), as well as *Agave americana* and *A. salmiana* (Asparagaceae) (Suzán-Azpiri *et al.* 2011). Other studies have focused on describing demographic parameters of populations in order to design conservation strategies to reduce the extinction probability of threatened species, such as *Resinanthus aro-*

maticus (Palacios-Wassenaar *et al.* 2016), *Zamia inermis* (Octavio-Aguilar *et al.* 2017), and *Magnolia vovidesii* (Galván-Hern*á*ndez *et al.* 2020).

Niche modeling studies with different climate change scenarios have been published, aiming to identify future environmental changes and species or populations at risk of disappearing. Among the species included in these studies are *Fagus grandifolia* (Téllez-Valdés *et al.* 2006), *Echinocereus reichenbachii* (Butler *et al.* 2012), *Neobuxbaumia tetetzo* (Dávila *et al.* 2013), *Magnolia schiedeana* (Vásquez-Morales *et al.* 2014), *Coryphantha macromeris*, *Mammillaria lasiacantha*, *Echinocereus dasyacanthus*, and *Ferocactus wislizenii* (Cortes *et al.* 2014), eight species and two varieties of *Abies* (*A. concolor*, *A. durangensis* var. *duragensis*, *A. durangensis* var. *coahuilensis*, *A. fincki*, *A. guatemalensis*, *A. hickelii*, *A. jaliscana, A. religiosa*, and *A. vejari*) (Martínez-Méndez *et al.* 2016), *Arenaria bryoides*, *Castilleja tolucensis*, *Chionolaena lavandulifolia*, *Draba nivicola*, and *Plantago tolucensis* (Ramírez-Amezcua *et al.* 2016), as well as *Guadua inermis* and *Otatea acuminata* (Ruiz-Sánchez 2013), *Cedrela odorata* (Manzanilla-Quijada *et al.* 2020), *Laelia speciosa* (Flores-Tolentino *et al.* 2020), and *Pinus gregii* (Martínez-Sifuentes *et al.* 2020). In addition, there are studies evaluating the effects of climate change on the diversity of economically important crops and their wild relatives, which have allowed identifying geographic regions and taxa potentially vulnerable to extinction (*e.g.*, Cucurbitaceae, Lira *et al.* 2009b, and corn (Ureta *et al.* 2012). In this context, Goettsch *et al*. (2021) analyzed information from various sources and used the IUCN Red List to determine the conservation status of 224 wild taxa closely related to several crops (*e.g.*, corn, potatoes, beans, squash, chili, vanilla, avocado, tomatillo, and cotton); this work showed that 35 % of these taxa are threatened due to conversion of natural habitats for human use, abandonment of traditional agricultural methods and their replacement by intensified practices (*i.e.*, highly mechanized and with the use of herbicides and pesticides).

Moreover, studies on plant domestication have documented processes that not only contribute to the conservation of the diversity of perennial and annual plants, but also enhances such a diversity through artificial selection that has resulted in numerous variants of some of the traditionally managed species (Casas *et al.* 2007, 2016a, b, c). In this context, there are some paradigmatic case studies in various species of *Agave* used for the production of alcoholic beverages and other purposes in western Mexico (Colunga-GarcíaMarín & Zizumbo-Villarreal 2007, Vargas-Ponce *et al.* 2007, Valenzuela-Zapata *et al.* 2011, Zizumbo-Villarreal *et al.* 2013), southern Altiplano (High Plateau) of the central-northern region of Mexico (Mora-López *et al.* 2011), and the Tehuacán-Cuicatlán Valley (Casas *et al.* 2016b).

Other perennial useful plants whose incipient or more intense human management has also been studied in this century include several species of *Opuntia* (Reyes Agüero *et al.* 2005) in the Southern Altiplano of Mexico, some columnar cacti in the Valle de Tehuacán-Cuicatlán, such as *Escontria chiotilla*, *Polaskia chichipe*, *P. chende*, *Stenocereus pruinosus*, *S. stellatus*, *Myrtillocactus schenkii* (Cruz & Casas 2002, Arellano & Casas 2003, Otero-Arnaiz *et al.* 2003, Oaxaca-Villa *et al*. 2006, Parra *et al.* 2008, Blancas *et al.* 2009), some trees such as *Leucaena esculenta* ssp. *esculenta* (Fabaceae) in Guerrero (Zárate *et al.* 2005), *Prunus serotina* ssp. *capuli* in Tlaxcala (Avendaño-Gómez *et al.* 2015), *Sideroxylon palmeri* (Sapotaceae) and *Ceiba aesculifolia* ssp. *parvifolia* (Bombacaceae) in the Tehuacán-Cuicatlán Valley (González-Soberanis & Casas 2004, Avendaño-Gómez *et al.* 2006, 2009), and a palm species (*Sabal yapa*) in the Yucatán Peninsula (Martínez-Ballesté *et al.* 2005).

In the case of annual useful plants, although many of them are generally considered weeds, the value of several of them in the diet and/or health care in rural communities has been demonstrated (Vieyra-Odilon & Vibrans 2001, Blanckaert *et al.* 2007, Albino-García *et al.* 2011, Vibrans 2016). Among the most amply studied taxa in the last two decades, in terms of incipient domestication processes, are *Anoda cristata* (Malvaceae) in the State of Mexico, several species of *Amaranthus* in the state of Puebla, and *Dysphania ambrosioides* (Chenopodiaceae) in the Tehuacán-Cuicatlán Valley (Rendón *et al.* 2001, Rendón & Núñez-Farfán 2001, Blanckaert *et al.* 2012).

Ex situ conservation

Botanical Gardens. A botanical garden is an institution that preserves documented collections of living plants, both native and exotic, which are maintained with a specific arrangement, and duly identified and labeled. The purposes of these gardens are to develop scientific research projects that contribute to the conservation of biological diversity, and to carry out education activities. In Mexico there are 64 botanical gardens, arboreta or living plants collections, of which 40 are currently registered at the Asociación Mexicana de Jardines Botánicos, A.C. (AMJB, the Mexican Association of Botanical Gardens), founded in 1980, for promoting biological studies, conservation and sustainable use of the Mexican flora, along with the development of educational programs for public awareness on the relevance of plant diversity and its conservation (Herrera *et al.* 1993, Caballero 2012). Nonetheless, to date only 19 botanical gardens have available information on their living collections and their advances in their *ex situ* plant conservation activities, considering goals 1-10 of the Global Strategy for Plant Conservation (GSPC) (Sharrock 2020, CONABIO 2021).

Available information (CONABIO 2021) shows that progress in the GSPC goals is variable among botanical gardens, especially in goals 1, 2, 3, 7, and 8 (Figure 1). Villaseñor (2016) determined that in these 19 collections there are around 9,016 records of higher plants, corresponding to 4,900 species from 195 families, which only represents 25 % of the recorded vascular flora of Mexico. Moreover, among the seven most diverse families in Mexico, Villaseñor (2016) states that the Cactaceae family has the highest number of specimens, while Orchidaceae is the second-best represented family, with 16.9 % of its species in botanical garden collections (Table 2). The effort made by scientists working in botanical gardens to document species kept in their collection is very important, and so has been the increase of taxa in these collections during the past two decades. The transition from 3,275 species recorded by Coombes *et al*. (2003) early in the century to 4,900 currently represented in the 19 botanical gardens considered here represents a huge conservation step.

At the genus level, *Quercus* (Fagaceae), *Mammillaria* (Cactaceae) and *Agave* (Asparagaceae) have more than 50 % of their species represented in these 19 Mexican botanical gardens, while the rest have a modest representation (Table 3). According to CONABIO (2021), 12 of the 19 Mexican botanical gardens here considered keep species at risk in their collections. In this regard, it is remarkable that 48 % (458 species) of the species included in the list of the Mexican Official Norm of Threatened Species NOM-059-SEMARNAT-2010 (SEMARNAT 2010), are protected in botanical gardens. By contrast, the set of documented species in some of the IUCN risk categories is very low, since only 7.7 % (320 species) of the species included in the Red List are sheltered in Mexican botanical gardens.

Given the complexity and high maintenance costs of living collections, the AMJB adopted the concept of "national collection", which consists of sheltering a living heritage of a family or lower taxonomic group or a relevant thematic plant group, with the responsibility of having a curator or group of academics who can take care of the collections (AMJB 1994, Vovides *et al.* 2013). At present, eight national collections exist, seven of which represent taxonomic groups and one is thematic. Some have allowed advances in their biological knowledge, such as the bamboo collection (Ruiz-Sanchez 2013), or they have served as a basic complement for various floristic studies, such as the Palm Collection of the Culiacán Botanical Garden (Equihua Zamora *et al.* 2020). Others have allowed the development of propagation protocols such as the Crassulaceae Collection (Reyes Santiago *et al.* 2014), or *ex situ* rescue and conservation strategies as it occurs in the Cycad Collection (Iglesias-Andreu *et al.* 2017). Additionally, the AMJB has promoted the creation of networks among its members at national and international levels (Lascuráin *et al*. 2009, Vovides *et al*. 2013), and among its most remarkable objectives is a proposal to create a regional collection of cacti in the botanical gardens of southern United States and northern Mexico, as they share common arid environments (Hultine *et al.* 2016).

Seed Banks. One of the most efficient and affordable approaches for *ex situ* conservation is, undoubtedly, the safeguarding of seeds in the so-called "seed banks," which are ideal living species reservoirs with controlled humidity and temperature conditions that can be used to guarantee long term preservation of plant resources. The benefits of *ex situ* conservation of seeds are innumerable and go from those related to the survival of the human species, given the fact that agriculture depends on preserving plant biodiversity, to the conservation of wild species, as an insurance policy against extinction. *Ex situ* conservation allows the long-term preservation of thousands of plant seeds in a reduced space, at a much lower cost (about 1 %) than *in situ* protection strategies (Li & Pritchard 2009), and in many cases it guarantees a wide spectrum of genetic variation (Bacchetta *et al*. 2008).

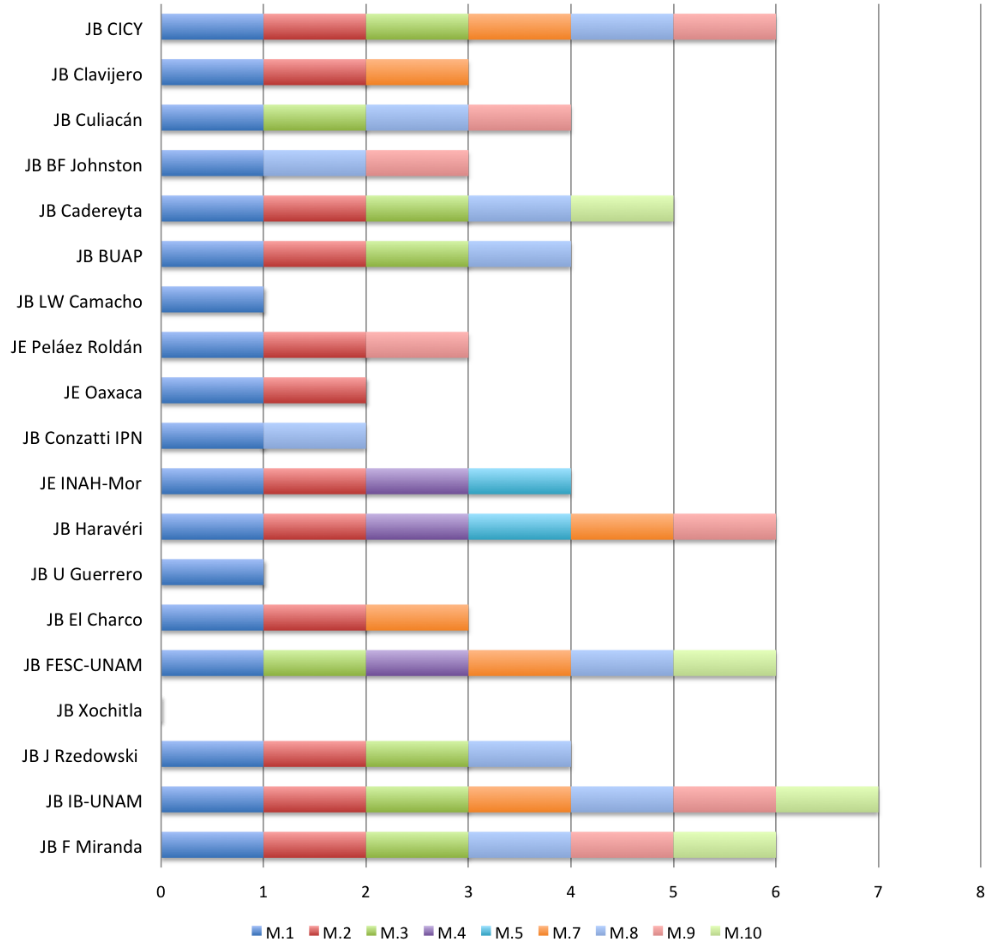

Figure 1. The 19 Mexican botanical gardens members of the Mexican Association of Botanical Gardens, with their advances in 9 of the 10 goals of the Global Strategy for Plant Conservation (GSPC): (M1) To compile the list of flora available on the Internet; (M2) To evaluate the conservation status of all species; (M3) To develop and share information; (M4) To ensure at least 15 % of each ecological region or vegetation type; (M5) To protect at least 75 % of the most important areas for the diversity of plant species; (M7) To conserve in situ at least 75 % of known threatened plant species; (M8) To conserve in ex situ collections at least 75 % of threatened plant species; (M9) To conserve 70 % of the genetic diversity of crops; (M10) To implement effective management plans to prevent further biological invasions.

In Mexico, there are more than 50 seed banks, most of which, unfortunately, protect only a few species, generally related to food or timber uses, and only 10 banks protect wild species native to the country (Table 4). In this latter group, the Seed Bank of the FES Iztacala (National Autonomous University of Mexico) stands out, whose main objective is to protect native wild species of Mexico. Since its inception, this bank has been directly linked to the Millennium Seed Bank of the Royal Botanical Gardens of Kew, United Kingdom and currently protects 4,950 accessions of native plants from 26 states of Mexico, of a total of 2,700 species, among which are many useful, threatened or narrowly distributed species (Dávila-Aranda *et al.* 2016, Rodríguez-Arévalo *et al.* 2017).

In the last 20 years, only seven research papers have been published addressing the conservation of Mexican plant species in seed banks. For instance, Ulloa *et al.* (2006) documented the collection and storage of the seeds of eight *Gossypium* species from western Mexico in the Cotton Collection of the US National Plant Germplasm System; Acosta-Diaz *et al*. (2015) carried out the collecting and characterization of 11 species of the genus *Phaseolus* from Nuevo León and Tamaulipas states in northeastern Mexico, which were deposited at the banks of the Western Region Conservation Center of the University of Guadalajara and the Northern Region Conservation Center of the Antonio

Table 2. Plant families with the highest species richness in Mexico and their representation in 19 Mexican botanical gardens.

Family	Total species in Mexico (Villaseñor 2016)	Botanical Gardens	Collections	Species in collections
Asteraceae	3,057	18	321	189
Fabaceae	1,903	16	191	105
Orchidaceae	1,213	15	328	205
Poaceae	1,047	13	57	47
Euphorbiaceae	714	17	194	104
Rubiaceae	707	15	65	36
Cactaceae	677	13	1,583	580

Narro Autonomous Agrarian University in Saltillo, Coahuila. Moreover, Ramírez-Villegas *et al*. (2020) used spatial modeling and conservation gap analysis to achieve optimal representation of genetic variation in the collections of *Phaseolus vulgaris* varieties, while Toledo-Aceves (2017) analyzed the germination rate of some tree species at risk of extinction in Mexico, to assess their potential for *ex situ* propagation. Furthermore, León-Lobos *et al*. (2012) analyzed the role of seed banks in plant conservation, and Dávila-Aranda *et al*. (2016) and Rodríguez-Arévalo *et al*. (2017) described part of the FES Iztacala Seed Collection and proposed strategies for the sustainable management of the species.

Scientific literature in public policy instruments in environmental issues

In Mexico, one of the main public policy instruments that regulates human productive activities considering environmental protection and biodiversity conservation are the Environmental Impact Assessments (MIAs, by their Spanish acronym) that are issued by SEMARNAT through public consultation processes and expert reviewers of the proposed projects. In this work, a total of 782 resolutions on tourism development projects were examined and only 524 MIA documents were found to have been reviewed. The review of MIAs aimed to find evidence of the incorporation of scientific literature on conservation matters for the environmental diagnosis and the design of mitigation or damage repair measures. The results of the MIAs review showed that only 32 % of the examined documents included references of scientific literature on conservation. Also, it became evident that most of the literature considered does not have updated information on biodiversity, which strongly suggests that the impact of research, in terms of development decision making on biodiversity and its conservation, especially in recent years, is very limited. Furthermore, the scarcity and publication dates of the literature listed in the MIAs does not allow us to conclude that plant conservation studies have an actual impact in this regard, at least through public policy tools on environmental matters.

Discussion and conclusions

The first reflection derived from our work is that, despite the wide temporal range considered in this review (2000-2021), and the abundant existing work regarding biodiversity characterization in Mexico, the actual use of this information in the development of strategies or specific activities for plant conservation in Mexico is remarkably low. Additionally, it should be noted that even publications focused on conservation are limited to strictly disciplinary areas, lacking connection with other disciplines or sectors and, therefore, are disjointed from other complementary initiatives, as well as from environmental, social, and regulatory contexts. It is also possible to observe that, despite the clear feedback of information that could occur between different conservation approaches, in many cases it does not seem evident that this occurs in the design of conservation strategies. An example of this situation is the lack of integration of genetic considerations and spatial distribution of biodiversity in the design of protected natural areas and also in the *ex situ* conservation collections. According to our analysis, despite notable efforts and the relatively important advances achieved in both conservation strategies, they are still far from being successful.

The causes of the disarticulation of both conservation strategies, as well as the disconnection of efforts and information from the environmental, social, and regulatory spheres may be explained by the lack of professional teams capable of seeking these connections and establishing communication bridges between sectors that allow the best possible use of knowledge to make decisions and design effective strategies that lead to scenarios of sustainable development and biodiversity conservation. Such articulation should not only consist in the agglutination of multidisciplinary efforts around a specific problem; it has been demonstrated that there is a large gap between theory and practice regarding the collapse of ecosystems and the implementation of practices for their management, which results in the few existing capacities to predict which species are facing higher risk due to human activities (Valiente-Banuet & Verdú 2013).

A second reflection is related to the scope shown by the scientific publications that were reviewed. While it is true that several of these studies have made it possible to implement or at least propose strategies for sustainable use and conservation, particularly for species with small population sizes, others are still required to evaluate and integrate, for example, genetic data with information on demographic parameters, ecological niche modeling, phylogeographic patterns, and even social and economic aspects that more clearly suggest the causes of the extinction threat to species. These studies would provide a more complete ecological and evolutionary context to establish better planning and stronger biodiversity conservation actions (Bosch *et al.* 2019, Lin *et al.* 2021). Regarding the studies that analyze the possible effects of climate change, although it is true that they provide information that can be used by scientists to analyze climate variation over time and evaluate its effects on the distribution patterns of biodiversity, the fact is that they work in a highly reduced time window and their applications are also quite relative. Nevertheless, the projections of expansion or contraction of species' distribution areas that can be derived from some of these studies could be important for Mexico. This type of information is fundamental to expand the sizes of protected natural areas, or to create new areas that conserve critical refuges (Michalak *et al.* 2018), and to seek the connection of habitats throughout the species' migratory routes (Carroll *et al.* 2015). All of this could facilitate the ability of species to persist,

Table 3. Plant genera with the greatest diversity in Mexico and their representation in 19 Mexican botanical gardens.

Genera	Total species in Mexico (Villaseñor 2016)	Botanical Gardens	Species in collections
Salvia	328	11	27
Euphorbia	245	18	43
Tillandsia	237	8	31
Quercus	174	11	98
Mammillaria	169	15	178
Ageratina	165	3	4
Verbesina	165	8	12
Agave	160	18	102

Table 4. Available information on germplasm collections in Mexico. CONAFOR reports 18 germplasm banks in the national territory but only one of them was found.

Official Name	Location	State	Objectives	Collections Type	Duration and storage conditions	Accessions	Species
Banco de Semillas FESI-UNAM	Facultad de Estudios Superiores Iztacala, UNAM	State of México	Wild and native germplasm	Wild and native species	Long term; -20 °C/14 % HR	4,948	2,692
Banco de Germoplasma Vegetal Coahuila	Universidad Autónoma de Coahuila	Coahuila	Forest seeds for production, conservation and supply to nurseries of the Secretaría de Medio Ambiente de Coahuila	Cold climate, arid and urban species	Medium term; 4 °C/40-60 % HR	90	30
Banco de Germoplasma de Maíces	Universidad Agrícola, Agraria, Antonio Narro	Coahuila	Mexican corn collections	Cultivated species. Corn from the states of Mexico and Tlaxcala. Some species from arid zones are currently being stored	Medium term; 4 °C/40-60 % HR	Unknown, but can hold up to 100,000	-
Banco de Germoplasma-UAQ	Universidad Autónoma de Querétaro	Querétaro	Native flora with an emphasis on plant genetic resources for food, agriculture, research and reintroduction	Wild and cultivated species	Short term; -5 °C	More than 800	336
BG-CICY	Centro de Investigación Científica de Yucatán	Yucatán	Conservation, reproduction, and availability of plant germplasm from the Yucatan Peninsula, and plant species from the Mexican tropics with emphasis on species related to the Mayan culture	Wild and cultivated species useful for the Mayan culture, other species that are under some type of threat, as well as wild relatives of cultivars. Some exotic species are also conserved	Long term; 4 -20 °C	560	208

Official Name	Location	State	Objectives	Collections Type	Duration and storage conditions	Accessions	Species
Banco Nacional de Germoplasma Vegetal	Universidad Autónoma de Chapingo (UACh)	State of Mexico	-	Wild species and for food, medicinal and fuel use	-	8,337	295
Banco de Semillas GUADA	Universidad de Guadalajara	Jalisco	-	-	-	-	-
	Universidad Veracruzana	Veracruz	Safeguarding the best germplasm of vegetables, fruit trees and other homegarden plants	Cultivated species	-	-	56
Centro Nacional de Recursos Genéticos	SINARGEN and INIFAP	Jalisco	Conservation, improvement and research for the rational use of Mexico's genetic resources for the benefit of society, and in the event of a catastrophic event, prevention of the loss of genes and ensure the survival of useful species	Cultivated and forest species	-18 °C	16,677	-
Banco de Germoplasma de la CONAFOR, Estado de México*	-	State of Mexico	-	-	Ten years; 5 °C/10 % HR	4,436 kg of seeds	36
Bancos de Semillas Comunitarios	SNICS and SINAREFI	Oaxaca, State of Mexico, Chiapas, Yucatán, Puebla Guanajuato, Mexico City, Coahuila, Chihuahua and Morelos	To preserve the diversity of wild species, as well as having the collection in case of a natural disaster, as well as conserving *in situ* the diversity of the area	-	-	-	-

Official Name	Location	State	Objectives	Collections Type	Duration and storage conditions	Accessions	Species
CIMMYT		State of Mexico	Develop nutritious, sustainable and resilient food systems to improve health and livelihoods	Improved corn and wheat lines	-	-	-

adapt and migrate. Future work based on the climate analogous models could show such efforts by integrating more detailed information about the target species (*e.g.*, dispersal distance), identifying important areas for their movement between protected natural areas (Littlefield *et al.* 2017) or critical refuges (Stralberg *et al.* 2018), considering habitat fragmentation impacts (Batllori *et al.* 2017). As a complementary effort, the fundamental role that botanical gardens and seed banks play in conserving the plant diversity not only of Mexico but worldwide is becoming increasingly evident. Nevertheless, there is still a very clear disconnection between those who work in these spaces and those that carry out *in situ* conservation and management, using different approaches and tools.

A final reflection is related to the fact that, even though the panorama shown from this review is inauspicious, it is encouraging that in various public educational institutions it is increasingly frequent to find study programs that pursue inter- and transdisciplinary training in sustainability matters. These programs are expected to contribute to solve, among other issues, the disarticulation of conservation strategies and plans. Given the enormous relevance and impact that biodiversity conservation at all scales has on the preservation of civilization, it is urgent to increase public investment in the training of professionals who can lead interdisciplinary research and professional work in conservation and sustainable development with a vision of knowledge-action. Similarly, it is essential to revise the regulatory processes in environmental matters and their correct and rigorous implementation. Often, MIAs are carried out in a purely administrative/bureaucratic manner, using outdated information, performing superficial analyses with poor technical-scientific rigor, and prioritizing in many cases the development of projects over their environmental impact.

Considering all the above, the following conclusions and perspectives are raised:

1.There are very few studies and works that really include conservation activities on wild plant species.

2. Little or no multidisciplinary or interdisciplinary work related to conservation activities is being carried out.

3. There is little interest from the environmental governmental sphere to consider the scientific works related to the knowledge and conservation of the wild flora of the country.

4. Many botanical gardens should join efforts to protect, study and propagate endemic or threatened wild species in the country.

5. A shift should be made in scientific work to become less descriptive and turn into a more analytical and proactive conservation approach.

6. The multi- and interdisciplinary work of scientists should be focused on contributing management programs and providing solutions for the conservation of plant germplasm in Mexico.

7. It is important that educational and research institutions include in their study programs and research projects theoretical and practical aspects related to the conservation of the Mexican flora.

8. Given its importance, *ex situ* conservation requires greater attention and support at the institutional and governmental levels. We need many Mexican scientists involved in the conservation of our country's flora.

9. Connectivity bridges should be strengthened between those carrying out *in situ* conservation activities with those who are interested in *ex situ* projects. The complementarity of both approaches will surely enhance the scientific documentation and conservation of species.

10. The criteria for the declaration of new protected natural areas in the country should be reviewed within the

framework of current conditions and the current knowledge on the many species of our flora, as well as the current and future data related to the changes on the distribution patterns of ecosystems and species due to climate change.

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Author contributions: PD design and conception of the study, as well as analysis and writing of the whole paper; FST analysis and writing of information about species, populations and taxonomic groups; IRA, analysis and writing of information about ex situ conservation, specially germplasm collections; AP analysis and writing of information about natural protected areas; SA analysis and writing of information about ex situ conservation, specially botanic gardens; AE analysis and writing of information about regions, ecoregions, communities, ecosystems and tourism development projects; OT analysis and writing of information about species, populations, taxonomic groups, regions and ecoregions; RL design, conception and coordination of the study, as well as analysis and writing of the whole paper.