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Floristics in Mexico today: insights into a better understanding of biodiversity in a megadiverse country

La florística en México en la actualidad: perspectivas para una mejor comprensión de la biodiversidad en un país megadiverso

José Luis Villaseñor[1*] and Jorge A. Meave[2]

[1] Departamento de Botánica, Instituto de Biología, Universidad Nacional Autónoma de México, Ciudad de México, Mexico.
[2] Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad de México, Mexico.
*Author for correspondence: vrios@ib.unam.mx

Abstract
Advancing our current knowledge on floristic richness in Mexico requires access to different sources, including published and unpublished inventories, fascicles of ongoing floristic projects, and publicly available online databases. The evaluation of these sources reveals how extensive the information available on the country's floristic diversity is, its heterogeneity, and the lack of protocols and standards for its proper organization, analysis, and synthesis. This review addresses the extent to which these sources of information provide the basis to achieve the long-awaited goal of completing the Flora of Mexico, and how traditional outputs of taxonomic work (Floras and checklists) are useful to other fields of biological research. We identified major knowledge gaps, as well as actual and potential uses by other scholars and the public. Although all reviewed sources focus on a better knowledge of the Mexican plant species, each one has its own approach, geographic coverage, and objectives, producing incompatibilities that hamper their integration for rapid and efficient synthesis and analysis. Such integration should offer an updated scenario of its taxonomic and geographical coverage, setting the foundations for organized protocols and strategies aimed to complete the Flora of Mexico in the short term. Floristic knowledge for the country continues to advance actively, as indicated by the growing number of floristic inventories and the buildup of online databases. This synthesis shows how much we know today about Mexico's vascular plant richness and highlights the relevance of this knowledge to other fields of study of nature, particularly those related to its plant component.
Keywords: Biomes, Checklists, Biodiversity, Databases, Floristic richness, Vascular plants

Resumen
Para que nuestro conocimiento actual sobre la riqueza florística en México siga avanzando, se requiere acceso a diferentes fuentes, incluidos inventarios publicados y no publicados, fascículos de proyectos florísticos en curso y bases de datos en línea disponibles públicamente. La evaluación de estas fuentes revela la magnitud de la información existente sobre la diversidad florística del país, su heterogeneidad y la falta de protocolos y estándares para su adecuada organización, análisis y síntesis. En esta revisión se analiza cómo estas fuentes de información brindan bases para poder finalizar la tan ansiada Flora de México, pero también cómo el trabajo taxonómico tradicional (Floras y listados florísticos) apoyan otros campos de investigación biológica. Identificamos lagunas de conocimiento y usos reales y potenciales para otros académicos y el público. Las fuentes revisadas se enfocan en un mejor conocimiento de las plantas mexicanas, pero difieren en enfoque, cobertura geográfica y objetivos; estas incompatibilidades dificultan su integración, síntesis y análisis. Tal integración deberá construir escenarios actualizados de su cobertura taxonómica y geográfica, así como sentar las bases para protocolos organizados y estrategias que permitan culminar la Flora de México en un plazo breve. El conocimiento florístico del país avanza activamente, como lo indica el creciente número de inventarios y la acumulación de bases de datos en línea. Esta síntesis muestra cuánto sabemos sobre la riqueza de plantas vasculares de México y destaca la relevancia de este conocimiento para otros campos de estudio de la naturaleza, particularmente los relacionados con su componente vegetal.
Palabras clave: Biomas, Bases de datos, Biodiversidad, Listados florísticos, Plantas vasculares, Riqueza florística

The publication of a Flora is perhaps one of the most universal aspirations among botanists. Lawrence (1951) defined *Flora* as "an inventory of the plants of a definite area". Such inventory derives from the study and examination of a set of herbarium specimens collected in localities or stations within the area under study. Floristic studies, as conceived at present, are considered to have begun in 1778 with Lamarck's study on the French flora; among other innovations, his work provided the first dichotomous keys to identify species and proposed recommendations and objectives that should be common to all Floras (Miller *et al.* 2015). From that year onwards, virtually all taxonomists around the World have followed a common route in preparing a Flora (Figure 1, upper branch).

Despite the universal acceptance and use among botanists, the term 'flora' is not completely free of ambiguity as it actually refers to different things. In its more general sense, flora denotes the total set of plant species occurring in an area. When narrowing down the concept to the academic works prepared by botanists engaged in its study, Palmer *et al.* (1995) point out that some authors use the term *flora* (not capitalized) to refer to a checklist or inventory for the studied area, while the term *Flora* (capitalized) is applied to a more comprehensive published work where descriptions and identification keys are provided. Although these authors highlight the wealth of information contained in both Floras and floras, they also recognize the importance of related publications with different characteristics that cannot be precisely classified as either one (*e.g.*, field guides, manuals, keys to identification, etc.).

The main goals of a Flora are three-fold: (1) to document (inventory) the species richness of the study region; (2) to provide tools for the proper identification and correct naming of the taxa occurring in the region, and (3) to provide data on their morphological features, geographic ranges, ecological relationships, and more recently, conservation status. The first goal is fully achieved with the completion of the floristic inventory (checklist), while the other two require extra activities including the preparation of identification keys, descriptions varying in length, contents, and detail, taxonomic discussions, and sometimes illustrations. Given the large differences in time and effort required in pursuing these goals, it is not surprising that there are many more products corresponding to the first objective. Indeed, the completion of a Flora requires accomplishing all facets of the floristic study, which often is extremely time demanding. This is the reason why complete and ongoing Floras are rather scarce, especially in countries like Mexico, where little attention is paid to the training of taxonomists (Paknia *et al.* 2015, Villaseñor 2015, Engel *et al.* 2021).

There is extensive literature dealing with the goals and methods of a Flora so no further consideration is offered here. Most Taxonomy textbooks include chapters on these topics and the many routes to achieve them (*e.g.*, Lawrence 1951, Radford 1986). Other publications concentrate on more practical aspects of the floristic work, including collecting specimens and the taxonomic process necessary to conclude a Flora (*e.g.*, Lot & Chiang 1986, Winston 1999, Borsch *et al.* 2020, Lagomarsino & Frost 2020, Miralles *et al*. 2020). In this contribution, we analyze the value and potential of traditional academic outputs of taxonomists (Floras and checklists, as well as taxonomic revisions or monographs) because they are increasingly influential in many other fields of biological research such as biodiversity assessment and its uses, biogeography, conservation, evolution, impact assessments or restoration (Dubois 2003, Funk 2006, Tahseen 2014, Thomson *et al.* 2018).

Geographic context and sources of information

This review deals with floristic information for Mexico; although fragmentary, it covers most of its territory. With a total terrestrial surface of almost two million kilometers squared, the country encompasses a broad elevational gradient, from very high mountains (the tallest being Citlaltépetl volcano, also known as Pico de Orizaba, with 5,610 m at the summit) to extensive coastal plains bordering both the Atlantic and Pacific Oceans. The climatic, geologic, and topographic complexity of the country provides a scenario conducive to the existence of an astonishing vegetational mosaic almost unrivaled. For this reason, different authors have recognized a varying number of vegetation types for this country, ranging from six (Shelford 1926), through ten (Rzedowski 1978, Meave *et al.* 2016), 12 (Leopold 1950), 32 (Miranda & Hernández-X. 1963), to as many as 53 (González Medrano 2003) or 71 (COTECOCA 1994). However, for the purpose of this review, the recognition of five main biomes (humid mountain forests, humid tropical forests, seasonally dry tropical forests, temperate forests, and xerophilous scrubs) provides an adequate vegetational framework to discuss floristic research. Villaseñor & Ortiz (2014) describe these biomes and include the synonymy related to each one used in papers as those cited before.

Floristic information compiled from many sources over several decades was published previously (Villaseñor 2016) and important diagnoses for some regions in the country have since discussed their floristic knowledge (*e.g.*, González-Elizondo *et al.* 2017, Pérez-Sarabia *et al.* 2017, De Nova 2018, Duno-de Stefano *et al.* 2018, León de la Luz *et al.* 2018). Hence, this review focuses exclusively on information published in the last five years and is supplemented with an extensive albeit non-exhaustive evaluation of the information from the digitized collections in two data banks: the Mexican Biodiversity Information System (*Sistema Nacional de Información sobre Biodiversidad de México*, SNIB: www.snib.mx), a database managed by the Mexican Biodiversity Commission (*Comisión Nacional para el Conocimiento y Uso de la Biodiversidad*, CONABIO), and IBdata (www.ibdata.abaco3.org), the web system that contains digitized records of Mexico's National Herbarium at the Institute of Biology, National Autonomous University of Mexico (MEXU-UNAM). Some databases do allow recovering information from herbarium specimens in a floristic list format and thus indeed function as information systems. At the time of consultation, these data banks comprised some three million records of vascular plants, of which just over one and half million have been validated already in their taxonomic and geographic information. Data for records from both collections were reclassified in a database containing specific fields for specific analyzes.

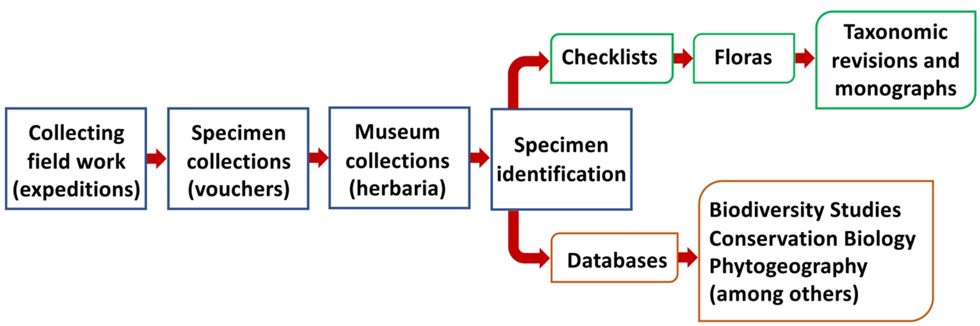

Figure 1. Flowchart depicting the common sequence of main activities followed in preparing Floras, including checklists (right-hand side, bottom part), and the applications of this activity to other fields of biological research (right-hand side, lower branch).

An update of floristic research conducted in Mexico

Palmer *et al.* (1995) estimated that about 8,000 floristic studies have been carried out in North America north of Mexico and showed that their information extends far beyond simple academic uses. Compared to the 284 inventories for Mexico reported by Villaseñor (2016), this figure implies that at the end of the 20th century nearly 30 times more floristic studies had been conducted in North America beyond Mexico. Because Mexico hosts almost 40 % more vascular plant species than the United States and Canada together, local inventories reflect several shortfalls that will be discussed more deeply later. The huge difference in inventoried species between Mexico and the rest of North America may be significantly reduced with the review of unpublished (gray) literature that documents species richness for a multitude of specific locations. For example, a recent inventory of the vascular plant species diversity in the State of Mexico based on literature (both published and unpublished) revealed that almost 30 % of the consulted sources represented gray literature (Martínez-De la Cruz *et al.* 2018). The corollary is that an important fraction of the available information on the occurrence and distribution of Mexico's flora is reported in many works that may never get published (especially undergraduate thesis).

Currently, not only the information reported in the literature (either gray or scholarly) provides information on the richness and distribution of the flora of Mexico. In recent decades, especially since 1992, the year when CONABIO was founded, intense efforts have been made to retrieve label information from specimens deposited in Mexican and foreign herbaria. This has led to the creation of different bodies of information besides that reported in the literature that is useful in evaluating Mexico's plant species diversity. One of the main results of this effort was CONABIO's publication of one of the most complete inventories of this country's floristic richness (Llorente-Bousquets & Ocegueda 2008). Later, Villaseñor (2016) synthesized and updated this knowledge on Mexican vascular plants; underlying his summary there is a vast body of floristic/taxonomic information that supports his conclusions.

The first published checklist of vascular plants of Mexico (Villaseñor 2016) was incorporated into an account of the floristic diversity of the Americas a year later (Ulloa-Ulloa *et al.* 2017). Among other things, this made it possible to determine the country's ranking regarding its floristic richness in these two continents; for example, the Mexican flora ranks third in terms of the number of species, only surpassed by Brazil and Colombia, and second by its number of endemic species, only after Brazil.

Since 2016, almost 400 new taxa have been added to the national checklist, and some 190 additional species have undergone nomenclatural changes. On average, in the last five years, 117 additions or nomenclatural changes per year have been recorded. This average is less than the 158 records per year reported by Villaseñor (2016) for the 2006-2015 period; however, this search was not exhaustive, and the figures suggest that the rate of addition of new species is still significant (see for example Alvarado-Cárdenas *et al.* 2021). In addition to the events discussed so far, in the last decades' important contributions have been made, both by ongoing floristic projects and the descriptions of new taxa. As an example of this situation, Table 1 synthesizes the scientific production of the most important ongoing floristic projects in the last decades in Mexico. All these projects combined have reviewed and discussed totally or partly around 249 out of the 306 families recorded so far in Mexico. Collectively, all issues or fascicles produced by them provide an important amount of taxonomic literature for anyone interested in the topic. Nonetheless, it is noteworthy that there are still 57 families which have not yet been covered by any single project, so today they still lack sound reports of their taxonomy, at least in some parts of Mexico; among them Amaranthaceae, Euphorbiaceae, Loranthaceae, Oxalidaceae, or Ranunculaceae can be cited.

In addition to the floristic/taxonomic issues published by the studies in Table 1, in the last five years, important checklists have been published for many regions across the country, documenting new records to the floras of some Mexican states, and even to the entire country (see Table 2). Several examples from the following areas may be cited: Baja California peninsula (Rebman *et al.* 2016), Campeche Municipio (*municipios* -abbreviated Mun.- are territorial units in which the Mexican states are divided and thus equivalent to counties in other countries), Campeche (Gutiérrez-Báez *et al.* 2016), San Cristóbal de Las Casas Mun., Chiapas (Beutelspacher *et al.* 2017), Tacaná-Boquerón Conservation Priority Region, Chiapas (Martínez-Camilo *et al.* 2019), Sierra Azul, Chihuahua (Vega-Mares *et al.* 2020), Zapalinamé Mountain Range, Coahuila (Encina-Domínguez *et al.* 2016), Hidalgo State (Villaseñor *et al.* 2022), Sayula River basin, Jalisco (Macías-Rodríguez *et al.* 2018), State of Mexico (Martínez-De La Cruz *et al.* 2018), Zicuirán-Infiernillo Biosphere Reserve, Michoacán (Steinmann 2021), La Cantera and Delgado Hills, Jantetelco Mun., Morelos (Cerros-Tlatilpa *et al*. 2020), Chinantla Region, Oaxaca (Meave *et al.* 2017), El Pelado Range, Acatlán Mun., Puebla (Rojas-Martínez & Flores-Olvera 2019), Sierra del Abra-Tanchipa Biosphere Reserve, San Luis Potosí (De-Nova *et al.* 2019), El Palmito Sanctuary, Sinaloa (Ávila-González *et al.* 2019), Guaymas region, Sonora (Felger *et al.* 2017), Pantanos de Centla Biosphere Reserve, Tabasco (López-Jiménez *et al.* 2020), Los Tuxtlas Region, Veracruz (Villaseñor *et al.* 2018), and Mesa Alta, Jerez Mun., Zacatecas (Ramírez-Prieto *et al.* 2016). Without being exhaustive, during the last five years around 118 inventories have been completed (Supplementary material, Table S1), a figure that represents almost half of the inventories reported by Villaseñor (2016), conducted over a much longer period. Therefore, such efforts provide evidence for the growing interest to continue inventorying the floristic diversity of Mexico, despite a worrisome shortage in the number of taxonomists (Villaseñor 2015).

Combining inventory information, the advances of floristic projects (Table 1), and the partial analyses of public databases, a total of 25,077 species (both native and naturalized) have been scored to date, distributed in 3,231 genera and 306 families. The dissection of this total richness by major plant groups is shown in Table 2, where these updated figures are also compared with those previously reported by Villaseñor (2016), although this author includes native species only.

In a critique of an important floristic contribution from the Neotropics, Kress (2004) underscored the relevance of having data organized according to updated classification systems. Although it may be confusing for many users of floristic information, it is imperative that new inventories reflect recent changes in plant systematics (see for example Villaseñor 2016). Table 3 shows the Angiosperm data from Table 2 adjusted to the classification criteria of APG IV (2016). The numbers shown in Tables 2 and 3 include 1,071 alien (introduced) species, most of which are fully naturalized so that they already are integrated into the Mexican plant species diversity.

Table 1. Scientific production of the most important ongoing floristic projects in Mexico. In the footnote the links are provided to the websites where the fascicles published to date are available for consultation.

Floristic project	Publication date of the first issue	Number of issues published to date	Families included*
Flora de Veracruz[1]	1978	166	150
Flora Novo-Galiciana[2]	1983	8	58
Flora de Jalisco[3]	1986	27	26
Flora de Guerrero[4]	1989	82	90
Flora del Bajío y regiones adyacentes[5]	1991	223	137
Flora del Valle de Tehuacán-Cuicatlán[6]	1993	110	96
Flora Mesoamericana[7]	1994	4	118

* Several families are only partially covered.

1. http://www1.inecol.edu.mx/publicaciones/LISTADO_FLOVER.htm
2. https://searchworks.stanford.edu/view/1596984
3. http://www.cucba.udg.mx/documento/publicaciones-del-cucba
4. http://biologia.fciencias.unam.mx/plantasvasculares/publicaciones.html
5. http://inecolbajio.inecol.mx/floradelbajio/index.php/fasciculos/publicados
6. http://www.ibiologia.unam.mx/barra/publicaciones/floras_tehuacan/florastehucan.htm
7. http://legacy.tropicos.org/Project/FM

Table 2. Taxonomic distribution of the native and naturalized vascular flora of Mexico. Figures in Villaseñor (2016) do not include the 608 exotic species recorded by that time.

Vascular plants	Species	Species reported by Villaseñor (2016)
Ferns and Monilophytes	1,083	1,039
Gymnosperms	170	149
Angiosperms	23,824	23,044
Total	25,077	23,932

Shortfalls in the knowledge of the floristic diversity of Mexico

Various authors have identified several shortfalls in biodiversity knowledge (*e.g.*, Hortal *et al.* 2015, Oliveira *et al.* 2016), among which the following three can be highlighted: (1) the Linnean deficit, which is related to a large number of unknown or undescribed species in a country or region; (2) the Wallacean deficit, which refers to insufficient knowledge on the geographic distribution of species; and (3) the Hutchinsonian deficit, which refers to the poor understanding on the climatic and other abiotic factors that determine ecological tolerances.

Floristic studies and the review of herbarium specimens digitized in two databases enable the assessment, at least in part, of the floristic richness of Mexico, as they provide insight into these three shortfalls. For example, Table 4 shows the frequency distribution of the number of species by state and by grid cells (1° latitude and longitude in size) used to assess geographic distribution patterns. Species incidences are shown according to the canonical distribution discussed by Preston (1962a, b), which corresponds to a normal distribution of $\log_2$ transformed data (log-normal distribution).

According to updated information, 4,898 native species have been recorded in just one state and 4,633 in one grid cell (singletons); in turn, 3,943 species have been scored in two states and 3,061 in two grid cells (doubletons). Using the *Chao2* equation ($S_{est} = Q1^2 / 2Q2$, where *Q1* is the singletons and *Q2* the doubletons (Chao & Chiu 2016), we can estimate the expected richness that could still be added to the known richness (Villaseñor 2003). The expected addition of unknown species was estimated at about 3,018 species based on state distribution data, and at about 3,340 species based on grid cell distribution. These calculations suggest that the Linnean deficit in the flora of Mexico may range between 12.6 and 14 %, with the total flora likely reaching figures between 27,024 to 27,346 species. These new figures are lower than older estimates, which were as high as 29,000 to 30,000 species (Villaseñor 2003).

Table 3. Major Angiosperm clades following the APG IV (2016) scheme and its taxonomic diversity in Mexico

Plant group	Orders	Families	Genera	Species
Basal Angiosperms (Austrobaileyales and Nymphaeales)	2	3	6	17
Magnoliids (including Chloranthales)	5	13	44	661
Monocots	9	41	639	4,943
Eudicots (including Ceratophyllales)	6	12	45	253
Rosids (including Dilleniales and Saxifragales)	18	98	943	7,396
Asterids (including Caryophyllales and Santalales)	15	91	1,396	10,554

Table 4. $\log_2$ frequency distribution of the number of species by number of Mexican states (*N* = 32) and grid cells (*N* = 253) where they occur.

$\log_2$ Class	Mexican states	Grid squares
No information	71	537
1	4,898	4,633
2-3	7,034	5,331
4-7	5,819	4,837
8-15	4,149	4,024
16-31	2,923	3,259
32-63	54	1,828
64-127		489
128-253		10

Counteracting the Wallacean deficit (ignorance about the geographic distribution of species) requires specific information on the locations where populations of the different species are present. Point distributions of a species allow distribution map production with known information, estimating areas of distribution (either Area of occupancy [AOO] or Extent of Occurrence [EOO], IUCN 2012), or more recently, developing potential distribution models. It is common practice among taxonomists to include dot maps in Floras or taxonomic revisions to illustrate broad species distributions. Based on floristic information and databases, conservationists define AOO or EEO to evaluate distribution areas and thus assess the risk status of species. Potential distribution models, on the other hand, are being widely used to assess many aspects of the ecology and natural history of species (Araújo & Guisan 2006, Marcer *et al.* 2013). The main source of data used in building these models is the records of species collected mainly for floristic studies.

To provide a geographical context to this analysis, Figure 2 shows the known spatial distribution of the floristic diversity documented to date (Table 2) in the territory of Mexico. Figure 2A depicts floristic richness (alpha diversity) in squares of 1° latitude and longitude, whereas Figure 2B shows the estimated richness from 2A using a Kriging interpolation method (ESRI 2013). On these figures, diversity gradients become apparent from south to north, with a noticeable decrease in richness north of the Tropic of Cancer. Figure 2 illustrates how floristic information contributes to minimizing the Wallacean deficit in our knowledge of the Mexican flora.

The Hutchinsonian shortfall (*i.e.*, poor knowledge of the ecological tolerances and requirements of species) may be minimized by collating information on the environmental factors related to species distributions. It is common for Floras and inventories to include some pieces of this type of information, for example, elevational range, vegetation type, or soil characteristics. Villaseñor & Ortiz (2014) assessed the distribution of the flowering plants (Magnoliophyta) of Mexico using the biome concept (Krebs 1978, Gurevitch *et al.* 2002), defined according to climate, substrate (both geological and edaphic), and floristic richness. These authors considered five major biomes (Table 5) and discussed the characteristics of each one and their floristic richness. Table 5 updates this information, arranging the richness data according to major taxonomic groups (Table 2), and classifying Angiosperms according to APG IV (2016).

Table 5 demonstrates how some biomes concentrate an important species richness for some taxonomic groups. The Humid Montane Forest (HMF), for example, is the main habitat for most ferns and allies and shares with the Humid Tropical Forest (HTF) the largest number of Magnoliids. Likewise, HTF is the main habitat for basal Angiosperms and Rosids. By contrast, Gymnosperms, Monocots, and Asterids are best represented in the Temperate Forest (TEMF).

Users of floristic studies from other disciplines

Plant taxonomists, conservationists, ecologists, policy advisors, students, and non-specialists at large constantly use published results from floristic studies (Thomson *et al.* 2018, Hobern *et al*. 2021). For the species occurring in each area, users may seek information related to aspects as dissimilar as growth forms, geographical distribution, flower color, uses, or common names, among many others. All these users require updated and complete information, but large inconsistencies in the sources pose difficulties that may discourage them. Common problems faced when consulting floristic reports may include information incompleteness or inaccuracy, which are mostly due to the constant taxonomic changes, additions of new species, transfer of species between genera (for example, the status change of species of *Cryptantha* Lehm. ex G. Don to *Johnstonella* Brand in Boraginaceae), transfer of genera to other families (for example, *Penstemon* Schmidel formerly in Scrophulariaceae, now in Plantaginaceae), or synonymy updates (for example, *Eupatorium odoratum* L. is now a synonym of *Chromolaena odorata* (L.) R.M. King & H. Rob.). As said, in the last five years about 190 species names underwent taxonomic changes not reported in previous studies of the Mexican flora.

Well-structured Floras are the main or even the only source of biological information for many species. Unfortunately, there is no single protocol guiding standardized morphological descriptions of species or the organization of the additional information provided in descriptions. This causes disappointment or delay in recovering the required data; once these data have been organized, a large array of information contained in floristic studies becomes apparent. Table 6 exemplifies some plant groups defined by different traits commonly sought after by specialists. For example, biogeographers generally investigate floras for information on endemic taxa, those interested in invasive plants require data on which species are native and which are exotic, ecologists require information on growth forms (*e.g.*, trees) or fruit size, and ethnobotanists search for remarks on plant uses.

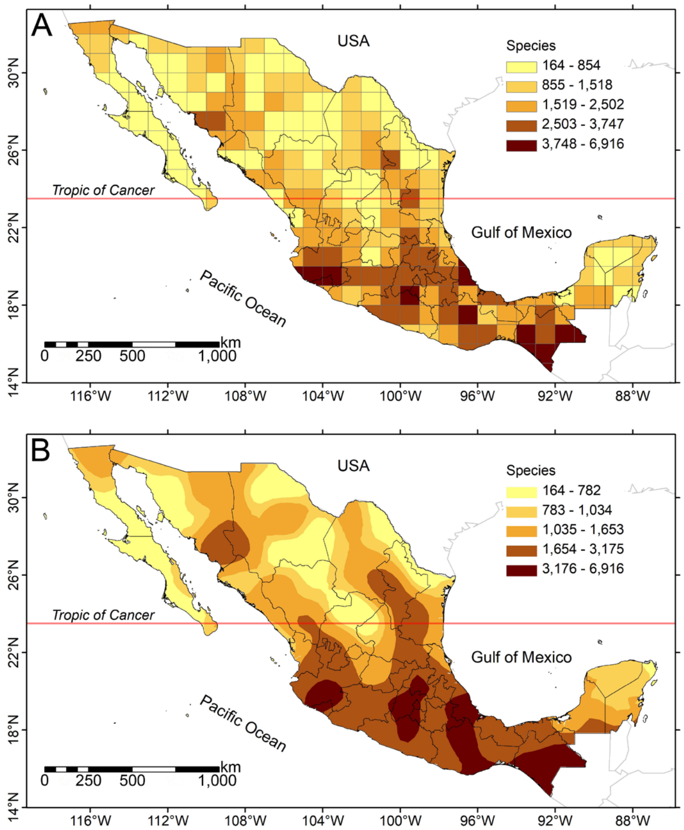

Figure 2. Geographic richness patterns of vascular plant species in grid cells of 1° latitude and 1° longitude in size. A. Alpha diversity per grid cell. B. Estimated smoothed richness based on A using a Kriging interpolation method.

Being in possession of broad floristic knowledge, taxonomists are capable of synthesizing useful information for other specialists (*e.g.*, Pendry *et al.* 2007, Hobern *et al.* 2021) in the form of inventories that are specific to the trait of interest. For example, in the case of Mexican plants there are checklists for endemic species (*e.g.*, Rzedowski 2015, Villaseñor 2016, Salinas-Rodríguez *et al.* 2017, Villarreal-Quintanilla *et al.* 2017), alien species (Villaseñor & Espinosa-García 2004, Espinosa-García & Villaseñor 2017), trees (*e.g.*, Villaseñor *et al.* 2012, Ricker *et al.* 2013, 2016, Steinmann & Ricker 2020), woody vines (Ibarra-Manríquez *et al.* 2015), strict aquatics (Mora-Olivo *et al.* 2013), epiphytes (Espejo-Serna *et al.* 2021) or useful plants (J.L. Villaseñor, unpublished data).

The usefulness of floristic research for other biological disciplines

Plants are the key elements of primary productivity in terrestrial communities (Gurevitch *et al.* 2002). For this reason, many researchers view them as the main source of ecological information; for example, plants are consumed by herbivores and pollinated by many insects, birds, and mammals. Therefore, ecologists who study plant-animal interactions require reliable information on the plants associated with these phenomena, for example, growth form, flower color, phenology, fruit type and size, etc. Similarly, scholars like biogeographers, conservationists, and modelers of the spatial distribution of species require reliable data on species, including morphology, geographic distribution, habitat preferences, or risk status (Thomson *et al.* 2018, Hobern *et al.* 2021). Floras and inventories have always been sources of this kind of information, in addition to the fact that they assist with the identification of unidentified material in collections. Biologists, foresters, chemists, medical researchers, and scholars from many other disciplines are in constant demand of reliable information on plant species. Villaseñor (2015) provides examples of situations in which this information is required. For one, international commitments made by most countries, including Mexico (*e.g*., CITES, the Nagoya Protocol or the Mexican National Strategy on Biodiversity (CONABIO 2016) require reliable information on the plant species occurring in their focal territories.

Using the correct name of an organism underpins many areas of research (ecology, biodiversity conservation, ethnobotany, etc.) and is key to the literature on the various aspects of its biology and natural history (Tahseen 2014). Control of weeds and invasive plants, for example, requires using the same scientific name for the same organisms across their geographical ranges. Likewise, ecologists, managers of natural protected areas, or those interested in modeling species' potential distributions require detailed data on morphology, geographic distribution, preferred vegetation types, etc., for the species of interest.

Table 5. Number of vascular plant species in Mexico dissected by major taxonomic groups, recorded in the five main biomes recognized by Villaseñor & Ortiz (2014). HMF = Humid Montane Forest, HTF = Humid Tropical Forest, TEMF = Temperate Forest, STF = Seasonally Dry Tropical Forest, XER = Xerophytic Scrub.

Taxonomic group	HMF	HTF	STF	TEMF	XER
Ferns and Monilophytes	717	485	214	538	194
Gymnosperms	70	31	22	103	46
Basal Angiosperms (Austrobaileyales and Nymphaeales)	3	7	1	1	3
Magnoliids (including Chloranthales)	348	353	150	219	31
Monocots	1,802	1,494	1,402	2,163	1,153
Eudicots (including Ceratophyllales)	86	47	46	107	85
Rosids (including Dilleniales and Saxifragales)	2,233	2,918	2,219	2,684	2,250
Asterids (including Caryophyllales and Santalales)	3,120	2,254	2,949	4,854	4,023

Illustrated floras

Floras and, recently, specimen image databases available on the internet have become important tools to confront the biodiversity crisis; each of these tools provides basic information for many potential users (Mayo *et al.* 2018). Digital images are non-traditional resources in identification whose use is witnessing a recent increase (see Andleeb *et al.* 2021 for an application in earthworm taxonomy). However, little has been discussed about the potential of including color images in floras, which is perhaps due to high printing costs, although this problem is dwindling with the growth of electronic publications. Morphological characters shown as images offer a better understanding that permits more concise descriptions and facilitates the correct identification of plant specimens (Pendry *et al*. 2007, Cope *et al.* 2012). Often, published floras include drawings of some or most species to accompany descriptions, but few authors have included photographs of specimens or characters. Fortunately, this situation is changing, and at present, the inclusion of photographs in descriptions of new species, in addition to the use of traditional line drawings, is becoming increasingly frequent. The ease of posting electronic publications online has facilitated the use of images to supplement descriptions. Consequently, one may foresee in the near future an increasingly common practice of producing illustrated floras that include high-resolution images of plant traits in taxonomic discussions.

Interesting examples of this trend in the Mexican context are some illustrated monographs for different groups that are part of the Flora of Morelos (Cuevas-Ríos 2020, Soriano-Pantaleón 2020), with plates that synthesize key morphological information and depict the variability of a given taxon. Figure 3 shows an example of such a plate that will be incorporated into the printed publication for the Asteraceae family in the Huautla Biosphere Reserve (Soriano-Pantaleón 2020). This image includes important structures that make it possible to distinguish the species from other related species and genera, thus facilitating botanical identification.

Current problems faced by the production of Floras

Floras and checklists are conceived as an end in themselves; once assembled and published they are hardly ever subjected to periodical updating (but see for example Pérez-García *et al*. 2001 and 2010, Céspedes *et al*. 2018). The discouragement for those who must rely on obsolete information adds to the confusion caused by the large variety of names for the same species in different publications, online databases, or herbarium specimens. To inexperienced readers, the inability to integrate the information reported under different names in all these sources makes its study difficult. The retrieval of taxonomic or geographic information for a species from these sources is often slow, burdensome, and impractical for a meaningful analysis. A great challenge is to develop strategies that allow flora users to have up-to-date information from all sources consulted. In this context, automatized algorithms that allow homogenizing of large numbers of species in a short time have become valuable tools (Cayuela *et al.* 2012, Boyle *et al.* 2013).

The preparation of Floras and inventories is a time-consuming task, rarely acknowledged in fair terms but always in demand (Tahseen 2014). It is perhaps the time to assess whether the traditional way of producing Floras and checklists is one of the causes, if not the main one of a widely noted taxonomic impediment. Tools and protocols should be developed to accelerate their production, in particular those related to the description of species and the construction of keys for their identification. Currently, changes in floristic diversity are taking place forced by climate change and human interference in primary vegetation (Correa-Metrio *et al.* 2012, D'Amen *et al*. 2017), species are experiencing morphological variations in shorter times (Hairston *et al.* 2005, Anderson & Song 2020), as well as changes in their geographical distribution (Kelly & Goulden 2008). For these reasons, Floras should become more dynamic, as only in this way they will allow documenting changes in zones for which published studies are available (*e.g*., Castillo-Argüero *et al.* 2004, Céspedes *et al.* 2018). This will require new approaches and procedures like those being currently developed on the internet, such as that for the flora of Brazil (BFG 2015, BFG 2022, reflora.jbrj.gov.br), Flora of China (Brach & Song 2006) or World Flora Online (Borsch *et al.* 2020).

Herbarium specimens and databases

Herbarium specimens bearing correct identifications are the most important source of information to produce checklists, Floras, and databases (Figure 1). However, it must be emphasized that not all herbarium specimens are collected with these objectives in mind. Although all specimens may look similar in the collection, for a long time and depending on the goals, collecting specimens in the field has been made in different ways (Knapp 2015). For example, a col-

Table 6. Numeric distribution of species among groups representing some traits of Mexican Angiosperms commonly sought after by specialists in floristic studies.

	Endemics	Alien species	Trees	Woody vines	Strict aquatics	Epiphytes	Useful plants
Basal Angiosperms	1	1	1	1	15	-	5
Magnoliids	316	9	311	29	1	97	154
Monocots	2,221	274	237	49	137	906	1,100
Eudicots	97	12	55	32	8	-	69
Rosids	3,713	358	2,567	481	39	60	2,285
Asterids	5,832	388	1,487	647	30	105	2,777

lector associated with a herbarium herbarium may focus on studying poorly explored regions, covering large areas, and usually never collecting the same species more than once in the same expedition (ter Steege *et al.* 2011). In contrast, a taxonomist preparing the revision of a genus may attempt to collect numerous samples of the same species in nearby or previously collected localities. Likewise, a botanist carrying out a floristic inventory for a particular region can collect numerous samples of the same species to document as amply as possible its distribution within the area of interest. Consequently, specimens collected opportunistically can be mixed in herbarium collections with others that constitute the basis for systematic or floristic studies carried out in a completely non-opportunistic way. Even now, collections include vouchers backing up anatomical, molecular, or phytochemical studies, whose purpose was clearly unrelated to the support of floristic or taxonomic research (Besnard *et al.* 2018). Because of this not-so-obvious diversity of specimens, the information contained in them can be highly heterogeneous in accuracy and completeness.

Currently, databases containing information retrieved from herbarium specimens provide many of the details required by researchers other than taxonomists. Because of Taxonomy's dynamism, generic reviews, as well as nomenclatural changes in species are published frequently. New, useful, and reliable information demands checklists and databases to be constantly updated; among other things, this task allows fine-tuning the known geographical distribution of plant species and conducting better-informed studies on the regional patterns of the distribution of plant diversity (Domínguez-Lozano *et al*. 2007).

Databases play an increasingly important role in organizing and analyzing information on collected specimens and their provenance. Customarily, checklists and Floras have been produced mainly based on specimens collected directly by the authors involved in the project, plus using additional material housed at their institution. If resources are available, sometimes one or two additional herbaria are consulted. At present, many more specimens available online from numerous institutions can be examined, either as databases only or as good resolution photographs (see for example Villaseñor *et al.* 2018, 2022, Martínez-Camilo *et al.* 2019).

Funk (2006) argues that online databases lack reliability because of numerous mistakes, especially on identifications. Although this statement is true in general, it must be noted that a printed checklist is not necessarily free from misidentifications. In fact, many mistakes contained in online databases are the result of the same mistakes reported in the printed inventories simply because they use the same sources of information, namely herbarium specimens. Such mistakes are now brought to a minimum with the inclusion of specimen images linked to several online databases (see for example IBdata (www.ibdata.abaco3.org)

Identification keys and the advancement of floristic knowledge

Ecologists and many other scholars engaged in the study of nature are in contact with plants in their study sites that are in the vegetative phase, *i.e*., lacking the reproductive structures commonly used in identification keys. These researchers require identification resources that go beyond the use of characteristics only relevant to the taxonomist. Hence, taxonomists should be committed to constructing keys also useful to other users. To this end, the challenge is to produce reliable taxonomic information for those who need access to it in an easier and more efficient way; in particular, identification keys to be used by the broader public need to be prepared urgently (see Gentry 1996 for a good example of identification keys based on vegetative plant features). This issue is a matter of increasing interest since the biodiversity crisis requires immediate actions based on solid scientific evidence; much of this information may only be obtained from a reliable and rapid identification process. Urgent measures to protect biodiversity are needed due to the intense reduction in the natural vegetation cover and overexploitation of resources, especially in countries like Mexico and other nations in tropical regions where deforestation rates are still very high (www.globalforestwatch.org). We are still at a stage characterized by low information availability to achieve efficient conservation strategies. Regrettably, in this enterprise taxonomic identification continues to be a major bottleneck (Kim & Byrne 2006).

Good identification keys must be clear and user-friendly, regardless of whether the user is a trained botanist, or a non-specialist interested in the subject. Completed print Floras and the published fascicles of Floras in progress,

Figure 3. Example of a plate included in an illustrated monograph that forms part of the Flora of Morelos (in preparation). The illustrated species is *Montanoa grandiflora* Alamán ex DC. (Asteraceae). A, branch. B, leaves. C, petioles. D, head, E, phyllaries. F, receptacle. G, radiate floret in lateral view. H, radiate floret in adaxial view. I, tubular floret. J, cypsela. Reproduced with permission from Soriano-Pantaleón (2020).

although especially important, are sometimes difficult to consult by non-botanists and their information is mostly aimed at experienced botanists and thus difficult to use by non-specialists for identification purposes. In addition, print Floras are usually quite expensive, and downright prohibitive for many people (especially students). Fascicles of floristic projects are especially useful for the groups studied, but the number of species and their geographic scope is necessarily limited; consequently, its relevance decreases as one moves away from its area of influence. The lack of botanical experience in the identification of species that prevails among many local and regional researchers constitutes a great hurdle in the crusade against the taxonomic impediment, namely the lack of taxonomic resources and expertise, both regarding the knowledge of the species (Linnean deficiency) and their geographical distribution (Wallacean deficiency). The internet provides a great opportunity to do away with identification deficiencies by providing friendly tools (see Murguía-Romero *et al.* 2021, for a review).

Concluding remarks

The preparation of Floras and checklists is and will continue to be a fundamental task in the daily work of taxonomists (Brach & Song 2006). Especially now, because of the biodiversity and climate change crises, we face the need more than ever to count on precise information about the natural history of species, their ecological requirements, and their distribution areas. A great deal of this information is included in the results of floristic studies, necessary by many other specialists.

Although inadequately valued, the relevance of floristic studies has been repeatedly emphasized (*e.g.*, Sosa & Dávila 1994, Krishnamurthy *et al.* 1995, Heywood 2004, Prather *et al.* 2004, Funk 2006, Pendry *et al.* 2007, Martínez-Camilo *et al.* 2019, Cutts *et al.* 2021). Luckily, in Mexico studies of this kind are still underway, apparently with increasing activity, despite insufficient academic and economic support, two conditions sadly shared with many developing countries of high diversity (Britz *et al.* 2020). It is not surprising, for example, that only two of ten randomly reviewed checklists received external funding in addition to their institutional support. By contrast, among 10 randomly selected ecological studies and 10 studies on molecular phylogenies, every one of them acknowledged financial support from some source external to their institution, and most of them used one way or another information derived from floristic studies, either by recovering the information provided on the label or by taking samples from the specimens and used as a source of material or identification.

The specimens kept in herbaria, many of which have their associated information currently digitized, are mostly material collected for floristic inventories. These specimens constitute the raw material for multiple biodiversity, biogeography, and macroecology studies, as well as a sound foundation to define conservation and ecological restoration strategies (see the lower branch on the right-hand side of Figure 1). Without inventories, critical information required by such investigations would be lacking. Undoubtedly, only with the continued inventory and production of Floras will we be able to transit from models and estimations to the real evaluation of our knowledge, hence alleviating our Linnean, Wallacean, and Hutchinsonian shortfalls, and ultimately producing the Flora of Mexico.

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Supplementary material

Supplemental data for this article can be accessed here: https://doi.org/10.17129/botsci.3050

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