ARID AND SEMI-ARID ZONES OF MEXICO:

A COMPREHENSIVE EXPLORATION OF BIODIVERSITY, ECOLOGY, AND CONSERVATION

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FOREWORD

This book is an introduction to the arid and semiarid zones of Mexico, their biological and cultural diversity, and the problems that threaten their conservation. The authors, all scientists from different academic institutions in Mexico had the challenge of writing chapters on a huge area comprising almost half of the country's territory, covered by these ecosystems. The areas within the polygon defined by arid and semiarid regions were organized along a climatic gradient of increasing aridity from central to northern Mexico. In the central region, the Mexican Altiplano, which is part of the Chihuahuan Desert, is an extensive strip that reaches the southern U.S. border in Texas and includes the states of Chihuahua, Coahuila, Durango, San Luis de Potosí, Sonora and Zacatecas.

Also in central Mexico, the Tehuacán-Cuicatlán Valley region, the southernmost arid zone in Mexico, in the states of Puebla and Oaxaca, is outstanding. It is a region surrounded by complex mountain ranges that form an extraordinarily heterogeneous landscape that harbours great biological and cultural diversity. Attached to the continental territory, it is highly relevant to the arid region of the peninsula of Baja California. In total, the arid and semiarid zones studied in this book include 18 of the 32 states that constitute Mexico.

Although arid environments are generally considered hostile, because of the high temperatures and scarcity of water that characterize them, human communities have found food, medicines, resources for shelter, and clothing in these regions and have occupied them since prehistory. Several studies have recorded nearly 8,000 plant species used by Mexican human cultures throughout the country, about 3,000 of which are from arid and semiarid areas. The interactions with other groups of organisms, including vertebrates and invertebrates are also outstanding. Some chapters of the book illustrate this situation. One of them, for example, compiles information on more than 300 species of medicinal plants from arid environments. In addition, in the arid zones of Sonora, several species of *Euphorbia* have been identified that contain eugenol, which is effective against microbial biofilms and has high medical potential in combination with antibiotics. Also of note are the diverse species of prickly pear cactus of the genus *Opuntia*, which have provided edible cladodes and fruits, together with hose produced by the giant columnar cacti such as cardon and saguaro, which have also been basic sources of material for the construction of houses and fences.

The cactus family is the most emblematic plant group of the arid zones of the Americas, and it finds the main centre of diversification in Mexico. Nearly 1520 species of Cactaceae have been recorded worldwide, all of them in the Americas, with the only exception of *Rhipsalis baccifera* that also occurs naturally in eastern tropical Africa and Madagascar. Almost half of this diversity (850 species) occurs in Mexico and 500 species are endemic to this country. One of the chapters characterizes the distribution of cacti in Mexico and finds that almost 80% of the species are found in arid zones. But this diversity is threatened, as discussed in another chapter of the book, which analysed the Mexican system of natural protected areas and found that the highest proportion of arid and semiarid zones are outside the system and any form of protection.

Not only cacti are important, they are also representative of rich and complex ecosystems, interacting with numerous species of plants, animals, fungi, and microorganisms. Some chapters are dedicated to documenting part of this diversity. One of them analyses groups of invertebrates that play a key role in maintaining ecosystems. Ants, for example, play a crucial role in the flow of matter and energy occurring in arid ecosystems, but the authors estimate that only half of the species living in these areas in Mexico have been described. Similarly, complex assemblages of birds and mammals live in these areas and carry out crucial interactions for the overall maintenance of ecosystems. The study of the diversity of species and especially the diversity of their interactions is of great importance for the design of strategies to conserve the biodiversity of these areas.

Conservation strategies require agreements and participation of the people living in the areas. Social participation is another issue addressed in the book. The use of land and natural resources has had a long history, but especially in the last century, it has been problematic, as large areas have been included in government plans of agroindustrial transformation, cattle ranching, mining, urban expansion, and other destructive activities. These processes are illustrated by the case of the Comarca Lagunera region, in Durango and Coahuila, northern Mexico, where contamination and degradation of soils result from a combination of factors related to human activities. Protecting and restoring the drylands of Mexico require planning, participation, and effective public policies to regulate human actions. Ex-situ conservation of germplasm has been considered a complementary strategy to ensure conservation, especially of plant species. A relevant chapter of this book is dedicated to sharing the inventory of species of arid zones with the readers, which are represented in the Collection Banco de Semillas of the FES Iztacala, UNAM.

This book is an important contribution for all readers interested in the conservation of biocultural diversity in general, and especially for those concerned about the future of the arid and semiarid lands of Mexico and the world.

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PREFACE

We are pleased to present the book *Recent Advances in Biotechnology: Arid and Semi-Arid Zones of Mexico: A Comprehensive Exploration of Biodiversity, Ecology, and Conservation*. This book includes assorted topics focused on biodiversity assessments for distinct taxonomic groups, a proposal for the conservation of arid and semi-arid areas, and seed collection as a strategy for underpinning species conservation. Moreover, the conservation issues in these regions were discussed from the perspective of social participation. In addition, other chapters analyzed ecological processes such as the nursery and local effects of contamination in arid regions.

We have to mention that most of the contributors to this book analyzed a large study area in their respective chapters that included 18 Mexican states. Thus, our study area represented the four most relevant and recognized arid regions: the Baja Californian Desert, the Chihuahuan Desert, which included the interesting Queretaroan and Hidalgoan semideserts; the Sonoran Desert; and the southernmost Tehuacán-Cuicatlán Valley.

Across this large study area, Chapter 1 identified climatic heterogeneity, which was classified into 15 climatic domains; moreover, a latitudinal pattern of aridity that increased from central to northern territories was also described. Many chapters of this book base their analysis on these climatic classifications to describe and discuss their results.

This latitudinal aridity gradient is reflected in the fact that most of our study area was covered by vegetation; however, in areas with extreme aridity, vegetation is almost absent (*i.e.*, deserts). Thus, the Mexican arid and semi-arid regions are covered by different types of vegetation (*i.e.*, xeric scrublands, meadows, and prickle pears) adapted to scarce precipitation and high temperatures; however, in some areas in the northwestern territories (*e.g.*, the Chihuahuan and Sonoran deserts), aridity is extreme and resembles the typical desert of the Sahara in Africa. This variation in aridity levels has caused some regions to be named “desert” and “semidesert” instead of arid or semi-arid regions; thus, this interchange of terms is common in the literature.

Lastly, the reader will find in these book chapters an assessment of the levels and distribution of diversity for different taxonomic groups. Most of these chapters have complementary results presented as appendices, which are also available at the following link: https://posgrado.iztacala.unam.mx/recent-advances-in-biotechnology-ari--and-semi-arid-zones-of-Mexico-a-comprehensive-exploration-of-b-odiversity-ecology-and-conservation/?preview=true.

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PRESENTATION

In the world, arid and semiarid areas are one of the major and widely distributed ecosystems, covering nearly 41% of the surface. Particularly, these types of ecosystems are well recognized in Africa, southwestern Australia and southern Asia, Mexico and the southern United States of America, northwestern China, and South America. In the North American Subcontinent, Mexico and the USA have the largest extensions of this type of ecosystem. This book was focused on arid and semiarid regions of Mexico, a country where nearly 60% (56.92 million hectares) are covered by these environments, which give biological support for nearly 18% of the national population. This book was led by academics of the Research Unit of Biology Technology and Prototypes (UBIPRO), FES Iztacala, UNAM. Since this unit was established (1997), it has focused on arid and semiarid ecosystems in order to describe physical variation across these types of ecosystems, as well as to identify and understand biological, ecologic, genetic, and phylogenetic patterns and processes. In addition, in this unit, there are academic groups dedicated to the isolation of chemical compounds of plants and the transfer of knowledge through social participation. Academics at UBIPRO planned the general content of this book; and invited academics from other institutions. The topic was freely decided by the authors of each chapter, as well as they decided to contribute with advanced research or a completely new idea developed *ad hoc* for this book. The costs of each chapter were paid by the authors themselves. The geographic context of this book was arid and semiarid zones of Mexico: the Peninsula of Baja California, the Chihuahuan Desert, the Sonoran Desert, and the Tehuacán-Cuicatlán Valley. In this book, most of the chapters deal with the challenge of integrating their analysis as geographic study areas with these four emblematic arid-semiarid areas. Moreover, readers will have in a single book and most of the individual chapters, comparative biological assessments across these four emblematic arid and semiarid areas, in diverse taxonomic groups (Chapters 3, 4, 5, and 6). The most important national seed collection for Mexican native wild plant species contributed in this book with results of the accessions deposited in such collection (Chapter 14). Moreover, medicinal plants traditionally used by local human communities across the arid Mexican territories are presented in this book (Chapters 7 and 8). The lack of natural protected areas in Mexican arid and semiarid regions was identified (Chapter 13) by using the emblematic group of cacti. The climatic heterogeneity across the four main arid and semiarid regions was shown in Chapter 1, and their effects on biological diversity were discussed in other chapters. In addition, the Chihuahuan Desert is considered a biological reservoir, and particularly its southern portion has been addressed as a center of origin, diversification, and endemisms, and in this book, a detailed physical description was integrated (Chapter 2). Chapter 10 presents the use of state and transition models to explicate vegetation changes in this type of ecosystem. In addition, Chapter 11 reviewed the theme of nursery in order to evaluate the role of ecological vegetation dynamics and to identify environmental management strategies. Since the relationship between social and ecological systems is relevant, Chapter 9 examined a knowledge model to transfer technical results to the local human communities. The arid and semiarid areas are under the pressures and local effects caused by human communities, and this book includes the study case of Comarca Lagunera (Chapter 12). Although this book has a technical format, we expect that readers both from the public and academic sectors will enjoy a friendly narration and fashioned figures of diverse and exciting themes that are presented in this book.

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PART 1
PHYSICAL ENVIRONMENT CHARACTERISTICS OF ARID AND SEMI-ARID ZONES

CHAPTER 1

Climatic Domains of the Arid and Semiarid Zones of Mexico

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Abstract: The arid and semiarid zones of Mexico occupy more than half of the country's territory, a characteristic that makes them extremely heterogeneous. It has been suggested that climate heterogeneity promotes biological diversity; consequently, different climatic factors are important for explaining species distribution patterns at different scales. Multiple studies have considered climate as a substitute for biodiversity; therefore, describing environmental characteristics is of great interest in understanding biological diversity. The objective of this chapter is to perform a climatic characterization of the arid and semiarid zones of Mexico through climatic domains to understand the climatic heterogeneity in these environments. We defined climate domains as geographic units with similar environments through nonhierarchical multivariate classification of a dataset comprising climate estimates for points along a 1-km grid throughout the study area. As a result, we defined 15 climatic domains that allowed us to recognize regional environmental variations. According to the row fusion dendrogram, three groups were identified according to their environmental characteristics, and two domains remained independent. In this chapter, we present a classification of climatic domains for the arid and semiarid zones of Mexico to show part of the variation within these zones and as a form of regionalization that allows us to make sense of the biological patterns that will be studied in other chapters. Consequently, a better understanding of climate heterogeneity within a region can support the selection of areas with distinct environmental attributes and biological patterns.

Keywords: ANUCLIM, Environmental Heterogeneity, Evaporation, Geographical Units, Regionalization.

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INTRODUCTION

Arid zones are characterized by regions where water loss through evaporation is much greater than the input from precipitation and where temperatures are extreme [1, 2]. Although the concept of aridity has been defined by several authors, all of them involve the amount and efficiency of precipitation and its relationship with temperature [3]. In Mexico, the National Commission for Arid Zones (CONAZA) defines arid zones as those areas of the national territory where rainfall is 250 mm per year or less and semiarid zones as those areas where rainfall ranges between 250 and 500 mm [3]. However, there are other factors that promote or maintain aridity in a region, such as latitude, height above sea level, prevailing winds, the season of the year, the proximity of the sea, cold or warm sea currents, and orography, such as depressions or mountain massifs [3].

Mexico has a high level of environmental heterogeneity due to its complex geological and climatic history [4, 5], with several mountain systems converging throughout the country, such as the Sierra Madre Occidental, the Sierra Madre Oriental, and the Trans-Mexican Volcanic Belt. In Mexico, the arid and semiarid zones are mainly located in the Sonoran and Chihuahuan Deserts; in the central regions due to the effect of orographic shadows generated by the Sierra Madre Oriental, the Sierra Madre del Sur and the Occidental at altitudes below 1500 meters above sea level; the coastal areas of the Baja California Peninsula; the central area, which is less exposed to the influence of humid winds; and the lower parts of the Balsas River Basin, among others [6].

Arid and semiarid zones cover 56.92 million hectares of forest out of the 138 million hectares that the country has, which represents 54% of the territory and is mainly located in the northern and central regions of the country (CONABIO). Furthermore, arid and semiarid zones provide numerous resources and environmental services such as a source of various food and medicinal products, and provide spaces for the conservation of biodiversity, provision of fresh water, energy production, tourism, and recreation, among others [7]. In addition, they represent one of the main terrestrial carbon reservoirs [8].

The distribution and abundance of organisms are closely related to environmental factors [9]. It has been suggested that climate heterogeneity promotes biological diversity [10]; therefore, different climatic factors are considered important for explaining species distribution patterns at different scales. Consequently, a better understanding of climate heterogeneity in a region can support the selection of areas with distinct environmental attributes and different patterns of biological richness and would even allow us to identify species adapted to particular conditions such as endemism [11].

There are regionalizations of the Mexican territory in biogeographic regions [12 - 14], floristic provinces [15], and terrestrial ecoregions [16], among others. With respect to climate, there are classifications such as those of García [17], who adjusted the Köppen classification system to the particular conditions of Mexico on a national scale. Likewise, environmental characterizations have been carried out at different scales to efficiently define sampling localities that encompass the greatest environmental heterogeneity [18] and to analyze whether there is a relationship with areas of endemism [19]. At the regional scale, the climatic characterization of the Sierra Madre Oriental was carried out, and its relationship with floristic diversity was analyzed [20] as a surrogate for biodiversity in protected natural areas [21].

In this sense, multiple studies have considered climate as a substitute for biodiversity [11, 22 - 24]; therefore, knowing and describing the environmental characteristics within the arid and semiarid regions of Mexico is of great interest for understanding biological diversity. Therefore, the objective of this chapter is to perform a climatic characterization of the arid and semiarid zones of Mexico to identify geographical units with similar environments (domains) that allow an understanding of the climatic heterogeneity that exists in these environments.

The classification was developed to provide a spatially explicit delimitation of the climatic variables of the arid and semiarid zones of Mexico. It can be used in various management activities, such as identifying priority biodiversity areas for conservation, environmental monitoring, and assessment of risks associated with human activities. This chapter is intended to be a guide for users of the classification, and not just a brief description, mainly on the possibility of more detailed analysis as applied in other chapters of this book (Chapters 6, 11, 13, 14). It also addresses important concepts such as environmental heterogeneity, spatial errors, and the limitations of the classification itself when analyzing the phenogram, which is crucial for understanding the classification.

The classification has two main features. First, numerical data layers have been used to describe several fundamental aspects of the climate of Mexico's arid and semiarid zones. The second is the use of a computerized classification that allows grouping of similar environments based on their environmental characteristics, regardless of their geographic location. Since previous classifications have had some subjective elements, such as the selection of variables and the respective weighting of these, the present classification is less subjective in categorizing the arid and semiarid zones of Mexico [17]. These layers were interpolated in the topographic context of Mexico (slope and aspect), using the digital elevation model and temperature and precipitation data from about 5,500 meteorological stations as a base [25]. Some of these layers are available on the National

CHAPTER 2

The Arid and Semi-arid Regions of Puebla-Oaxaca and Querétaro-Hidalgo: A Look from the Physical-Geographical Perspective

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Abstract: The geological, geomorphological, and pedological elements that provide the framework for the development of life and biological diversity on Earth come from nature through its physical and geographical environment. This constitutes the most widely accepted definition of the concept of geodiversity. Proposed in the 1990s, this concept has gained relevance in the last decade as it seeks to establish relationships and interactions with various factors (biotic and abiotic) at different spatial and temporal scales. The firm intention is to seek answers regarding ecological dynamics, anthropic activities, and social processes. In this chapter, we offer a broad and general view of the different elements that make up geodiversity, focusing on the arid and semi-arid zones of central Mexico. Additionally, we provide a current overview of the importance of incorporating the physical-geographical environment and its potential for understanding ecological and environmental studies at any scale of work. The actualization of the knowledge of these regions' purposes is the understanding of their environmental dynamic, productive potential, diversity, strategies, and management proposals considering their fragility and susceptibility to climate change. Finally, we establish a physical-geographical comparison based on the similarities and differences between the Puebla-Oaxaca and Querétaro-Hidalgo regions, demonstrating that their different components and characteristics, based on geological history, provide valuable information for identifying numerous environmental services and social benefits that distinguish them from other regions. These studies are mainly based on abiotic factors and their direct relationships as the foundation for the development of the biotic environment.

Keywords: Geological diversity, Geological heritage, Geological history, Semi-arid zone.

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INTRODUCTION

The set of geological, geomorphological, and soil-related elements that provide the framework for the development of life and biological diversity on Earth comes from nature itself through the physical geographical environment. These elements constitute the most widely accepted definition of the concept of geodiversity, which is considered the equivalent of the concept of biodiversity today [1].

This concept, proposed in the 1990s, has gained relevance in the last decade. It aims to establish relationships and interactions with various factors (biotic and abiotic) at different spatial and temporal scales, with the firm intention of seeking answers regarding ecological dynamics, anthropic activities, and social processes [2].

On the other hand, the arid and semi-arid zones of Mexico cover a little more than half of its total surface area. This characteristic is associated with its geographical location, the direct influence of the global aridity belt, as well as orogenic and physiographic factors that determine significant climatic variety. These characteristics influence, to a greater or lesser extent, the formation and distribution of arid and semi-arid regions throughout the national territory.

Given the importance of arid, semi-arid, and dry sub-humid regions, it is extremely necessary to establish a detailed characterization of them in relation to their environmental components. Updating and increasing knowledge of these regions aims to understand their ecological dynamics, productive potential, and diversity, as well as to develop care and management proposals, considering their fragility and susceptibility to climate change.

Currently, both globally and in our country, arid and semi-arid zones are very important due to their role in human development and the ecological services they provide to society and living systems. When integrated, they define complex socio-ecosystems composed of physical-geographical, biotic, and socioeconomic components. In this way, the arrangement of these elements determines a structure and specific biophysical and anthropic processes that distinguish these regions from others.

However, moisture deficiencies and spatial-temporal heterogeneity make these zones highly vulnerable and fragile systems that easily lose their resilience, causing environmental deterioration that primarily manifests as increased desertification. This leads to decreased productivity, the production of goods and raw materials, loss of biodiversity, modification of water and nutrient cycles, and human migration. Additionally, these changes can result from natural processes such as earthquakes, erosion, and others, providing opportunities for anthropic activities to express themselves through the overexploitation of natural resources, changes in land use and management, agricultural and cultural practices unsuitable for the land, and landscape alterations due to mining activities.

Under this complex approach to the elements that make up geodiversity, this chapter aims to establish a comprehensive overview of the physical-geographical regionalization elements that give rise to the arid regions of south-central Mexico. Since, to a large extent, the configuration, distribution, and extent of these biomes are regulated by the very nature of the origin and geological history of Mexico, predominantly supported by stratigraphic and paleontological data from the last 600 million years.

Therefore, the states of Querétaro-Hidalgo and Puebla-Oaxaca, located in central Mexico, are notable for their contrasting, heterogeneous, and complex geological varieties that directly influence their climatic, soil, and biotic characteristics. These unique geological conditions have created dynamic forest ecosystems characterized by significant matter and energy exchanges, supporting high biodiversity and complex ecological interaction networks. The drylands of Central Mexico have historically demonstrated remarkable productive potential, providing substantial benefits to human populations for over 500 years. These benefits encompass significant mining and agricultural activities that have been fundamental to the growth and development of central Mexico´s population. Moreover, these regions continue to provide essential ecosystem services, including freshwater supply, food, and medicinal products, as well as fibers and construction materials. This ongoing contribution highlights their importance for both human development and ecological sustainability. The selection of these arid regions of Central Mexico was guided by the mission and fundamental principles of the UBIPRO project, which focuses on conducting interdisciplinary research on the abiotic components of Central Mexico´s drylands to promote sustainable natural resource utilization.

For the preparation of this chapter, an exhaustive investigation was conducted, including different bibliographic sources, consultations with specialists from various fields, the use of thematic cartography, satellite images from various platforms, and database consultations (Fig. **1**). Additionally, direct observations were made through field surveys, geological prospecting, territorial surveys, soil profile sampling, floristic listings, and meetings with residents, producers, and civil society organizations, as well as researchers from various public and private institutions. This information, largely generated by the authors themselves, forms the basis of this chapter.

PART 2
BIODIVERSITY - ANIMAL SECTION

CHAPTER 3

Ants from Mexican Arid and Semiarid Zones

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Abstract: Arid and semiarid zones are generally considered places that contain few species; however, a high diversity of ants has been recorded in these areas. These organisms exhibit morphological, physiological and behavioral adaptations in response to the extreme environmental conditions of these ecosystems. In this study, we focused on ants in the arid and semiarid zones of Mexico, where 286 species belonging to 54 genera and 8 subfamilies were identified. Analysis of an accumulation curve of the species that have been reported over the last 44 years in these areas indicates that we currently know approximately 50% of the expected species; therefore, there are still many unknown species because the species accumulation curve calculated by randomization is far from reaching an asymptote. Ant studies that have been carried out in Mexico cover different aspects, such as understanding the factors that affect the structure of ant communities, which are related to vegetation and soil variables. The activity patterns of some species as well as the interactions between ants and plants have been studied. Work has also been done on the registration and description of new species for these areas. Although the number of studies on ants in the arid and semiarid zones of Mexico has been increasing in recent years, there are still many gaps in the knowledge of these insects, especially in arid zones like the Northeast region of the country.

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Keywords: Ant community structure, Ant-plant interactions, Arid zones, Ants, *Camponotus*, Deserts, Distribution of ants, Diversity, Exotic ants, Formicidae, Functional groups, Invasive ants, Mexico, *Myrmecocystus*, *Pheidole*, *Pogonomyrmex*, Semiarid zones, Semideserts, Species accumulation curve, Tehuacán-Cuicatlán.

INTRODUCTION

It is often thought that few species live in arid and semiarid zones; however, these sites usually host great biodiversity [1]. A group of insects that are among the main components of arid zones are ants [2]. For example, in the Australian desert, up to 150 species of ants have been recorded in an area of less than one hectare [2], while in Deep Canyon, California, up to 59 species of ants have been recorded, with the arid zone of North America having the greatest species richness [1]. Arid and semiarid lands have harsh environmental conditions characterized by frequent high solar radiation, wide fluctuations in temperature, and low precipitation [3]. These environmental conditions impose severe restrictions that could limit the distribution and abundance of ants. Some ant species inhabiting these ecosystems have wide physiological tolerances and feeding habits [2, 4]. However, other species with low physiological tolerances and restricted feeding habits are also found in these habitats [5, 6]. The presence of species with low physiological tolerances strongly depends on the modification of physical factors, which in turn provide suitable conditions for their activity [5, 7, 8]. For this reason, the interactions of ants with their biotic and abiotic environments, such as the characteristics of the vegetation, interactions with other organisms, and the type of soil and rainfall regimes, may determine their distributions and abundances in these ecosystems [2, 9].

In addition to the characteristics of arid zones that are associated with the adaptations and distribution of different species, other aspects related to the evolution of socialization and colony organization have been recently documented, emphasizing the relevance of deserts. It has recently been proposed that arid areas are hot spots of complexity in ant colonies [10] since the probability of finding polymorphic species is greater in warm and very dry regions of the world, including deserts and tropical savannahs. Most polymorphic species are in hyperdiverse genera, such as *Camponotus* and *Pheidole*, which are very common groups in arid and semiarid areas of the world.

ANT ADAPTATIONS TO LIFE IN DRY AREAS

Desert and semidesert areas are ecosystems that represent complex adaptive scenarios for the ants that inhabit them. To survive under the selective pressures that these systems impose on them (extreme temperature and humidity, excessive sunshine, and ultraviolet radiation, among others), these insects have developed different adaptations and strategies that allow them to live in these environments [11].

Morphological Adaptations

Pigmentation and Hairiness

Nocturnal ants living in arid and semiarid ecosystems tend to possess dark colors, as well as large eyes and ocelli, while diurnal species have light coloration. Although not a universal pattern, this correlation between foraging schedules, eye size, and color has been found in some species of the genera *Myrmecocystus*, *Aphaenogaster*, *Temnothorax,* and *Veromessor* [12]. For hairiness, the most extreme case is presented by *Cataglyphis bombycina,* which has triangular hairs that allow it to reflect and dissipate some of the heat from sun rays [13].

Specialized Structures

The psamophore is a convergent structure in the genera *Pogonomyrmex*, *Myrmecocystus*, *Dorymyrmex* and in the species *Pheidole psammophila* and *P. barbata* [14]; it consists of a basket-shaped structure with modified long hairs, found on the ventral surface of the head and mandibles and on the anterior edge of the clypeus of some ant taxa from sandy habitats [15, 16]. The psamophore was shown to facilitate the transport of seeds and sand particles in dry ecosystems [12, 17].

Fast Scrolling

In African ants of the genus *Cataglyphis*, the ability to move quickly in hot, sandy soils was found to prevent death due to high temperatures [11]. These ants have a high stride frequency carried out by long legs, short and fast posture phases, and rocking movements to achieve high running speeds, together with a high synchrony of the legs that allows them to reach speeds of up to 855 mm/second, as in the case of *Cataglyphis bombycina* [18].

Specialized Castes

Polymorphism is the difference in size and scale of the head with respect to the ant's body that the workers of the same colony may have; it is generally related to the morphology and age of the workers, as well as of the colonies themselves [19, 20]. Two adaptations in the castes of some genera present in deserts require particular attention. The first adaptation is developed in honey ants of the genus *Myrmecocystus*. This genus has specialized workers called "repletes" which serve

CHAPTER 4

Avian Diversity in the Arid and Semiarid Regions of Mexico

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Abstract: The arid and semiarid areas of Mexico are complex natural systems influenced by the transitions between desert vegetation and other more humid, warmer, or higher-altitude environments. To describe the species richness and faunistic relationships in Mexican arid zones, we analyzed bird data from the Global Biodiversity Information Facility (GBIF). These records document these ecosystems, spanning 12 orders and 43 families. Among these species, 158 are resident and 151 are migratory or transient species. The distribution of records and species richness helped identify information gaps and revealed that species richness is greater than that estimated by previous studies. Moreover, there was strong similarity (*i.e.*, low species turnover) among the vegetation types, with no clear distinction among the chaparral, shrubland, and grassland bird communities. However, there were important differences when comparing records from polygons of the Important Bird Areas, revealing a clear distinction among the three regions. The first region corresponds to the northern half of the Baja California Peninsula and is distinguished mainly by species with restricted distributions. The second group includes systems in the southern half of the Baja California Peninsula, islands of the Gulf of California, and northwestern Mexico. The third comprises the environments of the Mexican Plateau and the Gulf of Mexico slope. This study highlights the importance of considering the complexity of interactions between vegetation and birds in the arid and semiarid regions of Mexico in the design of effective conservation strategies. It also identifies key areas for conservation in different regions of the country.

Keywords: Agricultural areas, Arid zone, Chaparral, Distribution limit, EBird, Ecotone, Grassland, Important Bird Area, Migratory bird, Resident bird, Spatial richness patterns.

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INTRODUCTION

The avifauna of the arid and semiarid regions of Mexico are strongly linked to the vegetation present in those regions, which arises from the interaction of geological, geographical, climatic, edaphic, and biogeographical factors [1]. In contrast to other regions of the planet located at the same latitude, where extreme aridity results in a predominance of deserts, Mexican arid zones contain a broad range of vegetation types [2], resulting in a complex mosaic of transitional zones between xeric environments and temperate forests, low and medium tropical forests, wetlands, and even coastal systems [3]. Their varied floristic assemblages combine annual plants with other features, such as succulent stems, reduced or absent leaves, and areas dominated by herbs, shrubs, or even tree elements [1, 4].

The environmental conditions and specialized vegetation of arid and semiarid zones constitute selection pressures for the rest of the biota. Regarding birds, some exhibit physiological and behavioral adaptations, such as reduced metabolism, decreased water loss, and hyperthermia [5]. They have also developed dietary plasticity to adjust to the unpredictability of resource availability, the need for shelter during peak solar radiation and low nighttime temperatures, and nomadism, among other traits [6, 7]. Consequently, not just any bird can venture into such extreme environments.

How Many Bird Species Inhabit Mexico's Arid Zones, and What Insights do they Provide into the Ecological Affinities of Mexican Biodiversity?

The research question we pose here seems simple but is not easy to answer. Many studies of “arid zones” have been conducted in locations adjacent to temperate or tropical forests or even wetlands, resulting in inventories that include species from other vegetation types as well as aquatic birds [8, 9]. Fortunately, significant efforts are underway to synthesize the information available about the birds of Mexico. For example, the Avesmx portal displays birds at the state level by biome and by Important Bird Areas [10]. However, given the country's biogeographical complexity, these listings include birds from a variety of environments. Another complication is that the classification of Mexico's arid zones varies according to the author, and some vegetative assemblages have no equivalent in the desert ecosystems of the United States [1, 4, 7].

An important precedent is the study of bird richness patterns by Navarro-Sigüenza and colleagues [11], who identified a maximum of 130 total species and up to 90 resident species in biogeographical provinces that contain concentrated arid environments. In the same study, total richness numbers ranging from 4 to 143 species were recorded for five types of shrublands (lowland arid, highland arid, humid/semihumid mountain, riparian, and secondary growth), whereas 25 and 48 species were observed in two types of grasslands (lowland and northern, respectively) [11]. Notably, this information was obtained through fundamental niche modeling based on specimen collections, literature, and recent field data. As the only study estimating richness components for the entire region, this study will serve as the primary reference for comparison.

AVIFAUNA IN DRY ENVIRONMENTS: AN ANALYSIS OF ARID AND SEMI-ARID ZONES

We focused this study on the species composition and richness of birds in arid environments. Over the past two decades, knowledge of wildlife, particularly birds, has been revolutionized by the creation of collaborative portals, such as eBird [12] and iNaturalist [13], where members of academia and civil society share their observations. The databases generated by these portals have grown exponentially in recent years, and their records are periodically integrated into the Global Biodiversity Information Facility (GBIF). We have used this powerful tool for the study of birds in Mexico's arid environments.

Data Source

Birds

We downloaded all of the bird records from Mexico from the GBIF [14], a total of slightly more than 10.5 million records. From these, we selected records that had georeferencing and species-level identification. We then removed records of domestic birds and exotic species (that were likely present due to escaping captivity) that were not established species in the country. From the resulting information, we obtained a single record per species per coordinate.

Study Area

The study area was delineated on the 'Land Use and Cover' map (Uso de Suelo y Vegetación) of the Instituto Nacional de Estadística y Geografía (INEGI) [3], selecting polygons that corresponded to arid and semiarid vegetation types, including chaparral, various types of shrubland, and xerophytic vegetation, along with their respective polygons of disturbed vegetation. For grasslands, only natural grassland vegetation was included.

Analysis Database

With the use of the QGIS [15], the study area model was intersected with the species/coordinate records. From the resulting map, aquatic birds were removed because their presence in these zones is due to the existence of floodable areas,

CHAPTER 5

Hummingbird (Aves: Trochilidae) Diversity in Arid Zones

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Abstract: Arid and semiarid regions cover a large part of the Mexican territory and are characterized by high temperatures and low precipitation. Several species of hummingbirds, including endemic species such as the Beautiful Hummingbird (*Calothorax pulcher*) and the Dusky Hummingbird (*Phaeoptila sordida*), inhabit these areas. Using citizen data from the GBIF, we estimated the taxonomic richness and abundance of hummingbirds in the Mexican arid zones. We created a grid with cells of 0.5° latitude by 0.5° longitude covering arid and semiarid areas. Subsequently, we calculated the richness and abundance for each grid. Additionally, we used the Jaccard dissimilarity index to estimate the hummingbird species turnover between adjacent cells along the grid. Finally, we estimated the degree of association between hummingbirds and arid and semiarid areas. To achieve this goal, we calculated the geographic area that each hummingbird species occupies within Mexico and subsequently calculated the proportion of this area that is found within the arid zones of the country. We found 22 species in arid and semiarid zones, with most records corresponding to the Broad-billed hummingbird (*Cynanthus latirostris*), while the Beautiful Hummingbird (*Calothorax pulcher*) was less abundant. The arid and semiarid zones of Mexico have a high species richness of resident and migratory hummingbirds that increases from north to south. The areas with the highest species richness were Guanajuato, Querétaro, Hidalgo, and Puebla. However, no information on hummingbird records was available for 25.9% of the cells. Within the arid and semiarid regions of the country, there is a great turnover of hummingbird species, which reflects the complexity and ecological heterogeneity of these regions. Finally, the degree of association between the hummingbird species and the arid zones presented a great amplitude. This association gradient includes species with total dependence and species that sporadically use these areas. These results highlight the biological relevance of these regions for the conservation of resident and migratory hummingbirds. However, some areas, particularly in northern Mexico, lack records. In these areas, it is important

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to implement strategies to promote research and citizen science focused on filling these knowledge gaps.

Keywords: Arid and semi-arid regions, Citizen science, Jaccard Dissimilarity Index, Mexico, Species composition, Species turnover.

INTRODUCTION

Arid and semiarid regions cover approximately 41% of the global surface area [1]. These areas are characterized by high temperatures, extreme drought, and sparse vegetation cover [2]. One of the most widespread types of vegetation coverage in arid and semiarid regions of Mexico is xerophytic shrub [3]. This vegetation predominates in the northern part of the country, almost entirely representing the vegetation of Baja California and Baja California Sur; large areas in the states of Sonora, Chihuahua, and Coahuila; and, to a lesser extent, in Central Mexico, in the states of Puebla and Oaxaca, among others [3]. This vegetation comprises plant species adapted to low availability of water, notably cacti and legumes with numerous spines [3]. Some typical plants of arid scrubs are extensively visited by hummingbirds. For example, many columnar cacti and *Agave* spp., although not adapted for bird pollination, are visited by these birds. Additionally, species such as ocotillos (*Fouquieria* spp.), which have bird pollination syndromes, are visited by hummingbirds in these regions [4].

The arid regions of Mexico are home to several hummingbird species, including some endemic species, such as the Beautiful Hummingbird (*Calothorax pulcher*) and the Dusky Hummingbird (*Phaeoptila sordida*), as well as widely distributed species, such as the Broad-billed Hummingbird (*Cynanthus latirostris*) and the Buff-bellied Hummingbird (*Amazilia yucatanensis* [5]). Additionally, several latitudinal migratory hummingbird species, such as the Rufous Hummingbird (*Selasphorus rufus*), Allen's hummingbird (*S. sasin*), and the Black-chinned Hummingbird (*Archilochus alexandri*), use these corridors during their migration [4]. It was reported that the Rufous Hummingbird utilizes migratory corridors within the Sonoran Desert, feeding on the flowers of ocotillos and Boojum trees (*Fouquieria diguetii, F. macdougalii*, and *F. splendens*), palo blanco (*Ipomoea arborescens*), and chuparosa (*Justicia californica* [4]).

Unlike other birds, the survival of hummingbirds (Trochilidae) depends on the availability of the nectar produced by flowers [6]. Even the migratory movements of hummingbirds are synchronized with the flowering season of plants [7]. Due to the mutualistic relationships that hummingbirds establish with some plants that have diversified in these regions (*e.g.*, *Agave* spp, Cacti), we expect that arid areas will have a high richness of hummingbird species. In this chapter, we examined the patterns of taxonomic richness of hummingbirds distributed in Mexico's arid zones. Additionally, we estimated the dissimilarity in species composition within these arid regions and assessed the degree of association of hummingbirds with these areas.

METHODS

We determined the patterns of taxonomic richness and abundance of hummingbirds distributed in the arid zones of Mexico through the analysis of available biological records from the Global Biodiversity Information Facility (GBIF). We downloaded a database containing the presence records of the 59 hummingbird species found in the country (https://doi.org/10.15468/dl.6a4szg). This database was curated using the 'rgbif' package [8]. Posteriorly, we included only species that met the following criteria: 1) the species' biological records were aggregated within one of the polygons that define the arid zones of the country, and 2) the species had more than 15 records within Mexico's arid zones. These criteria allowed us to verify the geographic continuity of the records of the presence of each hummingbird species and avoid the inclusion of accidental records or misidentifications. We used a geographic information system [9] to ensure that these criteria were met.

To determine the patterns of richness and abundance of hummingbirds, we projected a grid with cells of 0.5° latitude by 0.5° longitude covering the entire extent of Mexico's arid zones (420 cells; Fig. **1**). We then projected the biological records of each hummingbird species that met the criteria onto this grid. Additionally, we calculated the number of hummingbird records in each cell to obtain a surrogate measure of the abundance of each hummingbird species. Finally, we grouped the hummingbirds according to their clade [10] and projected these biological records onto the grid to determine if species from any clade had a greater presence in the country's arid zones.

To estimate species turnover within the arid zones, we obtained the species composition for each of the 420 cells. Subsequently, we calculated the Jaccard dissimilarity index between adjacent cells following the order of cell numbering (Fig. **1**), starting with the comparison between cell 1 and cell 2 and ending with the comparison between cell 419 and cell 420. We only made comparisons between adjacent cells with data; that is, if a cell had no biological records of hummingbirds, the cell value was left empty, and no comparison was made with the adjacent cell. The Jaccard dissimilarity index ranges from 0 to 1, with values close to 1 representing high dissimilarity between cells. We estimated the Jaccard dissimilarity between each pair of adjacent cells using the 'betapart' package [11] in R v.3.5.3 [12].

PART 3
BIODIVERSITY - PLANT SECTION

CHAPTER 6

Cactus Diversity in Arid and Semiarid Regions of Mexico

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Abstract: Cacti are the most ubiquitous plants in the arid regions of the American continent and Caribbean Isles. Nearly 1427 taxa of cacti, which mainly inhabit the southern USA, Mexico, and South America, have been recorded. Since Mexico has 700 cactus species, 517 of which are endemic, this country is considered to be globally rich in cacti. In this chapter, we analyzed the number and distribution of cactus genera and species in 15 climatic domains. All available records for cactus species were downloaded from the GBIF website and manually curated to create a derived database containing individual records with coordinates and the scientific names of native taxa. This curated database contained 124789 records, which were mapped onto the 15 climatic domains to construct a binary matrix composed of genera and species. We estimated β diversity (βJ) to compare turnover in species composition among domains. We documented a total of 64 genera with 654 species, 78.6% of which were distributed in some of the 15 climatic domains. The number of genera and species were positively correlated (r^2=0.92, p<0.05). Domain 15 contained the highest number of genera (40) and species (214), while the lowest numbers were documented in domains 1 (13 genera) and 18 (35 species). Among the 15 domains, the genera with the highest number of species were *Mammillaria* (129), *Opuntia* (62), *Echinocereus* (51), and *Coryphantha* (44). The mean value of βJ was 0.83, indicating high variation in species composition among the domains.

Keywords: Arid zones, Beta diversity, Cactus, Caryophyllids, Chihuahuan Desert, Climatic domain, Diversity, Peninsula of Baja California, Sonoran Desert, Tehuacán-Cuicatlán Valley.

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INTRODUCTION

Cacti are the (Fig. **1**) flowering plants that are most emblematic of arid and semiarid American environments. Cactaceae Juss. (Caryophyllales) records nearly 1427 taxa grouped into 124 genera, most of which are native to the continental lands of America [1], except for the Mistletoe Cactus *Rhipsalis baccifera* (J.S.Muell.) Stearn that has natural populations in tropical areas of Africa, Madagascar, and tropical America [2]. Accordingly, the presence of cacti in distinct regions of the world is not natural; they were transported to these regions by humans [3]. Since cacti are not woody plants, fossil records are lacking for these plants (*cf* [4]); for this reason, their origin was estimated to be 35 Mya based on molecular phylogenies [5], placing this family as the youngest of the order Caryophyllales [6]. Since Cactaceae represents the most recent family within Caryophyllids, it has been proposed that the current high cactus diversity was induced by a past global climatic temperature increment that promoted rapid and abundant diversification during the last 8 My [5, 7, 8].

Fig. (1). View of hills densely covered with columnar cacti in the locality of Dam of Zimapán, Hidalgo, Mexico (photograph courtesy of Sofía Solórzano).

Presently, Cactaceae has its highest levels of diversity in a few arid and semiarid regions distributed in Argentina, Bolivia, Brazil, and Mexico, as well as in three southern American states of the USA (Arizona, Nuevo Mexico, and Texas) [1, 9]. However, the highest degree of cactus richness in the world has been recorded in Mexico [9], and some authors have estimated that up to 850 cacti taxa are present [10]. In contrast, other studies reported 700 species, 517 of which were endemic to Mexican territories [11]. In Mexican arid and semiarid regions, up to 19-22 genera per square kilometer are recorded [9]. Based on an assessment of cactus diversity, seven principal centers were identified, four of which were located in Mexico. These four centers included 542 species grouped into 100 genera, and the Chihuahua Center included 64.73% of the species (367) and 43 genera, followed by the Puebla-Oaxaca Center, which included nearly 3.43 times fewer species (107 species) and only 27 genera [9]. Previous studies have shown that 324 Chihuahuan Desert species are grouped into 39 genera [12]. In contrast, in the Tehuacán-Cuicatlán Valley (in part Puebla-Oaxaca Center of [9]), which is the southernmost arid region in the Mexican territory, only 81 cacti species were previously reported [10].

Recently, the arid region of the Mexican Plateau (in part the Chihuahuan Desert) was identified as the center of origin and diversification of various modern genera of small globose cacti. During the last 4.5 My in this region, a high level of dispersal has occurred, together with abundant diversification that allowed colonization within and outside of this region [8]. Many studies have investigated Mexican cactus diversity, mostly from a local perspective. In this chapter, we followed the climatic classification of the arid and semiarid regions presented in another chapter of this book [13] to assess the taxonomic diversity (*i.e.*, genera and species) across 15 climatic domains covering mostly the arid and semiarid territories of Mexico. In addition, we estimated the rate of dissimilarity as well as the beta diversity in species composition across the 15 climatic domains.

DATABASE AND STATISTICAL ANALYSIS

For this study, we derived a database for native Mexican cactus taxa based on available coordinates and their associated scientific name. For this purpose, 184462 records for cacti reported in Mexico were downloaded from the GBIF website [14]. These records were manually curated, and 33243 of these records were discarded because they lacked species names or had incorrect geographical information. Accordingly, we recovered 151219 records, from which were eliminated hundreds of duplicated records or data of nonnative taxa, as well as records from private collections and public botanical gardens. In addition, also the geographical coordinates were curated to identify confident records following the

PART 4

SECONDARY METABOLITES AND BIOTECHNOLOGICAL RESOURCES

CHAPTER 7

Medicinal Flora and their Specialized Metabolites of Arid and Semi-Arid Areas of Mexico

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Abstract: This chapter compiles ethnobotanical records of medicinal flora in arid and semiarid zones of Mexico, covering 18 Mexican states. Phytochemical studies have been conducted on specialized metabolites of some species that, in some cases, attribute their medicinal properties. The flora compilation includes the scientific name, botanical family, popular name, and medicinal use. This review identified 691 records corresponding to 331 registered species, 219 genera, and 72 families. The five families with the highest numbers were Asteraceae (103), Fabaceae (40), Cactaceae (28), Euphorbiaceae (26), and Solanaceae (24). Popular nomenclature is recognized in 371 names in Spanish and/or indigenous languages. The plant most commonly mentioned is árnica (*Grindelia inuloides*), and some of its variants include árnica amarilla (*Haplopappus spinulosus*), árnica morada (*Xanthisma gymnocephalum*), and árnica silvestre (*Adenophyllum aurantium*). It is common for popular names to be related to the colors, chemical compounds, and/or biological forms of plants. The record of herbal resources associated with the illnesses grouped into systems shows that 122 species are used to treat digestive system conditions, whereas 61 species cure dermatological conditions. The states with the highest numbers of records were Aguascalientes, Puebla, and Sonora. Regarding specialized metabolites, studies have focused on phenolic compounds and terpenes in organic extracts. Mono- and sesquiterpenes are present in essential oils. Some species also have notable alkaloid

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contents. This chapter provides valuable information about the bioactive principles of plant-based medicinal resources in arid and semi-arid regions and demonstrates the therapeutic potential of Mexico's resources.

Keywords: Ethnobotany, Medicinal plants, Alkaloids, Terpenes, Flavonoids.

INTRODUCTION

Arid and semiarid zones cover approximately 60% of Mexico's territory [1]; these regions are characterized by low or deficient water supplies, resulting in a water deficit due to low atmospheric humidity. Arid zones typically receive an average annual precipitation of 250 mm or less, whereas semiarid zones receive between 250 and 500 mm annually. In these regions, evaporation exceeds annual rainfall [2].

The arid and semiarid Mexico zones include nine distinct regions: Sonoran, Chihuahuan, Hidalgo, Puebla, Tamaulipas, Guerrero, Tehuantepeca, Veracruz and Yucatecan [3]. A characteristic of these regions is their biological and cultural diversity; for example, approximately 50% of the flora is endemic [4]. Mexico has a great wealth of vascular plants, estimated to include 21,073 to 23,424 species, of which approximately 4,000 plants have medicinal attributes, constituting 15% of the total Mexican flora [5]. The bioactive compounds of numerous plant species within these arid and semiarid zones are often synthesized in response to climatic conditions [6].

Medicinal plants are rich in specialized metabolites (SMs), also referred to as secondary metabolites, which serve as active compounds that provide therapeutic properties [7]. SMs have been classified as phenolic compounds, alkaloids, terpenes, and pigments. Traditionally, SMs in plants are recognized for their roles in defense and adaptation to different types of stress, including biotic factors such as herbivory, allopathy, and attack by microorganisms, as well as abiotic factors such as UV light, drought, and salinity. However, it has been shown that the role of SMs in plants is crucial for processes such as adaptation, symbiosis, and the regulation of growth and development, and they participate integrally in plant metabolism [8].

Ethnobotanical Information on Medicinal Flora in Arid and Semiarid Areas

This chapter compiles information on the ethnobotanical records of medicinal flora reported in 18 states of the Mexican Republic [9 - 28] (Fig. **1A**). In this review, a total of 691 records were obtained and organized into a database including the scientific name, family, popular name, medicinal use, and federative entity. The database can be consulted in Appendix **F**.

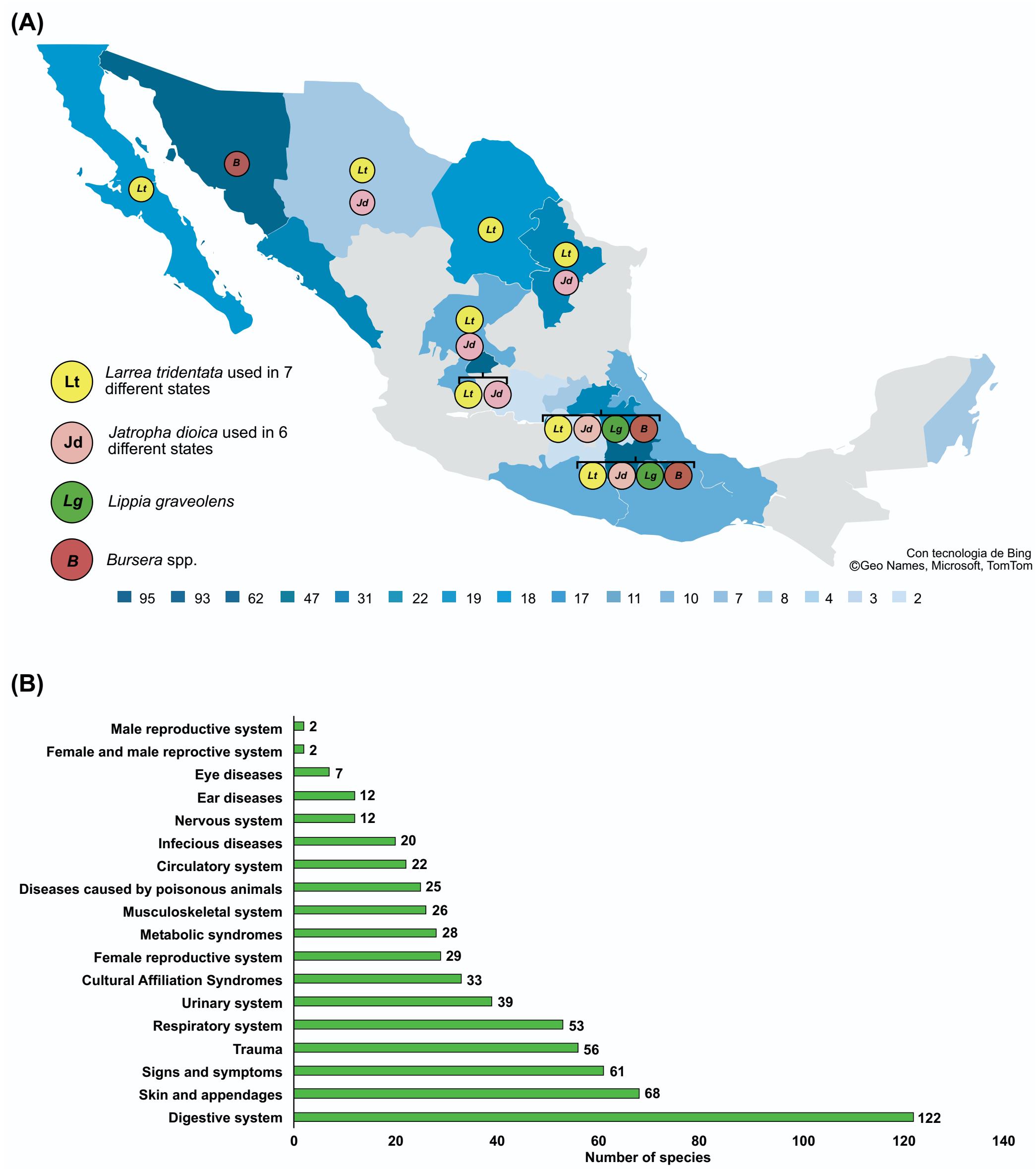

Fig. (1). Medicinal species plants registered in the database. A. Number of species by federative entities. Species with the highest number of mentions in the arid zones of Mexico are showing with rose and yellow circles. Signs and symptoms refer to pain, fever, and other discomforts not associated with a particular organ or system. Created in BioRender. Álvarez-Santos, N. (2024) https://BioRender.com/c18x885.

CHAPTER 8

Antimicrobial Properties of Eugenol in *Euphorbia* Species from Mexican Arid Zones

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Abstract: Owing to its privileged biogeographical location, Mexico has an incomparable wealth with other regions of the world. This location has allowed for the development of various ecosystems, and drylands have been particularly important for plant diversity. Within this taxonomic richness, the family Euphorbiaceae has been highlighted due to its ecological and medicinal importance. This chapter explores the antibacterial properties of eugenol. It has been reported that this compound is present in some *Euphorbia* species, focusing on its antimicrobial activity in performed experiments. Comprehensive research has been conducted on this compound regarding its antimicrobial, anti-inflammatory, antioxidant, and anticancer properties. In this study, eugenol showed potential activity against microbial infections; it also showed activity for avoiding the development of biofilms and an increase in antimicrobial resistance when used in combination with antibiotics. In this case, the tested antibiotics were cefuroxime and cefepime. Previous studies have shown that eugenol, when combined with antibiotics, can produce sensitivity in *Staphylococcus aureus*-resistant strains, producing a significant reduction of the minimum inhibitory concentration (MIC). The MIC value was found to be between 125 and 1000 µg/mL. Eugenol can also initiate the apoptosis process and stop the cellular cycle process; in this regard, it was also found that eugenol at relatively low concentrations can inhibit the synthesis of biofilms in the evaluated microorganisms. This chapter details the characteristics and plant diversity of arid areas in Mexico, examines the traditional uses of *Euphorbia* in medicine, and highlights the potential medical benefits of its extracts and secondary metabolites, as well as some pharmacological properties of eugenol. More research is needed to understand the safety and efficacy of *Euphorbia* products given their diversity and endemism in Mexico.

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Keywords: Antibacterial, Antibiofilm, Antibiotics, Antifungal, Arid zones, Biofilm, Carvacrol, Cefepime, Cefuroxime, Essential oils, *Euphorbia*, Euphorbiaceae, Eugenol, Farnesol, Medicinal plants, Mexico, Molecular docking, Phenolic compounds, Secondary metabolites, Terpene.

ARID ZONES IN MEXICO

An estimated 43% of the world's emerging areas are arid and semiarid regions. These deserts cover large areas of the Americas, with an estimated one-third of North America's land area being arid or semiarid [1].

Several articles discuss the environmental diversity of Mexico and highlight discoveries in the so-called "arid zones", but initially, we must define this type of environment.

References in environmental classification worldwide are somewhat outdated, and classifications such as the one proposed by Cloudsley-Thompson in 1979 [2] are considered to classify zones depending on the amount of precipitation reported in millimeters (mm):

- Extremely dry areas—0 to 100 mm;
- Arid zones—100 to 250 mm;
- Semiarid zones—250 to 300 mm.

However, these values are somewhat relative because aridity does not depend solely on rainfall; it is also influenced by the annual temperature and the type of vegetation characteristic of the environment, which is responsible for retaining moisture and providing orographic shade.

The most widely used definition is the one proposed by Rzedowski in 1968 [3], in which arid zones are described as regions where the water supply is poor; their humidity and atmospheric precipitation values are usually below the annual global averages.

However, evaluating these types of definitions at the global level is important because of the climate changes experienced in recent years, and because of human activity, drastic environmental changes that modify the environmental values of different regions have been unleashed.

Once the concept of arid zones has been defined, the statistics of this type of environment in Mexico must be identified.

Arid zones cover just over 50% of the national territory, and five regions have been identified, each of which has a different classification according to its characteristic vegetation:

- Sonoran arid zones;
- Chihuahua arid zone;
- Tamaulipas semiarid zone;
- Hidalgoan semiarid zone;
- Poblano–Oaxacan semiarid zone.

Floristic Diversity in the Arid Regions

According to several authors, most floristic vegetation in the Mexican arid zones is of tropical origin, and the genera are classified depending on the region of origin [1, 4]:

- Pantropical: *Acacia*, *Mimosa*, *Euphorbia*, *Hibiscus*, *Buddleja*, *Rhus*, *Cassia*, *Boerhavia*, *Jatropha*, *Aristida*, *Croton*, *Panicum*, *Ipomoea*, *Commelina*, *Heliotropium*, and *Prosopis*, among others;
- Dry tropics (hot and dry) —*Ephedra*, *Peganum*, *Lycium*, *etc*.;
- Neotropical (warm parts of North America) —*Calliandra*, *Bursera*, *Zexmenia*, *Verbesina*, *Flaveria*, *Perezia*, *Dyssodia*, and *Tillandsia*;
- Common in the arid areas of southern America—*Larrea*, *Castela*, *Prosopis*, *Flourensia*, *Opuntia*, *Ximenia*, *etc*.;
- Of Mexican origin (groups that evolved in Mexico or neighboring areas): *Agave*, *Hechtia*, *Fouquieria*, *Yucca*, *Cercidium*, *Sartwellia*, *Zaluzania*, *Leucophyllum*, *Mortonia*, *Dasylirion*, *Rzedowskia*, *Neoeplingia*, *Villadia*, *Zinnia*, *Simmondsia*, and *Olneya*, among others;
- Boreal affinities—*Penstemon*, *Berberis*, *Antirrhinum*, *Castilleja*, *Oenothera*, and *Haplopappus*.

Plant Resources

These regions have been inhabited since ancient times by different ethnic groups, some of whom were nomadic or seminomadic, and others were sedentary, especially in northern, central, and southern Mexico. They have met their needs in one way or another through the natural resources available in different regions [1].

Traditionally, the rural population, especially indigenous peoples, has always had a very broad knowledge of the surrounding natural resources, especially plants. In some regions, some of this knowledge has been lost because of the acculturation process, but much of the information is still recovering slowly.

PART 5

MANAGEMENT OF SOCIO-ECOLOGICAL SYSTEMS

CHAPTER 9

Participatory Territorial Planning: A Knowledge Management-Based Tool for Socioecological Analysis in Arid Zones

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Abstract: This chapter examines participatory land use planning as a knowledge management tool for socioecological analysis in arid zones. It underscores the deep interdependence of social and ecological systems, advocating for an integrated management approach to tackle the complex challenges inherent in these environments. This approach is especially critical in Mexico's arid and semiarid regions, where the convergence of ecological fragility and social vulnerability makes sustainable management a pressing necessity. The Knowledge Management (KM) model is operationalized through the establishment of Citizen Science Nodes, which serve as platforms for collaboration among local stakeholders, academic researchers, and government agencies. These nodes enable a more inclusive and informed decision-making process by integrating diverse perspectives and various knowledge systems. The KM model uniquely merges traditional, locally rooted knowledge with contemporary scientific insights, fostering a comprehensive approach to community territorial planning to ensure thorough analysis and planning. Participatory methodologies, such as social mapping and community workshops, are employed. Accordingly, in this chapter, the construction process of an analytical model is derived from three case studies carried out in the Mixteca Poblana region and the accumulated field experience during the past nineteen years. In this model, traditional agricultural

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practices and ancestral knowledge are key factors in achieving ecological sustainability. Additionally, this chapter addresses modern challenges such as urbanization and globalization, which have a significant impact on the resilience of complex socioecological systems. The main findings suggest that integrating a socioecological approach with effective knowledge management not only strengthens community participation but also enhances resilience, offering a highly adaptable framework for sustainable natural resource management in arid zones.

Keywords: Arid zones, Climate change, Community participation, Community Territorial Planning, Ecological resilience, Geographic information systems, Interdisciplinary collaboration, Land use, Mixteca Poblana region, Natural resource management.

INTRODUCTION

In recent years, there has been a formal and growing recognition of the interconnection between social and ecological systems. This understanding has led to the conceptualization of socioecological systems, which emphasize the dynamic and reciprocal relationship between human activities and the natural environment.

Socioecological systems are complex networks of interactions between social and ecological components, where changes in one system can have cascading effects on the other. This perspective challenges the traditional view of human societies and ecosystems as isolated entities, underscoring the need to understand and manage them as integrated or coupled systems [1].

The incorporation of the concept of socioecological systems into the study of arid and semiarid zones has significant implications for understanding the functioning of many territories in Mexico, which are characterized by ancestral, complex, and unique ecological and sociocultural dynamics. These dynamics are closely linked to the use and management of natural resources such as water, land, and biodiversity [2].

Structurally, the socioecological systems of arid and semiarid zones in Mexico are shaped by various factors, including cultural practices, economic activities, governance structures, and external drivers such as globalization and climate change. Functionally, the interdependence between the social and ecological systems in these areas leads to a context of low resilience and high ecological and social vulnerability.

To guide territorial development toward sustainability models, a comprehensive and integrated approach that considers the social and ecological dimensions of the territories, as well as the participation of various actors and interest agendas, is required. This is crucial for gaining a more in-depth understanding of both challenges and opportunities related to developing effective policies and interventions that promote resilience, improve ecosystem services, and benefit the quality of life in communities. It is a priority to recover, revalue, and link traditional knowledge systems with other forms of knowledge to guide decision-making processes and strengthen the determination of their territorial development objectives [3].

According to this framework, territories are considered not only physical spaces but also social constructions shaped by historical, cultural, political, and economic dynamics. Therefore, any analysis of arid and semiarid zones must consider the sociocultural context to fully understand the complexities and challenges associated with sustainability in these areas.

The adoption of a knowledge management (KM) perspective that integrates territories as socioecological systems in arid and semiarid zones can enable an understanding of the complex interconnections among social, ecological, and cultural factors that influence sustainability in these regions [4]. In addition, this perspective emphasizes the recognition and respect of community rights and land tenure systems, as well as the dynamic relationship between the conservation and use of biodiverse areas. Overall, this perspective informs an alternative framework for a comprehensive approach (theoretical-methodological and operational) to the research-action-co-management of socioecological systems in arid and semiarid zones.

Understanding the Territory: Definitions and Implications

The concept of territory encompasses much more than the delimitation of a geographic area under the authority of a governmental entity. It is especially relevant in socio-ecological contexts and sustainability studies in arid and semiarid regions, where the interaction between social, economic, and environmental factors is complex and crucial for the survival and development of human communities. In these areas, the scarcity of water resources is a determining factor that poses significant challenges to local populations [5]. Therefore, the understanding of the territories in these regions goes beyond political limits to include both the physical space and the human and natural systems that compose it. This holistic approach recognizes that territorial dynamics are intrinsically linked to human adaptation, economic viability, and environmental preservation.

The sustainable management of these territories implies the development of strategies that prioritize human needs together with the conservation of the environment. This not only guarantees equitable access to limited water resources

PART 6
ECOLOGY AND EVOLUTION

CHAPTER 10

State and Transition Models as Useful Tools for Understanding Vegetation Change in Mexican Deserts and Semideserts

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Abstract: State and transition models are proposed to explain changes in vegetation in deserts and semideserts. These models provide a framework for organizing complex ideas about the multiple ecological processes and management practices that drive vegetation change. However, these models have not been used to study vegetation change in the Mexican deserts and semideserts, although these ecosystems occupy approximately 50% of the country's land area. The aim of this chapter was to describe the use of state and transition models for studying vegetation change in the Mexican deserts and semideserts. To achieve this goal, we first provide an overview of state and transition models. We then describe the use of state and transition models for different deserts and semideserts around the world. Finally, we use empirical evidence to illustrate the use of state and transition models to study vegetation change in the fluvial terraces of the Zapotitlán Salinas Valley, a semidesert located within the Tehuacán-Cuicatlán Valley. The state and transition models for fluvial terraces had different states: abandoned crop fields with weeds, abandoned crop fields with mesquite, closed mesquite shrubland, open mesquite shrubland, and badlands. The transitions between these states were related to the decrease in canopy cover and visual obstruction caused mainly by rained agriculture and firewood extraction. We hope that this chapter encourages the use of state and transition models to elucidate vegetation changes in Mexican deserts and semideserts.

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Keywords: Asteraceae, Fine-textured soils, Firewood extraction, Fluvial terraces, Grazing, Leguminosae, Mexico, *Prosopis laevigata*, Rainfed agriculture, Semideserts, Tehuacán-Cuicatlán Valley, Vegetation change, Vegetation cover, *Viguiera dentata*, Zapotitlán Salinas Valley.

INTRODUCTION

Vegetation change in deserts and semideserts depends on biological and physical factors that differentially affect the natality and mortality of plant species that compose the vegetation. Biological factors can include seed production, herbivory, competition, and facilitation. Physical factors can include rainfall, fire, erosion, and perturbations caused by management practices [1].

Different models have been proposed to explain vegetation change in deserts and semideserts. However, two widely known models are the successional model and the state and transition model [2, 3]. The successional model is based on Clements's theory of succession. This model assumes that vegetation changes along one axis, defined by succession, grazing intensity, and rainfall variability until a single climax plant community or stable state is reached [2, 3]. Empirical evidence, however, has shown that this model has low prediction capacity; thus, it was replaced by the state and transition model. The state and transition model assumes that vegetation changes along several axes defined by physical (fire, erosion, rainfall) and biological (species and growth form composition, spatial distribution of vegetation) factors, and management practices (grazing intensity), until multiple plant communities or stable states are formed [2, 3]. The state and transition model provides a framework for organizing complex ideas about the multiple ecological processes and management practices that drive vegetation change.

Studies on vegetation change in Mexico are especially important because deserts (Sonoran and Chihuahuan deserts) and semideserts (Querétaro-Hidalgo and Tehuacán-Cuicatlán Valley) occupy approximately 50% of the country's land area [4]. Furthermore, these deserts and semideserts have a high biological diversity that includes cacti [5], ants [6], and birds [7], among other organisms. These deserts and semideserts differ in their physical and biological conditions and management practices [8]. The Sonoran and Chihuahuan Deserts are located in northern Mexico and are affected mainly by atmospheric circulation patterns and cold ocean currents. The mean annual precipitation ranges between 50 and 400 mm, and most rainfall occurs during summer, although it also occurs during winter. The main vegetation is characterized as xeric shrubland [4], and the main management practices are extensive livestock grazing and irrigated agriculture [9]. In contrast, the Querétaro-Hidalgo and the Tehuacán-Cuicatlán Valley semideserts are located in central Mexico, which are in the rain shadow zone of the Sierra Madre Oriental and the Sierra Madre Occidental mountain ranges. The mean annual precipitation ranges between 400 and 900 mm, and rainfall occurs only during summer. The main vegetation is characterized as xeric shrubland [4], and the main management practices are subsistence agriculture, transhumance grazing, and firewood extraction [9].

Differences in physical and biological factors and management practices between Mexican deserts and semideserts may have different effects on vegetation change; hence, it is necessary to study these effects with state and transition models to understand vegetation change. The state and transition models have been widely used in Australia, Argentina, and the USA to study vegetation change in deserts and semideserts [10, 11]. However, these models have not been used in the Mexican deserts and semideserts despite their large surface area and high biological diversity [5 - 7]. The aim of this chapter was to describe the use of state and transition models for studying vegetation change in the Mexican deserts and semideserts. To achieve this aim, we first provide an overview of the state and transition models. We then describe the use of state and transition models for different deserts and semideserts around the world. Finally, we use empirical evidence to illustrate the use of state and transition models for studying vegetation change in the Zapotitlán Salinas Valley, a semidesert located within the Tehuacán-Cuicatlán Valley.

We hope that this chapter encourages the use of state and transition models to elucidate vegetation changes in Mexican deserts and semideserts.

OVERVIEW OF STATE AND TRANSITION MODELS

The state and transition models are diagrams and synthetic descriptions of vegetation change in ecological sites with particular climate, vegetation, and soil conditions [11 - 13]. These models describe the natural events, ecological disturbances, and management practices driving vegetation change. The models can be theoretical, empirical or a combination of both, and different types of information can be used for their construction, such as historical data on management practices and vegetation change, empirical knowledge from peasants, ecological knowledge from researchers, and data from ecological experiments performed at ecological sites [11 - 13].

The state and transition models can include five elements: community phases, states, community pathways (also known as transient dynamics in [11]), transitions (also known as slow variables and triggers in [11]), and restoration pathways (Fig. **1**) [13]. Community phases are types of plant communities that can occur over time at a given ecological site. States are groups of community phases with species compositions, plant functional groups, and rates of ecological

CHAPTER 11

Functional Characters of Nurses and their Effect on Diversity in Semiarid Environments

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Abstract: Facilitation by nurse plants is one of the most commonly reported interactions and is considered a crucial factor in structuring plant communities, especially in arid and semi-arid ecosystems. This study is based on a comprehensive review of articles published between 1996 and 2023, aiming to select the main morphological characteristics of nurse species in these environments that are deemed most important in the beneficiary-protected interaction. From this review, we analyze this relationship from a functional perspective. This perspective allows taxonomically different species to be classified into groups that respond similarly to environmental conditions. Our hypothesis suggests that some species share morphological traits that can modify environmental conditions in various ways, potentially reducing the dimensionality of the study of interactions between pairs of species in these ecosystems. The most relevant characteristics are related to the improvement of microclimatic conditions, the decrease in herbivory, and the increase in nutrient availability in soil. Understanding these dynamics is essential because these studies help identify the main limitations of species regeneration and establishment in arid and semi-arid environments. Additionally, this information can be crucial for the conservation and restoration of these vulnerable ecosystems and provides a solid foundation for future research and environmental management strategies.

Keywords: Biodiversity, Coverage, Facilitation, Functional groups, Semiarid environmental.

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INTRODUCTION

Facilitation is one of the positive plant-plant interactions that strongly influence the biodiversity, structure, and dynamics of plant communities. Facilitation mechanisms by nurse plants can simultaneously produce competition for resources or allelopathy and create cascading effects, forming a complex of interactions. In addition, they can determine the spatial patterns of the community, allowing coexistence and improving diversity and productivity, which in turn has an impact on community dynamics [1, 2]. The nurse effect has been studied in various types of ecosystems [3]. In arid and semi-arid environments, the effect of facilitation is a crucial component in historical processes and is responsible for the composition and diversity of different plant communities [3, 4]. Species that act as nurses can generally reduce fluctuations in humidity and temperature, thus maintaining lower temperatures and higher humidity compared to open spaces, and produce modifications in nutrient concentration, protection against herbivores, and increased visitation by pollinators [2, 3].

These arid and semi-arid environments are characterized by extreme temperatures, low availability of nutrients in the soil, and atmospheric humidity and precipitation amounts below the annual world average. In Mexico, arid areas receive less than 250 mm of annual precipitation, while semi-arid areas receive between 250 and 500 mm [5, 6]. Therefore, water scarcity is the main problem. These are fragile ecosystems and the vegetation in these areas grows very slowly. Consequently, it can take years to restore [7]. Species that act as nurses can generally reduce fluctuations in humidity and temperature, thus maintaining lower temperatures and higher humidity compared to open spaces, and produce favorable modifications in nutrient concentration, protection against herbivores, and increased visitation by pollinators [2, 3].

Studies of Nurses in Arid and Semi-arid Environments Around the World

A bibliographic review was carried out using a Scopus search. Only those works that record the nurse-protected relationship for arid and semi-arid environments were considered. The keywords used to carry out the bibliographic search were “nurse,” “facilitation,” “beneficiary species,” “semi-arid and arid environment,” and “positive-positive interaction,” in addition to combinations of these words. Studies considered were those published in world-class high-impact and/or specialized journals. In the period from 1996 to 2023, a total of 280 records were obtained. However, for this chapter only those studies that were carried out in arid and semi-arid environments and which demonstrate interaction (nurse-beneficiary) were selected. For this reason, we only found 105 works published in the 28-year period that met the required criteria (Fig. **1**). Many of the studies that have addressed the effect of these interactions in recent years have been carried out in Mexico and Spain; 31 and 17 respectively (Fig. **1**). The greatest amount of research on nurses in arid and semi-arid environments tends to correlate with the extent and prominence of these areas in the countries studied. For example, Mexico, which stands out with the largest number of studies, has vast arid and semi-arid regions, such as the Sonoran Desert and the Chihuahuan Desert. Spain has extensive semi-arid regions in the southeast of the country. These areas provide a natural context conducive to research on the ecological and adaptive interactions of nurse plants under extremely arid conditions (Fig. **1**).

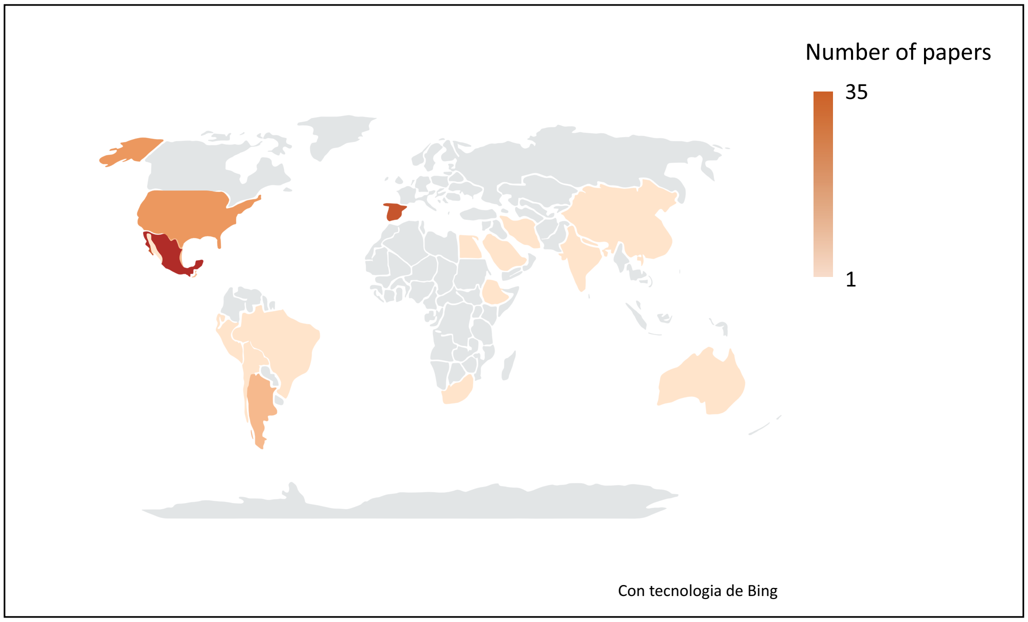

Fig. (1). Published studies of nurse-beneficiary species interactions in arid and semi-arid environments from 1996 to 2023. Dark orange indicates countries where more studies have been registered and lighter colors where fewer have been registered. The countries in gray represent where no studies of nurse-beneficial species interactions in arid and semi-arid environments have been recorded.

The United States and Australia, although with fewer studies than Mexico, also have significant areas of arid and semi-arid terrain, such as the deserts of the southwestern United States and the Australian outback. However, only 9 and 3 studies regarding protected nurse interaction were found for the period of time analyzed. These areas not only offer a wide field for ecological and biological research but also have greater availability of resources and research capabilities, which could favor the production of scientific studies on this topic.

PART 7
CONSERVATION

CHAPTER 12

Environmental Pollution in the Chihuahuan Desert and Risks to Human Health: The Case of La Comarca Lagunera

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Abstract: La Comarca Lagunera is a region in the states of Coahuila and Durango within the Chihuahuan Desert in Mexico. It is one of the regions with the greatest industrial and economic development in the country, mainly due to agricultural activities and the mining industry. The development of La Comarca Lagunera is associated with the deterioration of natural resources, mainly due to the filtration of various pollutants in the wells where the population obtains water for drinking, in addition to the contaminants that accumulate in the soil. An evaluation and analysis of the data available in the literature, including its own results and the data from 2012–2022 published by CONAGUA, allowed us to determine the levels of the main pollutants in the region and their relationships with the limits recommended by Norma Oficial Mexicana NOM-127-SSA1-2021 (NOM-127), as well as the main effects on human health. The results show that the concentrations of the main water contaminants are above the values of the NOM-127, and many of the water wells with high levels of contaminants are still in use; thus, the deterioration in health has increased. On the other hand, the results of the evaluation of contaminants in the soil, mainly the compounds used as pesticides, are an important source of contamination and health problems, mainly in children. However, there is a lack of recent studies on these health problems, so collaboration between various organizations is imperative to update the data.

Keywords: Agriculture, Arsenic, Coahuila, Cow manure, Drinking water, Durango, Environmental pollution, Environmental toxicology, Fluorides, Human health, Lead, Nazas River, Nitrates, OCPs, PCBs, Phosphates.

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INTRODUCTION

Environmental toxicology studies the effects of polluting chemical compounds and their impact on the environment and living organisms, including the health of human beings, and it characterizes, evaluates, monitors, and predicts the route and effects of these compounds [1]. There are a wide variety of chemical compounds that are discharged into ecosystems, including those from the production of food of both animal and vegetable origin, such as pesticide residues and manure, among others, as well as, to a large extent, those from various industries [2].

Arid zones, despite having lower population densities than other types of habitats, have become highly polluted sites due to a large number of economic activities and the consequent constant deterioration of their ecosystems, which includes changes in land use for agricultural activities, as is the case for the Chihuahuan Desert, where in the last 30 years, at least 10% of natural soils and vegetation have been replaced due to these activities [3]. Adverse health effects occur because intensive agriculture uses a large amount of water for these activities, which causes their extraction from increasingly greater depths, which has resulted in the deterioration of endangered ecosystems and of the health of the inhabitants [4].

There are several sources of pollution in arid zones, mainly related to mining and agricultural activities, including the use of organochlorine pesticides; these activities can cause significant problems to the environment, including soil infertility and the concentration of heavy metals in the soil and water bodies. This pollution impacts the growth and development of fauna and accumulates in plants, many of which are consumed by nearby populations [5]. The low production of organic matter in arid zones is responsible for the low retention capacity of soils, so leaching processes occur at a relatively high rate, meaning that groundwater contamination can be greater in arid zones than in other areas; *i.e*., the vulnerability of groundwater to pollutants is greater in arid zones.

LA COMARCA LAGUNERA

La Comarca Lagunera is part of the Chihuahuan Desert, located in the center of northern Mexico (24.37° N-26.84° N, 101.86° W-104.82° W), (Fig. **1**), in a basin where the Nazas and Aguanaval Rivers converge. It occupies a territory of approximately 43 000 km^2, which is 2.2% of the total area of Mexico; it is composed of fifteen municipalities belonging to the states of Coahuila (Francisco I. Madero, Matamoros, San Pedro, Torreón and Viesca) and Durango (General Simón Bolívar, Gómez Palacio, Lerdo, Mapimí, Nazas, Rodeo, San Juan de Guadalupe, San Luis del Cordero, San Pedro del Gallo and Tlahualilo), which are integrated according to their socioeconomic attributes [6].

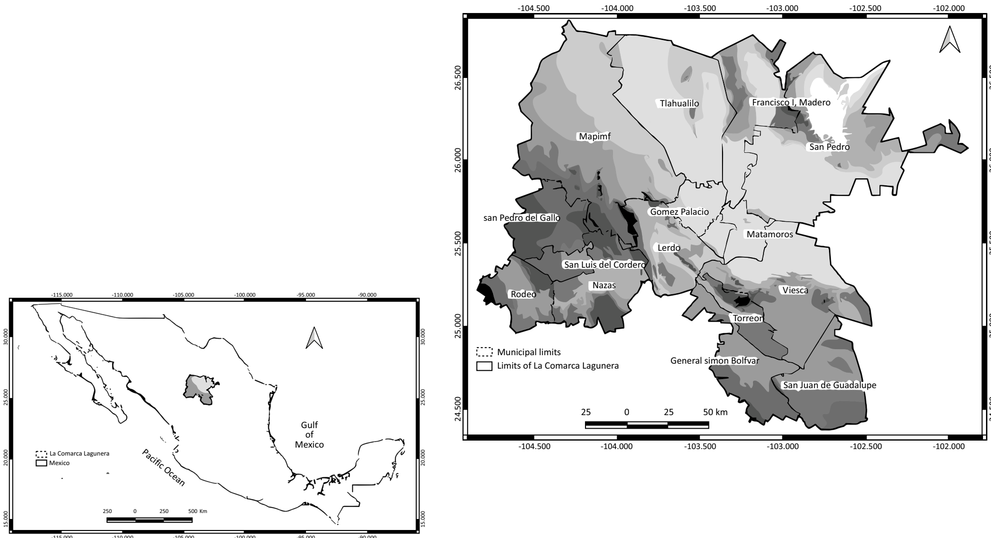

Fig. (1). Location of La Comarca Lagunera, Mexico and its municipalities.

La Comarca Lagunera is one of the regions with the greatest economic and commercial development in Mexico since the mid-twentieth century; the main economic activities of the region include agriculture, livestock, dairy, maquiladoras, and mining, which take place in an essentially flat territory with an average elevation of 1 200 m above sea level. In addition to increasing the demand for surface water and the amount of water used for activities, these activities release pollutants into the atmosphere, soil, and water, which impacts the environment by causing changes in land use and desertification [7].

La Comarca Lagunera receives its name from the Laguna de Mayrán, a body of water that was formed by the mouth of the Nazas River, an important tributary of approximately 500 km that descends from the Sierra Madre Occidental. This body of water was fundamental for the development of the region since, with the arrival of the railroad, it allowed the establishment of agricultural and livestock activities in the nineteenth century. The economic boom due to the cultivation of cotton during the first decades of the twentieth century caused a deterioration in the course of the Nazas and Aguanaval Rivers as a result of the construction of the Lázaro Cárdenas and Francisco Zarco Dams, which were built with the main objective of irrigating the crops of the region; both rivers currently face problems of overexploitation and pollution due to wastewater discharge from agricultural, industrial, and mining activities in the region [8].

CHAPTER 13

Identification of Priority Areas for Cactaceae Conservation in Arid and Semiarid Zones

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Abstract: *In situ*, species conservation demands that natural habitats be preserved, however, in a world characterized by pervasive human impact, the identification of pivotal regions harboring crucial species becomes imperative. Cactaceae species, prevalent and conspicuous in arid and semiarid areas, are predominantly included in national or international Red List categories. The primary aim of this chapter was to pinpoint the optimal selection of priority zones for the conservation of Cactaceae, focusing on levels of richness and endemism. The application of Possingham's algorithm and the principles of complementarity and irreplaceability were employed to determine these priority areas. The database utilized in Chapter 6 of this book was employed, housing 124,789 entries pertaining to 519 species of cacti. An area covering arid and semiarid regions was encompassed within a polygon that was partitioned into cells measuring 50x50 km. The geographical coordinates of each taxon were overlaid onto these cells. The risk classification documented in the Mexican Red List (NOM-059-SEMARNAT-2010) and the presence within a Protected Natural Area (PNA) were acquired for all 519 species. We identified 80 cells as priority areas for cactus conservation, and most of them were outside of some PNAs. Of the 519 species, 30.44% and 13%, are listed in risk categories and outside of PNAs, respectively. We concluded that arid and semiarid regions lack PNAs, and consequently, a large number of cacti as well as many other diverse taxonomic groups are not protected.

Keywords: Biodiversity, Cactus, Complementarity, Endemism, Irreplaceability priority areas for conservation, Protected natural areas, Richness.

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INTRODUCTION

Mexico is recognized as a megadiverse country on the basis of its already well-documented diversity [1, 2], but many taxonomic groups remain unprotected. As is the case with numerous species of the Cactaceae family, which is an extremely emblematic and important taxon in Mexico [2]. The National System of Protected Natural Areas recognizes 203 protected natural areas (PNAs) under different protection categories; which cover approximately 1,000,000 km^2 [3]. Nearly 1,478 cacti taxa are included in the Red List of IUCN [4], and 267 are listed in the NOM-059-SEMARNAT-2010 of Mexico [5]. The main threats to cacti are illegal trafficking and severe and rapid changes in land use [4].

The Biological Relevance of Cactus

Cactaceae is a monophyletic group that is mostly endemic to the New World and originated in South America but has the greatest radiation in the arid and semiarid areas of Mexico and North America [6, 7]. Cactaceae originated shortly after the global reduction in CO_2 from the Eocene to the Oligocene, and the radiation of Cactaceae generic richness coincided with the expansion of aridity in North America during the Miocene [8]. There is a significant correlation between Cactaceae life forms and pollination syndromes, as well as clear associations among the rate of diversification, pollination, and the evolution of growth forms [7]. Diverse authors have recognized that there is a complex scenario underlying Cactaceae's diversification. Diversification is not only a response to the availability of new niches resulting from aridification but also correlates with the evolution of new growth forms and reproductive strategies [7, 8]. In addition, it has been mentioned that soil composition, bioclimatology, topography, geographic range size, and chromosome number contribute to cacti diversification [8]. Regarding the richness of Cactaceae in Mexico, the most recent estimate indicates that Mexico has a total of 660–700 species, 78% (517) of which are endemic [2, 9]. The level of endemism of Mexican cacti is as evident as that in other countries: Brazil (176 taxa), Peru (170), Argentina (158), Bolivia (153), the United States (86), and Chile (83) [9]. The objective of this chapter was to identify the best set of priority areas for the conservation of Cactaceae in the arid and semiarid zones of Mexico based on the Cactaceae richness and endemism of the areas using Possigham's algorithm and considering the concepts of complementarity and irreplaceability.

METHODOLOGICAL STRATEGY

The study area was circumscribed with the help of a potential vegetation polygon for Mexico [10], from which a polygon with cells for 50 records of the species was constructed according to the coordinates. The number and species in each cell were established in this manner for subsequent analyses. The cell size was set such that in the smallest number of cases, there were empty cells.

Additionally, the layers of 19 bioclimatic parameters were interpolated on the basis of this polygon [11], and these parameters were classified to propose a climatic regionalization of 15 different climatic domains in the arid and semiarid zones of Mexico [12]. The nonhierarchical classification was performed, given the number of cells with climate values, using the PATN v. program 4 [13], which includes different algorithms and metrics. Cluster analysis was performed using the Gower metric, which is robust and allows values from different measurement units to be mixed.

The cactus database used here was processed in another chapter of this book [Appendix **D**, 14]. However, it is pertinent to note that a different taxonomic scheme was followed than that recognized by Kew Plants of the World [15] and Tropicos [16] for the genera and species of this family. The taxonomic scheme was based on our working hypothesis concerning additional taxonomic differentiation that proposes the recognition of different genera that other classifications do not and that reasonably reflect biogeographic patterns, which are related to the geology and morphotectonics of the country. Among the different genera, *Mammillaria*, *Mammillopsis*, *Neolloydia*, *Cochemiea*, *etc*., geographically reflect diversification events and can be seen in the data analyzed in this work [17, 18].

To identify priority conservation areas, a mathematical algorithm that allows cells to be selected mainly according to their richness [19] is used, which in this case also includes endemic species. As endemic, these species are considered to have an evidently restricted distribution or even wide distribution, but this distribution is restricted to the arid and semiarid zones bordering the areas of interest in this study. This exercise considers the concepts of complementarity and irreplaceability in identifying the best APC set [20, 21].

PRIORITY AREAS FOR CACTI CONSERVATION

Overall, 80 cells were identified as the best set of priority areas for cacti conservation, where 519 species of Cactaceae from the arid and semiarid zones of Mexico are distributed (Table **1**). One cell had the highest richness (85 species), followed by six cells with 50, 40, 38, 33, 30, and 20 species (Table **1**).

CHAPTER 14

Ex situ Conservation of Mexican Flora from Arid Regions: How Well is it Represented in the FESI-UNAM Seed Bank?

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Abstract: The flora of the arid zones of Mexico is characterized by the high degree of diversity and endemism. Unfortunately, because it faces many threats, its study and conservation should be prioritized. One of the most efficient *ex-situ* conservation alternatives is the storage of germplasm in seed banks. The FESI-UNAM Seed Bank (SB) has the most extensive and diverse collection of species from the arid regions of Mexico, with more than 5,200 accessions of approximately 2,500 species. The objective of this chapter is to report the number of accessions and the floristic diversity for the five groups or 15 climatic domains into which the arid regions of Mexico are classified. Moreover, this chapter aims to identify regions with low representation in the SB and propose potential collection areas for future projects. The SB stores 2,135 accessions from arid zones, comprising 1,182 species from 547 genera and 108 families. Regions such as the center of the country and the Tehuacán-Cuicatlán Valley have the highest number of accessions, and families such as Asteraceae, Fabaceae, and Cactaceae account for approximately 45% of the collection. The need to strengthen the collection of seeds in arid zones is evident, and future projects should focus on the protection of endemic species and species under categories of risk, especially in regions not yet represented in the SB, whose role is essential for the conservation of the arid flora of Mexico.

Keywords: Accessions, Arid zones, Climatic domains, Desertification, Endemism, Fabaceae, *Ferocactus*, Floristic diversity, Germplasm, *Opuntia*, Orthodox seeds, Threatened species.

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INTRODUCTION

Arid zones are regions with very little water availability because their rainfall and humidity values are well below the world's annual average [1, 2]. According to the 2014 report of the Intergovernmental Panel on Climate Change [3], the increase in average temperatures worldwide continues and is a fundamental and general factor for the availability of water. In arid zones, the presence of little but torrential rainfall causes the loss of the most fertile layers of the soil; when these layers are washed away, the remaining soil is poor and unable to produce food [3, 4].

The territory of Mexico comprises almost two million square kilometers, but between 1,178,625 and 1,237,556 km^2, or 60% to 63% of the total territorial extent, is arid [5, 6]. The scale of arid ecosystems is one of the main reasons why the study of this type of region in the country is highly relevant. However, arid regions are also habitats of a high percentage of endemic species representing all groups of living beings and have high floristic richness [7, 8]. Among the 23,314 species of higher plants that have been identified in the country, approximately 6,000 are estimated to grow in arid regions, which represents approximately 27% of the national flora [9 - 12]. In addition, the arid areas of Mexico are inhabited by more than 40% of the total population of the country, a population that generally lives in very precarious conditions and even extreme poverty [13].

Of the 32 states that comprise the national territory, 25 contain arid regions to a greater or lesser extent; these regions almost completely cover the territorial surfaces of the states of Aguascalientes, Baja California, Baja California Sur, Coahuila, and Sonora and partially cover the states of Colima, Chihuahua, Nuevo León, Oaxaca, Puebla, Querétaro, San Luis Potosí, Sinaloa, Tamaulipas, Tlaxcala, Yucatán, and Zacatecas. Importantly, arid zones not only appear in the desert strip (latitude of 30°) but also occur within the tropical portion of the country, for example, in the basins of the Zacatula-Balsas and Mezcala-Tlapaneco rivers (Guerrero). Similarly, arid zones are also found at the confluence of the Tehuacán-Cuicatlán valleys (between Puebla and Oaxaca), on the NE coast of the Yucatán Peninsula, and in the arid temperate region of the San Juan-Perote valleys, on the border between the states of Puebla and Veracruz [14].

Although the heterogeneity of the arid zones prevents natural regionalization, the following can be recognized in Mexico: 1) the region of the Sonoran Desert, which includes the lower portions of the states of Sonora and the Baja California peninsula and extends to the United States of America; 2) the Chihuahuan Desert region, which includes portions of the states of San Luis Potosí, Zacatecas, and Coahuila, along with a portion of the United States; 3) the arid area of

Tamaulipeca NE of Tamaulipas, N of Nuevo León, and NE of Coahuila; 4) the semiarid Hidalguense zone, which includes portions of the states of Querétaro and Hidalgo; and finally, 5) the region known as Valle de Tehuacán-Cuicatlán, which includes portions of the states of Puebla and Oaxaca [1].

Currently, despite the heterogeneity and use of the available tools, a more detailed regionalization of the arid zones of Mexico is possible, such as the one presented in Chapter 1 of this book [15], in which the entire arid region of Mexico is proposed to be divided into 15 climatic domains according to regional environmental variation. After similarity analysis, these climatic domains are combined into five large groups of arid regions, which do not precisely coincide with the regions proposed by González-Medrano [1] but generally include them; although they extend beyond the initial proposal, Téllez-Valdés *et al*. [15] define them as Groups 1, 2, and 3 and Domains 4 and 14.

Beyond the importance of the regionalization of Mexico's arid zones is the presence and distribution of the different species of plants that inhabit them; as already mentioned, there are estimated to be approximately 6000 different such species. Plants are a group of living beings that, in arid regions, have developed characteristic adaptations that make them extremely efficient at surviving in environments where water and temperature, both fundamental factors for their proper development, represent important limitations.

Fluctuations in other climatic factors, mainly high levels of CO_2, and salinity, also have a negative impact on plants. The drought stress experienced by different plant species hinders photosynthesis, which ultimately leads to poor growth and yield [10]. As a consequence, it also affects the production of seeds and consequently the reproductive process in general.

Plants that grow in arid regions have developed some of the typical adaptations to survive under adverse conditions, for example, very wide and deep root systems, tissues that store water, protective covers, lost or minimal leaves, photosynthetic stems, and the production of seeds that are tolerant to desiccation [16 - 19]. This type of seed is known as orthodox [1].

The adversity that arid environments represent for the development of plant resources, combined with the fragility of arid region ecosystems that are not very productive and therefore force their inhabitants to introduce livestock, exploit useful plant resources, dismantle large areas of land in an effort to produce food, *etc*., leads to the need to implement urgent conservation actions [1, 4, 12]. For this purpose, more than 20 years ago, the idea of creating a seed bank was born, the main objective of which was the conservation of wild and native plant resources, especially in arid regions of the country. From its inception, the project has been

Overall Conclusion

Across the 14 chapters contained in this book, readers will discover valuable results for the four most world-recognized Mexican dry areas: the Peninsula of Baja California, the Chihuahuan Desert, the Sonoran Desert, and the Tehuacán-Cuicatlán Valley, which were together analyzed in individual and distinct chapters. Since Mexico is recognized as a world hotspot area by its high biological diversity and endemism levels, a priority of this book was to address this issue for the large geographic scale, including these four emblematic Mexican dry areas. A detailed climatic characterization of these areas is presented in Chapter 1. In addition, as the southern part of the Chihuahuan Desert was identified by several chapters of this book as an area underlined by biodiversity patterns, this book included in the Chapter 2 a detailed physical review of such area. In addition, this book contains four chapters (3-6) that assessed the biodiversity levels for distinct taxonomic groups; such chapters showed a notable variation in species composition and levels of diversity across the four geographic areas studied. This geographic perspective allowed us to identify a latitudinal pattern in the number of species that increases from the north to the south for cactus and birds, including hummingbirds. Interestingly, the southern Chihuahuan Desert (northern portions of domains 14 and 15, sensu Chapter 1; and Querétaro- Hidalgo regions of Chapter 2) concentrated the highest number of species of ants (Chapter 3), birds (Chapters 4 and 5), and cactus (Chapter 6). In addition, the inconspicuous group of ants still requires more fieldwork since it was estimated that only 50% of the native species have been documented (Chapter 3). The results of Chapters 4-5 addressed that Mexican arid and semiarid regions are the natural habitats for native and migratory bird species; moreover, these areas concentrated a high number of endemisms of ants (Chapter 3), birds (Chapters 4-5), and cactus (Chapter 6). It is a fact that arid and semiarid ecosystems have been inhabited for a long time by local human communities, which have recognized nearly 331 plant species as medicinal resources. Interestingly, specific illnesses are treated with particular parts of the plants (Chapter 7). Some plant species are known for their medicinal properties, and some of them contain authentic antimicrobial agents, as was shown in detail in Chapter 8 for the plant genus *Euphorbia*. Definitively, valuable scientific research has no sense if the results are not transferred to human local communities. Hence, Chapter 9 presents some social implications of the way of life in arid zones and gives examples of some sustainable projects. The local effects of human communities on the arid and semiarid ecosystems were assessed in Chapters 10 and 12. Chapter 10 applied state and transition models to identify the process and factors that cause the vegetation changes at the local scale. The findings of this chapter showed that the canopy cover is mainly caused by rained agriculture and firewood extraction. Regarding the results of Chapter 12, these showed that the local contamination caused severe changes in soil properties and severe concerning effects on human health, mainly in children. On the other hand, Chapter 11 evaluated the role of the nursery, and the authors concluded that this biotic interaction facilitates the survival and establishment of the plant species participants, which may affect the biodiversity levels and resilience of these ecosystems. Furthermore, in this book was assessed that the four emblematic dry areas contain nearly 80% of the native cactus species (Chapter 6), and Chapter 13 addressed that nearly 32% of them are listed as national conservation concerns. However, despite these relevant biodiversity results, these ecosystems have a deficit in the number of natural protected areas, and those few currently decreed as protected areas do not accomplish in practice a real protection of flora and fauna

(Chapter 13). Chapter 14 presents valuable information about the large number of plant species that are conserved as seeds in the collection harbored in UBIPRO, FES Iztacala, UNAM, where 2,135 accessions are from arid zones, comprising 1,182 species from 547 genera and 108 families.

SUBJECT INDEX

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Sofía Solórzano Lujano

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José Guillermo Avila Acevedo

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