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Ecology of Macrofungi

An Overview

Edited by Kandikere R. Sridhar
and Sunil Kumar Deshmukh



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Ecology of Macrofungi An Overview

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Preface

Mycology is one of the fast-developing disciplines that has been influenced by many facets of human life similar to plants and animals (Naranjo-Ortiz and Gabaldón, 2019). Macrofungi are natural bioresources with wide distribution responsible for the decomposition of lignocellulosic materials, mutualistic association with tree species as ectomycorrhizas, source of nutrition and possess or produce bioactive compounds valuable in human health, agriculture, and industries. Although a global conservative estimate of macrofungal diversity ranges from 0.14 to 1.25 million, a few thousand are described and very few of them are explored for their usefulness (Hawksworth, 2019). Evaluation of macrofungal resources, distribution, lifestyles, adaptations, substrate preferences and ecology in different ecosystems enhances our knowledge of their conservation and applications in various fields (Dighton, 2019). Macrofungal ecology is dependent on environmental variations, climatic conditions, substrates (availability and quality), disturbances, symbiotic partners, and insect population (Hussain and Sher, 2021; Čejka et al., 2022). In spite of considerable developments in applied mycology in the 21st century, there are several gaps in understanding the macrofungal ecosystem services (e.g., decomposition, enhancement of soil qualities, nutrient acquisition, mutualistic association, energy flow, biogeochemical cycles, bioremediation and conservation).

The book, *Ecology of Macrofungi: An Overview* projects some of the current developments in macrofungal ecology in different habitats. Contributions of 41 researchers from 11 countries offered chapters on different facets of macrofungal ecology. This volume emphasizes four subdivisions of macrofungal ecology: (1) Importance in forest ecosystems; (2) Ectomycorrhizal associations; (3) Wood preference of macrofungi; (4) Polymorphism in macrofungi. The first subdivision highlights the role of macrofungi in forests such as nutrient cycling, mycorrhizal functions, prevention of soil erosion, animal nutrition, parasitic macrofungi, host preference, ammonia fungi and macrofungal dynamics. The second subdivision discusses the significance of ectomycorrhizal fungi in tropical and subtropical forest ecosystems. The third subdivision mainly delivers information about the macrofungal substrate ecology, wood-rot polypores, Pinus-dwelling Hymenochaetaceae and indoor macrofungi followed by fourth subdivision dealing with polymorphism in woody-decaying macrofungi.

We are optimistic that the efforts made by the authors of chapters in understanding the ecology of macrofungi in different ecosystems will be valuable for readers with a wide interest in natural science. Owing to the topics dealing with macrofungal diversity, distribution, dynamics, lifestyles, ecosystem preference, substrate preference and ecosystem services draw the attention of mycologists, botanists, zoologists, ecologists, foresters, geneticists, biochemists, agronomists, and field biologists.

We are indebted to the kind gesture of the contributors and reviewers for the on-time submission and meticulous evaluation. We are grateful to the CRC Press for its cooperation to fulfill several official formalities to bring out this book on time.

January 09, 2023
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Mycogeography and Ecology of Ectomycorrhizal Fungi in Northern México

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1. Introduction

Ectomycorrhizal fungi form associations with many hosts in different vegetation types of the world (e.g., oak and conifer forests) and both symbiotic partners obtain nutritional benefits (e.g., water, minerals, and photosynthesis products). The nutrients are shared via the functional mycelial nets starting from the soil and moving inside and outside of the ectomycorrhizal roots of their hosts. These relationships have a long evolutionary history starting at the Devonian period and it is suggested that such partnerships helped both associates to conquest new territories reaching the current biogeographic distribution of forests in the world (Retallack et al., 2014; Heads et al., 2017). Hosts involved in this evolution process belong to families (e.g., Pinaceae, Fagaceae, Betulaceae, Salicaceae, Ericaceae, Myrtaceae, Dipterocarpaceae and Caesalpiniaceae) (Smith and Read, 1997). They are well distributed in the world in Boreal, Temperate, Tropical, and semiarid conditions and

carry with them their fungal partners to survive obtaining better nutrition from the different soils where they grow. In every soil condition of the world where these mutualistic symbioses occur, the ectomycorrhizal fungi will produce fruiting bodies either on top (epigeous) or below the soil (hypogeous) during the rainy season (North, 2002). A great number of ectomycorrhizal fungal species are involved in these processes, and yearly they contribute millions of new spores to the forest ecosystem (Villarreal and Luna, 2019). Spores are dispersed by millions of insects, mites, worms, and other fauna (e.g., rodents, deer, wild pigs, and bear) as well as by rain and wind and each will germinate in the forest soil and will find plenty of new roots to colonize and form new ectomycorrhizas (Maser et al., 2008; Schiegel, 2012; Elliot et al., 2022). They will form agglomerates or complexes integrated by several species of ECM fungi with each tree species and they will be connected with a few other tree species via their mycelial nets, and they will also be exploring the soil for nutrients. These fungal nets contribute significantly to the nutrition of trees as well as to other organisms feeding on mycelium or fruiting bodies in the forest. Almost every terrestrial vegetation of the world functions associated with mycorrhizal fungi as they uptake and share nutrients with their hosts. Due to the nutritional contribution of the mycorrhizal associations to the forest of the world, their relevance is very high, and they also contribute to forest's health and biogeographical distribution. Understanding these nutritional processes from every vegetation type is a key subject that helps to understand their global contribution and generates local or regional knowledge from different geographical latitudes. The mutualistic associations are needed to carry out the management of specific associations (e.g., to improve the establishment of endangered host species *Picea*, *Abies* or *Pseudotsuga* spp. in Mexico, using inoculated seedlings or to carry out reforestation projects of burned sites) (Garza et al., 1985; Hall et al., 2019). Regarding taxonomical studies from different biogeographical regions, these studies are useful to know the diversity of species, their plant partners and some of the soil and abiotic conditions occurring in each region as well as some possible species of animals that might be contributing for their dispersion (Maser et al., 2008; Halling et al., 2008; Elliot et al., 2022). Some species of macromycetes might have had a wide distribution in the past and were separated in different continents. Nowadays they are forming ectomycorrhizal associations with oak forests in North America, Mexico and China (e.g., Boletales: *Harrya chromipes*, *Tylopilus cyaneotinctus*, *T. griseus*, *Tylopilus felleus* and *Sutorius eximius*) (Arora, 1986; Wu et al., 2016; Yan-Chun Li and Zhu L. Yang, 2021). Some populations of Boletes might have been isolated for long periods (Halling et al., 2008). According to the geological substrate, vegetation type, soils, and climatic conditions from every region of the world, the mycorrhizal associations form symbiosis with many hosts (Garza et al., 1985, 1986, 2002, 2019, 2022; García et al., 2014, 2016). Examples of the latter can be observed in the fungal diversity present in western and eastern North America and in the past, some of these associations moved with their partners (e.g., the genus *Pinus*, southwards into Mexico reaching the big Sierra Madre Occidental) (SMW) in the northwest and the Sierra Madre Oriental (SME). Some fungal species remained in north America in boreal and temperate climatic conditions associated with different tree species and they are not found in the north of Mexico. However, some fungal species grow in both, the south of North America and the north of Mexico associated with different host species (e.g., nut pines, other conifers, and oaks species) (Bessette et al., 1997, 2016, 2019; Beug et al., 2014; García, 2016; Baroni, 2017). In Mexico, pine and oak forests are widely diverse and dispersed and the ectomycorrhizal fungi are associated to all the species, so far, no studies comparing the similarity of the diversity of ectomycorrhizal macromycetes species from both Sierras

(SMW) and (SME) with those from the Pacific and Atlantic coast from USA and Canada have been attempted. This study presents mycogeography of ectomycorrhizal fungi in the biogeographic regions in the western and eastern parts of Mexico and some of the animals that interact with them in the forests. An attempt to see similarities between the species found in the north of Mexico with some species reported from both the western and east southern regions of the USA, and it also includes some species reported from these zones in Canada.

2. Description of the Sierras at the North of Mexico

2.1 The Sierra Madre Occidental (SMW)

This biogeographic territory covers an area of 12.6% it has rocks belonging to the Paleozoic, Mesozoic, and Cenozoic eras mainly of extrusive volcanic origin and soils are represented mainly by litosol, regosol, fluvisol, rendzina and cambisol. The SMW adjoins the states of Durango, Coahuila, Sonora, and Sinaloa in Mexico, and in the north reaches the USA in Texas, New Mexico, and Arizona (Fig. 1). It has a mean elevation of 2,500 m.a.s.l and the highest elevation reaches 3,711 m.a.s.l. at Cerro El Moinora at the municipality of Yecora. This Sierra has a 75% dry or arid (B) climate type, followed by temperate (C) in 13% semiarid, temperate, subhumid (A) with 12% A cold-temperate (C) climate is the predominant one at high altitudes. Mean rain ranges from 550–750 mm and temperate forests cover 25.3% of the state and it has pine, oak and mixed pine-oak forests, and the more open areas of these forests have *Arbutus* and *Juniperus*. January is the coldest month and lower temperatures are reached at the high Sierra with a mean of -5°C and June is the hottest and temperatures reach a mean of 35°C (Gonzalez et al., 2012; Reyes Gomez and Nuñez López, 2014).



Fig. 1. Location of both Sierras at the west and east of Mexico.

2.2 The Sierra Madre Oriental (SME)

This Sierra is a physiographic province and as in the SMW it has its own topographical, geological, and climatological characteristics (Fig. 1). The SME covers an area of ca. 220,192.3 km² and is almost 1,250 km long and it is distributed in 11 states, it has a mean elevation of 1,313 m.a.s.l., and the highest elevation reaches 3,711 m.a.s.l. at Cerro El Potosí in the municipality of Galeana. The SME has rocks belonging to the Paleozoic, Mesozoic, and Cenozoic eras the Limestone the predominant, whereas the predominant soil type is Litosol and xerosol, rendzina, feozem, vertisol, luvisol, and yermosol are also present. Due to its size, the SME has 14 climate types and the predominant is dry (BS), in the northern and western regions, it is followed by the humid-warm type (A) (C) and sub-humid-warm type (Aw) that are in the eastern and southern regions. A cold-temperate (C) climate is the predominant one at high altitudes and main rain ranges from 600–700 mm (Cervantes-Zamora et al., 1990; Salinas et al., 2017).

3. Sampling Data and Vegetation

A sampling of ectomycorrhizal fungi was carried out at both Sierras: in the last 25 years. The main vegetation types are temperate forests with conifers (e.g., *Pinus*, *Pseudotsuga*, *Abies*, *Picea* and *Cupressus* and Oaks *Quercus* spp.). Altitude at the different Sierras vary from 500 to 3750 m and vegetation is formed by plant communities that are integrated into many associations (e.g., *Pinus-Quercus*, *Pinus-Pseudotsuga*, *Pinus-Abies*, *Pinus-Picea*, *Quercus-Pinus* and *Pinus-Quercus*) and they also form mixed associations with other species like *Arbutus xalapensis*, *Arctostaphylos pungens* and *A. manzanitae*. Some oak species are very small and grow at the soil level forming small communities of decumbent plants (e.g., *Quercus depressipes*), while others, when growing in semiarid conditions, form shrublike communities (e.g., *Quercus emory*). *Quercus grisea* may be found growing isolated in small hills surrounded by a semiarid environment at hundreds of kilometers away from the main forests, and they have exclusive ectomycorrhizal fungi associated. Visits at different locations in both Sierras were made in the rainy season to try to cover as much geography as possible, these Sierras are separated by more than a thousand kilometers. Collection of mushrooms was carried out from July to September at the SMW and in from September onwards at the SME. This is because the phenology of fruit bodies production and rainy seasons are different in each region (Garza, 1986; Garza et al., 2019; Quiñonez et al., 2008; Quiñonez et al., 2014).

3.1 Field Studies

In the field, the location was recorded with GPS, and the ecological information, such as the associated plant communities, the possible hosts of the mycorrhizal species, the habitat data, the date of the fruiting, and the characteristics of the fresh basidiocarps such as color, smell, and size. were recorded for each species. To obtain the macro chemical reactions, reagents such as NH₃ 25%, KOH 15% and FeSO₄ 10% were applied in the different parts of the basidiocarps. The specimens were taken to the laboratory for dehydration and final labeling. Specimens of the species and some strains obtained are deposited either at the mycological collection of Facultad de Ciencias Forestales, CFNL, Instituto de Ciencias Biomédicas,

UACH or Instituto Tecnológico de Ciudad Victoria (ITCV). Animals shown here were observed in the field at both Sierras and photography were obtained in situ.

3.2 Laboratory Studies

In the laboratory, mature specimens of each species were selected and used to determine the microscopic characteristics, and fine handmade sections were made from the different parts of the basidiocarps, the fine cuts made were moistened with water on a slide and then mounted in a solution of KOH 5% and NH₃ 3% or Congo red solution. All microscopic structures were measured to obtain a mean of length by width with a lens magnification of 1000X, a calibrated eye micrometer was used and the average sizes of each of the different structures were calculated for each species using a Carl Zeiss AxioStar microscope (Quiñonez et al., 2008).

4. Mycorrhizal Association with Vegetation

Apparently, the first evidence of the occurrence of Basidiomycetes forming ectomycorrhizal associations occurred in the Pennsylvanian during the Carboniferous 299 million years ago (ICCICS, 2014). It is speculated that ectomycorrhizal associations might have contributed to the survival of their associated partners and helped to the diversification and richness of species (Singer, 1986; Bruns et al., 1989; Binder and Bresinsky, 2002a; Binder and Hibbett, 2006; Wang and Qiu, 2006; Nuhn et al., 2013; Wu et al., 2014, 2016). Mirov (1967) mentioned that the genus *Pinus* might have migrated from boreal conditions existing in north America reaching its southwards distribution in Nicaragua with *Pinus caribaea* var. *caribaea*. Nowadays studies on Boletales from Mexico show that they are widely distributed and are intimately associated to *Pinus* and *Quercus* species (García and Garza, 2001; North, 2002). According to Haling et al. (2008), “the array of plant-associated distributions provides a potential handle for evaluating Bolete distribution on a global scale”. The species from the genus *Suillus* might be the most widely distributed in the Mexican territory and they form mycorrhizal associations with many different conifers but especially with the genus *Pinus* and might also be associated with some oak species (Garcia and Garza, 2001). The observation of this kind of ecological relationships is important to produce seedlings of every host (e.g., *Pinus*) in the wide geography of Mexico. Thus, inoculating conifer seedlings with their native ectomycorrhizal species strains or spores under greenhouse and nursery or field conditions is particularly important to obtain good field establishment results (Hall et al., 2019). Some other interesting examples of very close relationship might occur with the association formed between *Suillus lakei* and *Pseudotsuga menziesi* or *Turbinellus floccosus* and *Abies vejarii* or *Leccinum insigne* and *Populus tremuloides* in both Sierras (Garcia and Garza, 2001; Garza et al., 2019). These associations are very much specific and close and so far, the fungal partner has not been found associated with other hosts. Considering these field observations, it might be necessary to use these ecological associations when the reproduction of these hosts for reforestation or restoration procedures is required. *Pisolithus tinctorius*, *Scleroderma verrucosum*, *S. areolatum*, *S. texense* and *S. cepa* are widely distributed forming ectomycorrhizas with many oak species in both SMW and SME. Species of *Russula*, *Lactiflus*, *Lactarius*, *Cortinari*, *Boletus*, *Gyroporus*, *Amanita*, *Cantharellus*, *Inocybe* and *Astraeus* are widely distributed and form ectomycorrhizal associations with many oak species (Laferrriere and Gilbertson, 1996; North, 2002; García et al., 2014; Olimpia

et al., 2017; Flores et al., 2018). Interesting examples of mycorrhizal associations are found in either of the sierras (e.g., *Cortinarius magnivelatus* is associated to *Quercus sartorii* and *Q. depressipes* and *Boletus chippewaensis*, *B. rubripes*, *B. barrowsii* form associations with *Pinus chihuahuensis*, *P. herrerae* and *P. lumholtzii*) at the high Sierra of Chihuahua at the (SMW) (Perez et al., 1986; Quiñonez et al., 1999; 2008; 2015). Other interesting ectomycorrhizal associations formed by Boletales (e.g., *Suillelus amigdalinus*, *Rubroboletus eastwoodiae*, *R. pulcherrimus* and *Rhizopogon occidentalis* in forests with *Pinus quadrifolia*, *P. monophylla*, *P. coulterii* and *Quercus agrifolia*) in Baja California (Sánchez et al., 2015). At the SME several species of *Tuber*, *Sclerogaster*, *Rhizopogon*, *Hydnobolites*, *Hymenogaster*, *Gilkeya* and *Genea* form ectomycorrhizas with *Pinus culminicola* at a high altitude of 3700 m at cerro El Potosí at the (SME) and Tamaulipas (Garza et al., 1985; Garza et al., 2002; Guevara et al., 2014). It is interesting to mention that some Boletales (e.g., *Boletus luridellus*, *Boletus paulae*, *Hortiboletus rubellus*, *Boletus campestris*, *Boletinellus merulioides*, *Boletinellus romPELLI*, *Phlebopus portentosus*, *P. brassiliensis*, *P. mexicanus* and *Xerocomellus* spp.) grow at low altitudes 500–600 m associated either with oaks in the submontane forests at the SME or at lower altitudes 260–360 m with thorn scrubs to others potential hosts (e.g., *Acacia rigidula*, *Vachelia farnesiana*, *Helietta parvifolia*, *Ebenopsis ebano*) and other species at the low coastal province. Table 1 complies the ectomycorrhizal tree species in Mexico.

5. Ectomycorrhizae of Vegetation and Relationship with Animals

A review of the species of animals from the different taxonomic groups shows that there is quite a number, and some are endemic to either of the sierras. Very many species of mycophagous animals from different families have been recorded around the world (Elliot et al., 2022). Ectomycorrhizal fungi are very abundant, and they form mycorrhizas with all the species of host mentioned before establishing nutritional nets through which nutrients move actively in the soil of temperate forest ecosystem (Halling et al., 2008; Garza et al., 2019; Rilling and Allen, 2019). These fungi produce millions of spores in their fruiting bodies and for many animals, the water and wind are their main dispersers. Multisymbiosis systems are established in the temperate forest and many species are interconnected in some part of the nutritional chain (Maser et al., 2008; Elliot et al., 2022). More attention on all trophic interactions occurring in the temperate forest should be considered. Minerals in the soils require microorganisms to be dissolved, ectomycorrhizal fungi secrete enzymes and uptake the dissolved minerals in their nets, and they are then translocated to the inner tissues of the roots of every host plant, and they even share these minerals through these nets, from one host to another thus participating actively in the forest growth (Villarreal and Luna, 2019). Every year during the rainy season the spores of the ectomycorrhizal fungi germinate and find their genetic counterparts to produce secondary mycelia which will initiate the production of fruiting bodies. These will grow and produce attractive colors and volatile compounds to attract animals that will eat and disperse their spores all over the forest (Elliot et al., 2022). Mycophagy takes place not only in mammals but in very many species of other animals like earthworms, slugs, snails, plain worms, mites, collembola and many other insects either eat or use the fruiting bodies as a place lay their eggs which in turn will grow and use their “nursery beds” as food (Maser et al., 2008). This study aims to show some examples of the diversity of ECM fungi growing at both Sierras and give some examples of animals interacting with them. Mycophagy of fruiting bodies of ECM fungi forms an

important part of the diet of many animals during the rainy season. In the north of Mexico, some animals like the Peccary have incorporated ECM fruiting bodies in their diet and so they became active bioturbation species in the temperate forests in the north of Mexico, seeking actively for fruiting bodies of either epigeous or hypogeous ECM fungi. Fruit bodies are attractive by their colors and their volatile compounds which unveil them and make them detectable for very many animals. Apparently, these characteristics are evolutionary mechanisms that allow ECM fungi to survive after they have been eaten by animals. In Europe some truffle hunters follow truffle flies to their “source of food” and thus they will be able to find the black truffles! Trained dogs are used in the same way to find the truffles in the field or in truffle plantations. Maggots of many species of insects in the world use the fruiting bodies as food or a nursery to complete part of their life cycles. Beetles are very abundant the same as many species of Diptera (e.g., *Drosophila* spp.) (Schigel, 2012). These insects eat actively and are good spore dispersers but many times they are food for spiders and frogs that visit the fruiting bodies. Insects in the fruiting bodies are also sought after, by birds and many species of mice, rats and squirrels visit the fruiting bodies for food and frequently become food for snakes attracted by all of them. White-tailed deer and peccaries eat mushrooms and toadstools and become food for bobcats, wolves, coyotes, cougars, and black bear. Thus, the whole food chain is integrated in this yearly process of fruiting body production that resulted from the germination of primary spores that fuse together to form secondary mycelia. The rainy season brought the necessary water which permeates the spore cell wall and induces it to germinate in summer or autumn. The phenology of fruiting bodies production may vary from one region to another, and this is the case of both Sierras in which they are produced first in the SMW during July-August whereas at the SME they are produced mainly during September-October and the same happens in different parts of the world. Some of the main research themes of the last decades have been Global Change and Climate Change which have moved the seasons to an uncertain pattern around the world (Rilling and Allen, 2002). These changes in the weather of every region move the whole food chain habit and some species may not be fit to survive if they occur either frequently or last for long periods. In the case of ECM fungi changes in the periods of the rainy season might change the production of fruiting bodies and all the dispersers in the food chain may also have to change their feeding habits for some time. Translocation of nutrients from the soil to the forest trees via the ECM fungi might also change with climate change (Rilling and Allen, 2002). Apart from these, forest fires, cattle ranchers, logging activities, and other human activities cause changes in the forests that are difficult to overcome for the ECM fungal communities. Thus, forests have multidiverse and multisymbiotic associations, they are complex and many times they are very specialized and energy in the forest might not be unlimited. Once the ecosystems are altered by for example a forest fire the whole nutrition is gone. Multisymbiotic relationships occurring in the forests as food chains have taken millions of years to reach their current state of stability and climate change is happening every day. Ecosystems are fragile and reorganization of the species in the food chain is not as simple as establishing a new plantation with desirable edible mushrooms to replace a natural forest. The multiple associations of animals and ectomycorrhizal fungi are widespread in every terrestrial ecosystem of the world and are generally overlooked. However, most species are interconnected in the nutritional chain (i.e., fungi, hosts, and animals) and they have a high ecological significance (Elliot et al., 2022).

Table 1. Ectomycorrhizal host tree species in Mexico.

	SMW-MEX	SME-MEX
Family Pinaceae		
<i>Pinus pseudostrobus</i> var. <i>apulcensis</i>		●
<i>P. teocote</i>		●
<i>P. nelsonii</i>		●
<i>P. greggii</i>		●
<i>P. culminicola</i>		●
<i>P. cembroides</i>	●	●
<i>P. monophylla</i>	●	
<i>P. quadrifolia</i>	●	
<i>P. coulterii</i>	●	
<i>P. engelmannii</i>	●	
<i>P. lambertiana</i>	●	
<i>P. montezumae</i> var. <i>montezumae</i>		●
<i>P. johannis</i>		●
<i>P. hartwegii</i>		●
<i>P. leiophylla</i>	●	
<i>P. arizona</i> var. <i>cooperii</i>	●	
<i>P. duranguensis</i>	●	
<i>P. chihuahuana</i>	●	
<i>P. devoniana</i>		●
<i>P. discolor</i>	●	
<i>P. douglasiana</i>	●	
<i>P. patula</i>		●
<i>P. lumholtzii</i>	●	
<i>P. ayacahuite</i>		●
<i>P. flexilis</i>	●	
<i>P. herrerae</i>	●	
<i>P. strobiformis</i>	●	
<i>P. yecorensis</i>	●	
<i>P. arizonica</i> var. <i>arizonica</i>		●
<i>P. arizonica</i> var. <i>stormiae</i>	●	
<i>P. jeffreyi</i>	●	
<i>Abies duranguensis</i>	●	
<i>A. vejarii</i>		●
<i>A. concolor</i>	●	
<i>A. guatemalensis</i>		●
<i>Picea chihuahuana</i>	●	
<i>P. engelmannii</i> ssp.	●	
<i>P. engelmannii</i>	●	
<i>Pseudotsuga menziesii</i>	●	●
Family Fagaceae		
<i>Quercus affinis</i>		●
<i>Q. emoryi</i>	●	●
<i>Q. canbyi</i> Trel.		●
<i>Q. cupreata</i>		●
<i>Q. castanea</i>	●	
<i>Q. conspersa</i>	●	
<i>Q. crassifolia</i>	●	
<i>Q. crassipes</i>	●	
<i>Q. delgadoana</i>	●	
<i>Q. alpscens</i>	●	
<i>Q. depressa</i>	●	
<i>Q. flocculenta</i>	●	
<i>Q. fulva</i>	●	
<i>Q. furfuracea</i>	●	
<i>Q. galeanensis</i>		●
<i>Q. gentry</i>		●
<i>Q. graciliramis</i>		●
<i>Q. gravesii</i>	●	
<i>Q. hintoniorum</i>		●
<i>Q. hirtifolia</i>	●	

<i>Q. hypoleucoides</i>	●	
<i>Q. eduardii</i>	●	
<i>Q. hypoxantha</i>		●
<i>Q. jonesii</i>	●	
<i>Q. laurina</i>	●	●
<i>Q. mexicana</i>		●
<i>Q. miquihuanensis</i>		●
<i>Q. ocoteifolia</i>	●	
<i>Q. pinnativenulosa</i>	●	
<i>Q. runcinatifolia</i>	●	
<i>Q. rysophylla</i>		●
<i>Q. saliiifolia</i>	●	
<i>Q. saltillensis</i>		●
<i>Q. sapotifolia</i>	●	
<i>Q. sartorii</i>		●
<i>Q. sideroxyla</i>	●	●
<i>Q. skinneri</i>	●	
<i>Q. tenuiloba</i>	●	
<i>Q. viminea</i>	●	
<i>Q. xalapensis</i>	●	
<i>Q. chihuahuensis</i>	●	
<i>Q. convallata</i>	●	
<i>Q. diversifolia</i>	●	
<i>Q. edwardsae</i>	●	
<i>Q. fusiformis</i>	●	●
<i>Q. germana</i>	●	
<i>Q. glaucooides</i>		●
<i>Q. gregii</i>		●
<i>Q. intricata</i>		●
<i>Q. invaginata</i>		●
<i>Q. laceyi</i>		●
<i>Q. laeta</i>	●	
<i>Q. lancifolia</i>	●	
<i>Q. magnolifolia</i>	●	
<i>Q. microlepis.</i>		●
<i>Q. microphylla</i>	●	●
<i>Q. muehlenbergii</i>	●	
<i>Q. oblongifolia</i>	●	
<i>Q. obtusata</i>		●
<i>Q. oleoides</i>		●
<i>Q. opaca</i>	●	
<i>Q. pastorensis</i>	●	
<i>Q. pendicularis</i>	●	
<i>Q. polymorpha</i>		●
<i>Q. praeco</i>	●	
<i>Q. pringlei</i>		●
<i>Q. pungens</i>		●
<i>Q. rugosa</i>	●	●
<i>Q. sebifera</i>	●	
<i>Q. sinuata</i>	●	
<i>Q. splendens</i>	●	
<i>Q. striatula</i>	●	
<i>Q. supranitida</i>	●	
<i>Q. thinkhamii</i>	●	
<i>Q. toxicodendrifolia</i>	●	
<i>Q. monterreyensis</i>		●
<i>Q. vaseyana</i>		●
<i>Q. verde</i>	●	
<i>Q. mohriana</i>	●	
<i>Q. toumeyei</i>	●	
<i>Q. tarahumara</i>	●	
<i>Q. basaseachicensis</i>	●	
<i>Q. chrysolepis</i>		●

<i>Q. arizonica</i>	●	
<i>Q. durifolia</i>	●	
<i>Q. gambelli</i>	●	
<i>Q. grisea</i>	●	
<i>Q. potosina</i>	●	
<i>Q. tuberculata</i>	●	
<i>Q. mcvaughii</i>	●	
<i>Q. scytophylla</i>	●	
<i>Q. subpathulata</i>	●	
<i>Q. depressipes</i>	●	
<i>Q. intricata</i>	●	
<i>Q. tardifolia</i>	●	
<i>Q. clivicola</i>		●
<i>Q. sartorii</i>		●
<i>Q. agrifolia</i>	●	
<i>Q. dumosa</i>	●	
<i>Q. urbanii</i>	●	
<i>Q. virginiana</i>		●
<i>Q. coahuilensis</i>		●
<i>Q. carmenensis</i>		●
Family Ericaceae		
<i>Arbutus xalapensis</i> var. <i>texana</i>		●
<i>A. arizonica</i>	●	
<i>Arctostaphylos pungens</i>	●	
<i>A. glauca</i>	●	
<i>A. peninsularis</i>	●	
<i>A. platyphylla</i>	●	
Total species, 149; Common species, 6	101	55

5.1 Ectomycorrhizal Fungi

Some common species from the Sierra Madre Occidental SMW, Sierra Madre Oriental SME and boletes from submontane thorn scrubs close to the SME are represented in Figures 2, 3 and 4. Table 2 compiles ectomycorrhizal fungi in Mexico, USA and Canada.

6. Data Analysis

6.1 Qualitative Analysis

Qualitative similarity indices are non-parametric techniques that allow the analysis of the percentage of similarity between two communities based on the number of species they share, i.e., present at both sites, as well as the total number of species present. The index used was Jaccard.

6.1.1 Jaccard's Index of Similarity

According to the similarity matrix obtained with the Jaccard's index, it can be observed that the sites with the greatest similarity of fungal species are SME-Mex/NE-USA (79%), sharing 196 species and SMW-MEX/NW-USA (72%) sharing 176.

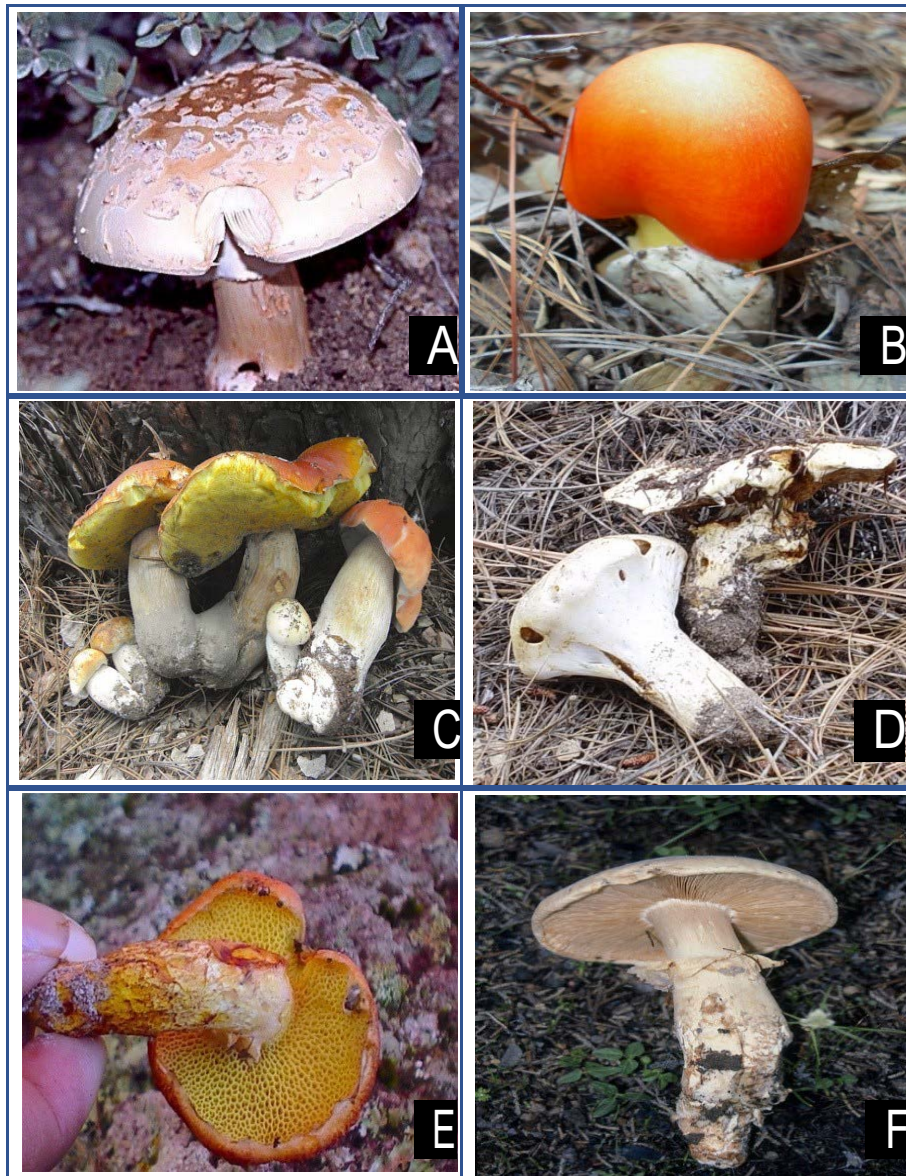


Fig. 2. Some common species from the Sierra Madre Occidental SMW: *Amanita rubescens* (A), *A. cochiseana* (B), *Boletus chippewaensis* (C), *Cortinarius magnivelatus* (D), *Suillus spraguei* (E) and *Tricholoma magnivelare* (F).

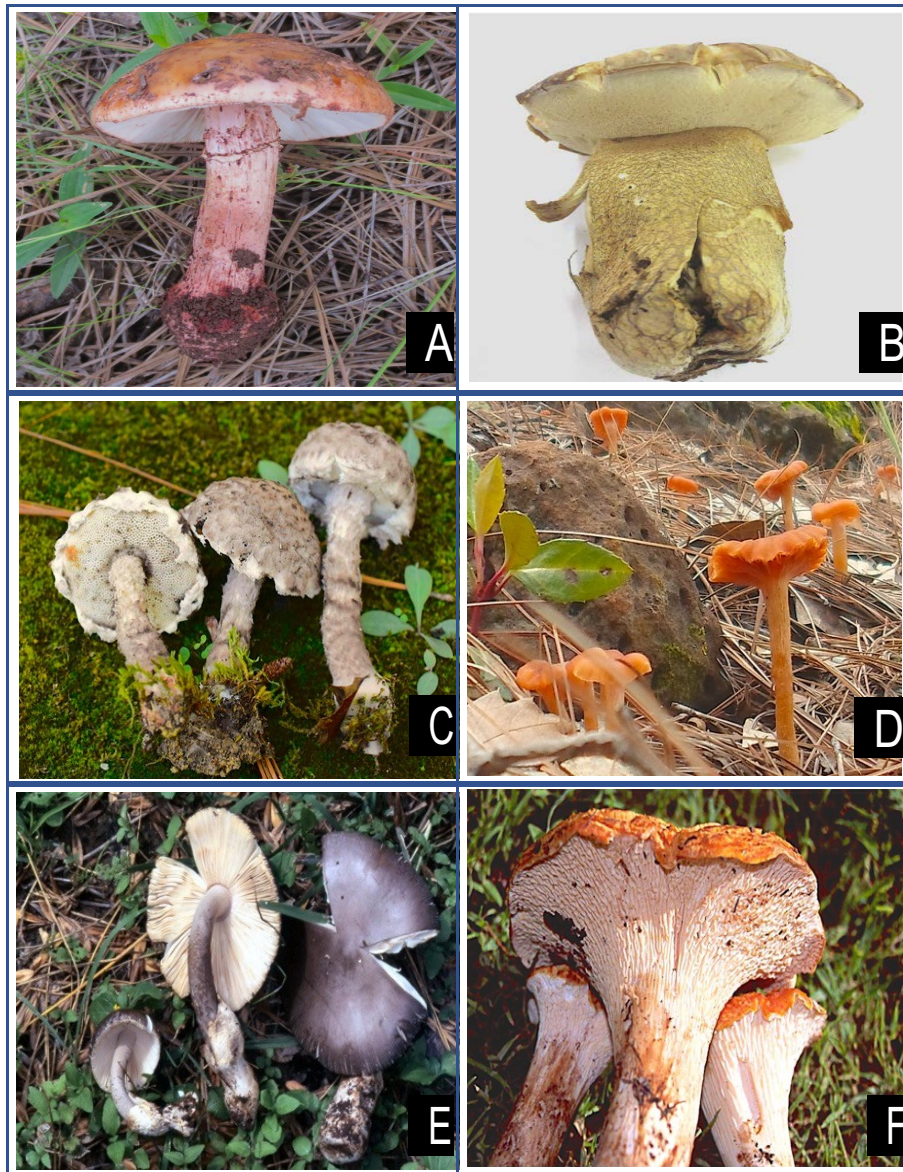


Fig. 3. Some common species from the Sierra Madre Oriental SME: *Amanita rubescens* (A), *Boletus inedulius* (B), *Strobilomyces dryinus* (C), *Laccaria laccata* (D), *Amanita vaginata* var. *plumbea* (E) and *Turbinellus floccosus* (F).

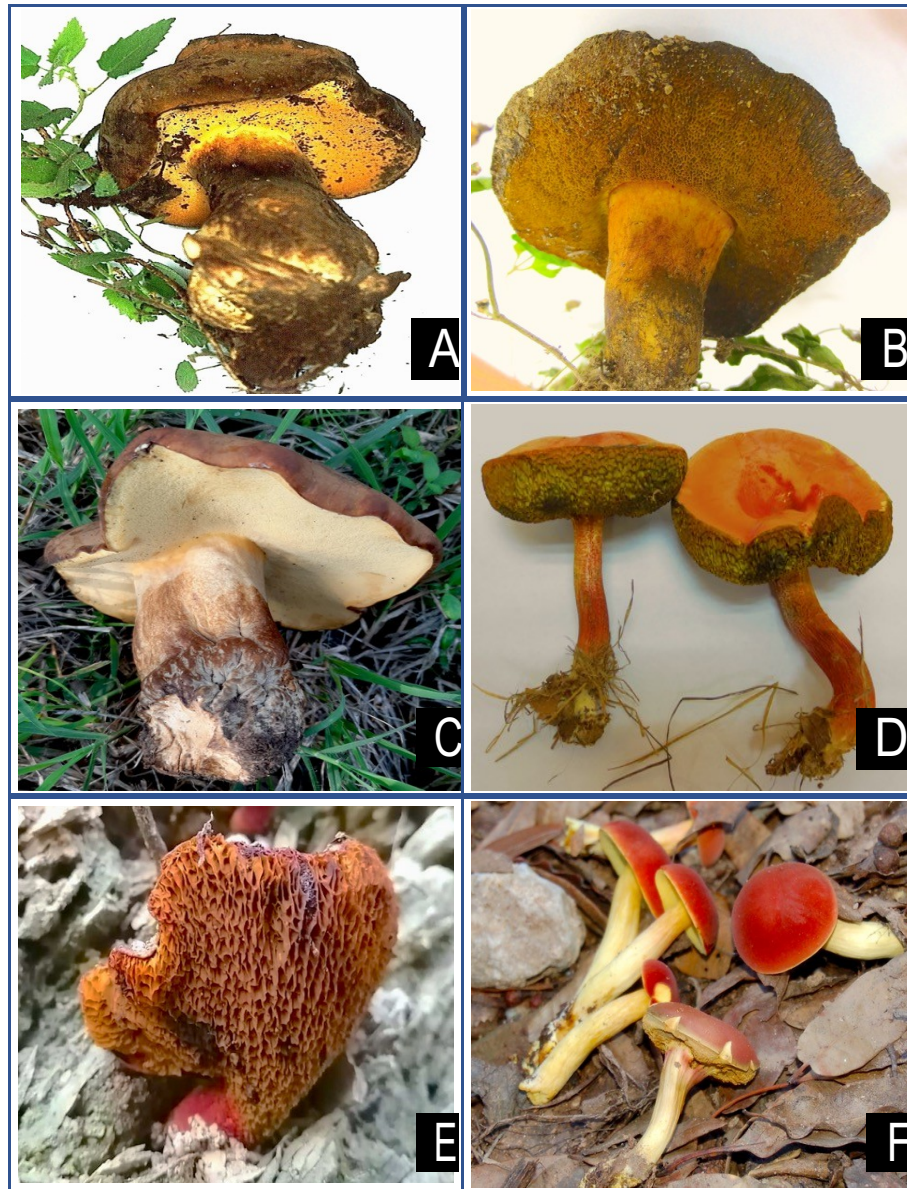


Fig. 4. Some common Boletes from submontane thorn scrubs close to the SME: A. *Phlebopus portentosus* (A), *Phlebopus brassiliensis* (B), *Phlebopus* aff. *mexicanus* (C), *Boletus paulae* (D), *Boletinellus romPELLI* (E) and *Hortiboletus rubellus* (F).

Table 2. Ectomycorrhizal fungi reported and their distribution in Sierras in Mexico, northwest of USA, northeast of USA and northeast Canada.

	SMW-MEX	NW-USA	SMEi-MEX	NE-USA	NE-CAN
ASCOMYCOTA					
ORDER EUROTIALES					
Family Elaphomycetaceae					
<i>Elaphomyces granulatus</i>			●	●	
ORDER PEZIZALES					
Family Discinaceae					
<i>Hydnotrya cerebriformis</i>			●	●	
Family Pezizaceae			●	●	
<i>Hydnobolites cerebriformis</i>			●		
<i>Pachyphlodes carnea</i>			●	●	
<i>P. citrina</i>	●	●	●	●	
<i>P. marronina</i>			●		
<i>P. virescens</i>			●	●	
<i>Sarcosphaera coronaria</i>	●	●	●		
Family Pyronemataceae					
<i>Genea hispidula</i>			●	●	
<i>G. arenaria</i>			●	●	
<i>Gilkeya compacta</i>			●	●	
<i>Sphaerosporella brunnea</i>	●	●			
<i>Tricharina gilva</i>	●				
<i>Trichophaea hemisphaerioides</i>	●	●			
Family Tuberaceae					
<i>Tuber candidum</i>			●	●	
<i>T. dryophilum</i>	●				
<i>T. lyonii</i>			●	●	
<i>T. regimontanum</i>	●				
BASIDIOMYCOTA					
ORDER AGARICALES					
Family Tricholomataceae					
<i>Infundibulicybe gibba</i>	●	●	●	●	
Family Amanitaceae					
<i>Amanita abrupta</i>	●	●	●	●	
<i>A. amerifulva</i>	●		●	●	
<i>A. amerirubescens</i>	●				
<i>A. atkinsoniana</i>	●				
<i>A. basii</i>	●	●	●		
<i>A. bisporigera</i>	●		●	●	●
<i>A. calypetroderma</i>	●	●			●
<i>A. ceciliae</i>	●		●	●	●
<i>A. chlorinosma</i>	●		●		●
<i>A. citrina</i>	●	●	●	●	●
<i>A. cochiseana</i>	●	●	●		
<i>A. cokeri</i>	●		●		
<i>A. crocea</i>	●		●		
<i>A. daucipes</i>	●			●	
<i>A. flavoconia</i>	●	●	●	●	●
<i>A. flavorubescens</i>	●	●		●	
<i>A. frostiana</i>	●	●	●	●	●
<i>A. fulva</i>	●	●			●
<i>A. gemmata</i>	●	●	●	●	●
<i>A. jacksonii</i>	●		●	●	
<i>A. magniverrucata</i>	●	●			
<i>A. multisquamosa</i>			●	●	

<i>A. muscaria</i>	●		●		
<i>A. ocreata</i>	●	●			
<i>A. onusta</i>	●	●	●		
<i>A. pantherina</i>	●	●	●		
<i>A. peckiana</i>	●	●			
<i>A. perpasta</i>	●	●			
<i>A. phalloides</i>	●	●		●	
<i>A. polypyramis</i>			●	●	
<i>A. porphyria</i>	●	●			
<i>A. rhopalopus</i>	●	●			●
<i>A. rubescens</i>	●	●	●	●	●
<i>A. smithiana</i>	●	●			
<i>A. sprete</i>	●	●		●	
<i>A. strobiliformis</i>	●	●			
<i>A. tuza</i>	●				
<i>A. vaginata</i>	●	●	●	●	●
<i>A. variabilis</i>	●	●			
<i>A. verna</i>	●		●		
<i>Aspidella solitaria</i>	●		●		
<i>Zhuliangomyces illinitus</i>			●	●	
Family Cortinariaceae					
<i>Calonarius odorifer</i>	●	●			
<i>Cortinarius alboviolaceus</i>	●		●		●
<i>C. atkinsonianus</i>			●	●	
<i>C. brunneus</i>	●	●			
<i>C. camphoratus</i>			●	●	
<i>C. caperatus</i>	●	●			●
<i>C. cinnamomeus</i>	●	●	●	●	●
<i>C. collinitus</i>	●	●	●	●	●
<i>C. corrugatus</i>	●	●			
<i>C. elegantissimus</i>	●	●			
<i>C. evernius</i>			●	●	
<i>C. flexipes</i>			●	●	
<i>C. hemitrichus</i>					
<i>C. iodes</i>			●	●	
<i>C. magnivelatus</i>	●	●	●		
<i>C. marylandensis</i>			●	●	
<i>C. pinetorum</i>					
<i>C. purpureus</i>	●				
<i>C. sanguineus</i>	●	●	●	●	●
<i>C. semisanguineus</i>	●	●	●	●	●
<i>C. smithii</i>	●				
<i>C. traganus</i>	●				
<i>C. violaceus</i>	●	●	●	●	●
<i>Thaxterogaster corrugis</i>	●	●			●
<i>T. talus</i>			●		
Family Hydnagiaceae					
<i>Laccaria amethystina</i>	●	●	●	●	●
<i>L. bicolor</i>	●	●	●	●	
<i>L. laccata</i>	●		●		
<i>L. laccata</i>	●		●		●
<i>L. proxima</i>	●				
<i>L. ochropurpurea</i>	●	●	●	●	●
Family Inocybaceae					
<i>Inocybe confusa</i>	●				
<i>I. geophylla</i>			●	●	
<i>I. geophylla</i> var. <i>geophylla</i>			●	●	
<i>I. hystrix</i>	●		●	●	
<i>I. lacera</i>	●	●	●	●	
<i>I. nemorosa</i>			●	●	
<i>Inosperma calamistratum</i>	●	●	●	●	
<i>I. erubescens</i>			●		
<i>I. maculatum</i>	●	●	●		

<i>Pseudosperma rimosum</i>	●	●	●	●	
<i>P. sororium</i>	●	●	●	●	
Family Tricholomataceae					
<i>Leucopaxillus albissimus</i>	●	●	●	●	
<i>L. gentianeus</i>	●	●	●	●	
<i>L. paradoxus</i>	●				
<i>Tricholoma caligatum</i>			●	●	
<i>T. equestre</i>	●	●	●	●	●
<i>T. magnivelare</i>	●	●			
<i>T. pardinum</i>			●	●	
<i>T. saponaceum</i>	●	●			
<i>T. sejunctum</i>	●	●	●	●	
<i>T. sulphurescens</i>	●	●	●	●	
<i>T. terreum</i>	●	●	●	●	
<i>T. ustaloides</i>	●	●	●		
<i>T. vaccinum</i>	●	●	●	●	●
<i>T. virgatum</i>			●	●	●
ORDER BOLETALES					
Family Boletaceae					
<i>Aureoboletus auriporus</i>	●		●	●	
<i>A. betula</i>	●	●			
<i>A. moravicus</i>			●	●	
<i>A. russellii</i>	●	●	●	●	●
<i>A. projectellus</i>			●	●	
<i>A. gracilis</i>	●	●	●	●	●
<i>Baorangia bicolor</i>	●	●	●	●	●
<i>Boletellus ananas</i>	●		●	●	
<i>B. chrysenderoides</i>	●	●	●	●	●
<i>B. coccineus</i>	●				
<i>B. flocculosipes</i>	●				
<i>B. pseudochrysenderoides</i>	●		●		
<i>B. meruloides</i>			●	●	●
<i>B. rompelii</i>			●	●	
<i>Boletus aureissimus</i>	●		●	●	
<i>B. barrowsii</i>	●	●	●		
<i>B. chippewaensis</i>	●	●			
<i>B. edulis</i>	●	●	●		●
<i>B. flammans</i>	●	●	●	●	
<i>B. luridellus</i>			●	●	
<i>B. paulae</i>			●		
<i>B. pinophilus</i>	●	●	●	●	
<i>B. pseudopinophilus</i>	●	●	●	●	
<i>B. rubriceps</i>	●	●			
<i>B. sensibilis</i>	●	●			
<i>B. subgraveolens</i>			●	●	
<i>B. subluridellus</i>	●	●	●	●	
<i>B. variipes</i>	●	●	●	●	
<i>B. vermiculosus</i>	●	●			
<i>Buchwaldoboletus hemichrysus</i>	●	●			
<i>Butyriboletus brunneus</i>			●	●	
<i>B. floridanus</i>	●	●	●	●	
<i>B. frostii</i>	●	●	●	●	●
<i>B. peckii</i>			●	●	
<i>B. regius</i>			●	●	
<i>Caloboletus rubripes</i>	●	●			
<i>Chalciporus piperatus</i>			●	●	
<i>Cyanoboletus pulverulentus</i>			●		
<i>Harrya chromipes</i>	●	●	●	●	●
<i>Heimioporus ivoryi</i>			●	●	
<i>Hemileccinum rubropunctum</i>	●		●	●	
<i>Hortiboletus campestris</i>			●	●	
<i>Hortiboletus rubellus</i>			●	●	

<i>Imleria badia</i>	●		●	●	
<i>Leccinellum albellum</i>			●	●	
<i>L. griseum</i>	●	●	●	●	
<i>L. quercophilum</i>	●	●			
<i>L. rugosiceps</i>	●		●		
<i>Leccinum aeneum</i>	●	●			
<i>L. aurantiacum</i>	●	●			
<i>L. insigne</i>	●	●	●	●	●
<i>L. manzanitae</i>	●	●			
<i>L. versipelle</i>	●	●			
<i>L. vulpinum</i>	●	●			
<i>Neoboletus luridiformis</i>	●	●	●	●	
<i>Phylloporus leucomycelinus</i>	●	●	●	●	●
<i>P. rhodoxanthus</i>	●	●	●	●	
<i>P. cyaneotinctus</i>	●	●	●	●	
<i>P. porphyrosporus</i>	●	●	●	●	●
<i>Pulchroboletus rubricitrinus</i>	●	●			
<i>P. ravenelii</i>	●	●	●	●	
<i>Retiboletus griseus</i>	●	●			●
<i>R. ornatipes</i>	●			●	●
<i>Rubinoboletus caespitosus</i>					
<i>R. eastwoodiae</i>	●	●			
<i>R. pulcherrimus</i>	●	●			
<i>Strobilomyces confusus</i>	●	●	●	●	
<i>S. strobilaceus</i>	●	●	●	●	●
<i>S. dryophilus</i>			●	●	
<i>Suillellus amygdalinus</i>	●	●			
<i>S. luridus</i>	●	●	●	●	
<i>S. hypocarycinus</i>			●	●	
<i>S. subvelutipes</i>	●	●	●	●	
<i>Sutorius eximius</i>	●	●	●	●	●
<i>Tylopilus alboater</i>	●	●	●	●	
<i>T. balloui</i>			●	●	
<i>T. felleus</i>	●	●	●	●	●
<i>T. ferrugineus</i>	●	●	●	●	
<i>T. plumbeoviolaceus</i>	●	●	●	●	
<i>T. subcellulosus</i>			●		
<i>T. tabacinus</i>			●	●	
<i>T. williamsii</i>			●	●	
<i>Xanthoconium affine</i>			●	●	
<i>Xerocomellus porosporus</i>			●	●	
<i>X. truncatus</i>	●	●	●	●	
<i>Xerocomus illudens</i>	●	●	●	●	
<i>X. subtomentosus</i>			●	●	
Family Boletinellaceae					
<i>Phlebopus brasiliensis</i>			●		
<i>P. mexicanus</i>			●		
<i>P. portentosus</i>			●	●	
Family Diplocystidiaceae					
<i>Astraeus hygrometricus</i>	●	●	●	●	
<i>A. pteridis</i>	●	●	●		
Family Gomphidiaceae					
<i>Chroogomphus jamaicensis</i>			●		
<i>C. rutilus</i>	●	●			●
<i>C. vinicolor</i>	●	●	●	●	●
<i>Gomphidius glutinosus</i>	●	●	●	●	●
<i>G. subroseus</i>	●	●			
Family Gyroporaceae					
<i>Gyroporus castaneus</i>	●	●	●	●	
<i>G. subalbellus</i>			●	●	
Family Paxillaceae					
<i>Melanogaster variegatus</i>					
<i>Paragyrodon sphaerosporus</i>	●				

<i>Paxillus involutus</i>	●	●	●	●	●
Family Rhizopogonaceae					
<i>Rhizopogon luteolus</i>	●	●			
<i>R. occidentalis</i>	●	●			
<i>R. roseolus</i>	●	●	●		
<i>R. subcaerulescens</i>	●	●			
Family Sclerodermataceae					
<i>Pisolithus arhizus</i>	●	●	●	●	
<i>Scleroderma areolatum</i>	●		●	●	
<i>S. cepa</i>	●	●	●	●	
<i>S. citrinum</i>			●	●	
<i>S. polyrhizum</i>	●	●			
<i>S. texense</i>			●	●	
<i>S. verrucosum</i>	●		●	●	
Family Suillaceae					
<i>Suillus americanus</i>			●	●	●
<i>S. cothurnatus</i>	●	●	●	●	
<i>S. brevipes</i>	●	●	●	●	
<i>S. cavipes</i>			●	●	
<i>S. granulatus</i>	●	●	●	●	●
<i>S. lakei</i>			●	●	●
<i>S. luteus</i>	●	●	●	●	
<i>S. placidus</i>			●	●	●
<i>S. pseudobrevipes</i>	●	●	●	●	●
<i>S. spraguei</i>	●	●			●
<i>S. tomentosus</i>	●	●	●	●	●
ORDER CANTHARELLALES					
Family Hydnaceae					
<i>Cantharellus cibarius</i>	●	●	●	●	●
<i>C. cinnabarinus</i>	●	●	●	●	●
<i>C. ignicolor</i>			●	●	
<i>C. lateritius</i>			●	●	
<i>C. minor</i>	●	●			●
<i>Clavulina amethystina</i>	●				
<i>C. cinerea</i>	●	●	●	●	
<i>Craterellus cornucopioides</i>	●	●	●	●	●
<i>C. tubaeformis</i>		●	●	●	●
<i>Hydnum albidum</i>			●	●	
<i>H. repandum</i>	●		●	●	
<i>H. rufescens</i>	●				
ORDER GOMPHALES					
Family Clavariadelphaceae					
<i>Clavariadelphus truncatus</i>	●	●	●		
<i>C. pistillaris</i>	●	●	●	●	
Family Gomphaceae					
<i>Gautieria</i> sp.			●	●	
<i>Gomphus clavatus</i>			●	●	●
<i>Ramaria botrytis</i>	●		●		
<i>R. flava</i>	●		●		
<i>R. formosa</i>	●	●	●	●	
<i>R. rubricarnata</i>			●		
<i>R. subbotrytis</i>	●	●	●		
<i>Turbinellus floccosus</i>	●		●		●
ORDER HYMENOGHAETALES					
Family Hymenochaetaceae					
<i>Coltricia cinnamomea</i>	●	●	●	●	●
<i>C. focicola</i>	●	●			
<i>C. montagnei</i>			●	●	●
<i>C. perennis</i>			●	●	●
ORDER RUSSULALES					
Family Albatrellaceae					
<i>Albatrellopsis ellisii</i>	●	●			
<i>A. flettii</i>	●	●			

<i>Albatrellus confluens</i>	●	●			
Family Russulaceae					
<i>Lactarius argillaceifolius</i>	●	●	●	●	
<i>L. camphoratus</i>			●	●	
<i>L. chelidonium</i>			●	●	
<i>L. chrysorrheus</i>			●	●	●
<i>L. corrugis</i>	●	●	●	●	
<i>L. croceus</i>	●	●			
<i>L. deterrimus</i>	●	●	●	●	●
<i>L. indigo</i>			●	●	●
<i>L. lignyotus</i>			●	●	
<i>L. olympianus</i>	●		●		
<i>L. paradoxus</i>			●	●	
<i>L. rimosellus</i>			●	●	
<i>L. rufus</i>	●	●	●	●	●
<i>L. rubrilacteus</i>	●	●			
<i>L. salmoneus</i>			●	●	
<i>L. scrobiculatus</i>	●	●	●	●	●
<i>L. subpalustris</i>	●	●			
<i>L. torminosus</i>	●		●	●	●
<i>L. uvidus</i>	●	●	●	●	
<i>L. vellereus</i>	●	●			
<i>L. zonarius</i>		●	●		
<i>Lactifluus corrugis</i>			●	●	
<i>L. hygrophoroides</i>					●
<i>L. piperatus</i>	●	●	●	●	●
<i>L. volemus</i> var. <i>volemus</i>	●	●	●	●	
<i>Laeticutis cristata</i>	●	●	●		
<i>Multifurca furcata</i>	●		●	●	
<i>Russula acrifolia</i>	●				
<i>R. aeruginea</i>	●	●	●		
<i>R. albonigra</i>	●	●	●	●	
<i>R. americana</i>	●	●			
<i>R. atropurpurea</i>			●	●	
<i>R. brevipes</i>	●	●	●	●	●
<i>R. claroflava</i>	●				
<i>R. cyanoxantha</i>	●	●	●	●	
<i>R. decolorans</i>			●	●	●
<i>R. emetica</i>	●	●	●	●	●
<i>R. flavida</i>	●	●	●	●	
<i>R. foetens</i>	●	●	●	●	
<i>R. foetentula</i>			●		
<i>R. fragilis</i>			●	●	
<i>R. mariae</i>	●		●		●
<i>R. nana</i>	●	●			
<i>R. adusta</i>	●		●		●
<i>R. ochroleuroides</i>			●	●	
<i>R. olivacea</i>	●		●	●	●
<i>R. parvovirescens</i>			●	●	
<i>R. risigallina</i>	●		●	●	
<i>R. rosea</i>	●		●		
<i>R. sanguinea</i>	●	●	●	●	●
<i>R. silvicola</i>	●				
<i>R. subgraminicolor</i>			●	●	
<i>R. subalutacea</i>	●	●			
<i>R. virescens</i>	●	●	●	●	
<i>R. xerampelina</i>	●	●	●	●	●
ORDER SEBACINALES					
Family Sebacinaceae					
<i>Sebacina schweinitzii</i>	●	●	●	●	
ORDER THELEPHORALES					
Family Bankeraceae					
<i>Hydnellum scabrosum</i>					

<i>H. scrobiculatum</i>			●		
<i>Sarcodon imbricatus</i>	●	●	●	●	
Family Thelephoraceae					
<i>Polyozellus multiplex</i>	●	●			
<i>Phellodon niger</i>	●		●	●	
<i>Thelephora caryophyllea</i>	●	●	●	●	●
<i>T. palmata</i>	●	●			●
<i>T. terrestris</i>	●	●	●	●	●
<i>Tomentella</i> sp.	●		●		
Total species, 350; Common species, 45	248	185	253	165	82

Note: The number of records covering the total regions is 350 species, of which 253 are present in the SME-MEX, 248 different species at the SMW-MEX, 185 species at NW USA, 165 in NE USA and 82 in the NE-CAN regions.

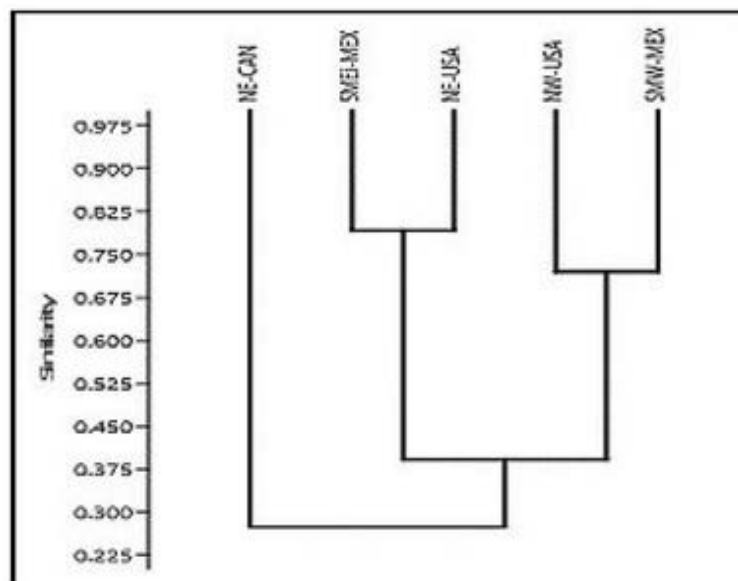


Fig. 5. Similarity analysis of ECM species.

related species, that is, present in both sites, being greater than 50% of the total species present throughout the area ($n = 175$). The Jaccard index ranges from 0 to 1 (0–100%). The lowest similarity values were for all NE-CAN-related areas (less than 30%) mainly because it is the area with the lowest species richness (Tables 3, 4).

6.1.2 Jaccard's Similarity Cluster

The cluster analysis indicates that two groups are formed between the study areas, the first and with greater similarity is formed by SME-MEX/NE-USA, while a second is formed by NW-USA/SMW-MEX (Fig. 5).

Table 3. Distribution of the species in different regions.

Region	Species richness	(%)
SMW-MEX	248	70.8
NW-USA	185	74
SME-MEX	253	72.2
NE-USA	165	65
NE-CAN	82	23.42
Total species richness (S)	350	100%

Table 4. Values above the diagonal indicate the percentage of similarity (%) according to the Jaccard's index (values below the diagonal indicate the number of species that share between pairs of sites).

	SMW-MEX	NW-USA	SME-MEX	NE-USA	NE-CAN
SMW-MEX		71.94	46.09	38.55	25.86
NW-USA	176		35.91	36.21	28.50
SME-MEX	151	114		79.15	26.42
NE-USA	122	99	196		28.76
NE-CAN	66	57	69	60	

7. Generalists with a Wide Distribution

A categorization of species was carried out based on their presence in the distribution areas. Generalist species that occur at the five study sites. A very frequent species is that species present in four sites of the five studied and a particular species is that present in a single record site. The results show that 52 species are reported at the five sites and can be considered generalists, i.e., with a wide distribution. Also, there are 51 very frequent species, that is, they occur in four sites and 28 are specific species, that is, they are only reported in a single site. Regarding the specific distribution species, 18 of them are reported only in the SMW-MEX area and 10 in SME-MEX.

8. Ecological Interactions of Mushrooms with Animals

Current knowledge on the diversity of macromycetes species from the north of Mexico is increasing due to the use of molecular methods that are helping to identify some species (Garza et al., 2022). Diversity of oaks and conifer species is high in both the SMW and SME

and together with soil, climate, and altitudinal variables they help to understand how the establishment of macromycetes species in different locations establish (Garza et al., 2019; Sridhar and Deshmukh, 2019). Oak diversity can reach more than 70 species and that of pines can be of more than 50 species (García, 2016). So far, results show that all oak and conifer species form ectomycorrhizas with a high diversity of macromycetes and they are widely dispersed in the geographic panorama in the north of Mexico (Pérez Silva and Acosta, 1986; Garcia and Garza, 2001; Quiñonez et al., 2008, 2014, 2015; García et al., 2019). The distances from one locality to another are huge and the phenology of fruiting body production varies from one place to another and from one Sierra to another, many fungal species have been found either in the Pacific or Atlantic coast of the USA, Canada, and Mexico. Others have not been studied so far and molecular studies are required to carry out identification studies. Molecular studies are solving many taxonomic problems and help the understanding of fungal distribution in some geographical regions (de la Fuente et al., 2020; Garza et al., 2022). However, even when correct identification has been carried out still many other data are required to understand a bit more about how they are surviving in the different locations (Maser et al., 2008). Thus, it is well known that animal dispersion occurs, and many species are involved in these procedures (Maser et al., 2008). Thus, chipmunks, squirrels, rats, and mice are actively involved in eating mushrooms, deer, peccary, black bear, and other big game species eat mushrooms or depredate mushrooms eater animal species! and, in this way, they also might contribute to dispersing spores in the forests. Thus, close relationships between animal spore dispersers and ectomycorrhizal fungi may explain to a certain extent the isolation that some species (e.g., *Pinus monophylla* in Baja California). If the animal dispersers are varied and different species occur in each of the big Sierras and their locations in the North of Mexico, this information could be very helpful to try to understand a little bit more how important these ecological relationships are for the functioning of forest ecosystems (Elliot et al., 2022). This may also explain to a certain extent how many ectomycorrhizal fungal species are associated with *Pinus cembroides* throughout its distribution in the north and central parts of Mexico as well as in some locations from Arizona. This condition also happens with many other species of ectomycorrhizal fungi that form associations with other conifers (e.g., *Pinus arizonica* or oaks *Quercus fusiformis*) in eastern and western north America and they also grow in the North of Mexico in both Sierras. Perhaps future studies of ectomycorrhizal fungi could elaborate a little more on ecological interactions of these fungal associations (e.g., mushroom dispersion by animals), local climate and soil conditions, altitudinal ranges, geologic substrates, phenology of fruiting bodies and their associated host's species (Elliot et al., 2022). The latter could help to generate more information on the multiple relationships occurring between ectomycorrhizal fungi species in the forests. Both small and big animals (e.g., insects, mites, earthworms, slugs, snails, nematodes, spiders, frogs and toads, birds, snakes, deer, peccary, bear, rats, mice, squirrels, chipmunks, and other species) play important roles either individually or together in the nourishment, recycling, and dispersion of ectomycorrhizal fungal species in the forests (Figs. 6–10) (Maser et al., 2008; Elliot et al., 2022). Mushroom dispersion is an active process, and it has been like that for millions of years up to the present day. Thus, studies considering a more complete analysis could show a different panorama as the mutualistic symbiosis is in fact part of multiple organisms' symbioses based on nutrition and occurring in the forest ecosystems of the world. There are several rare and edible species of mushrooms in Mexico (Figs. 11, 12). However, animal grazing, tree felling, and forest fire have severe threat to the biodiversity of mushrooms in Mexico (Fig. 13).

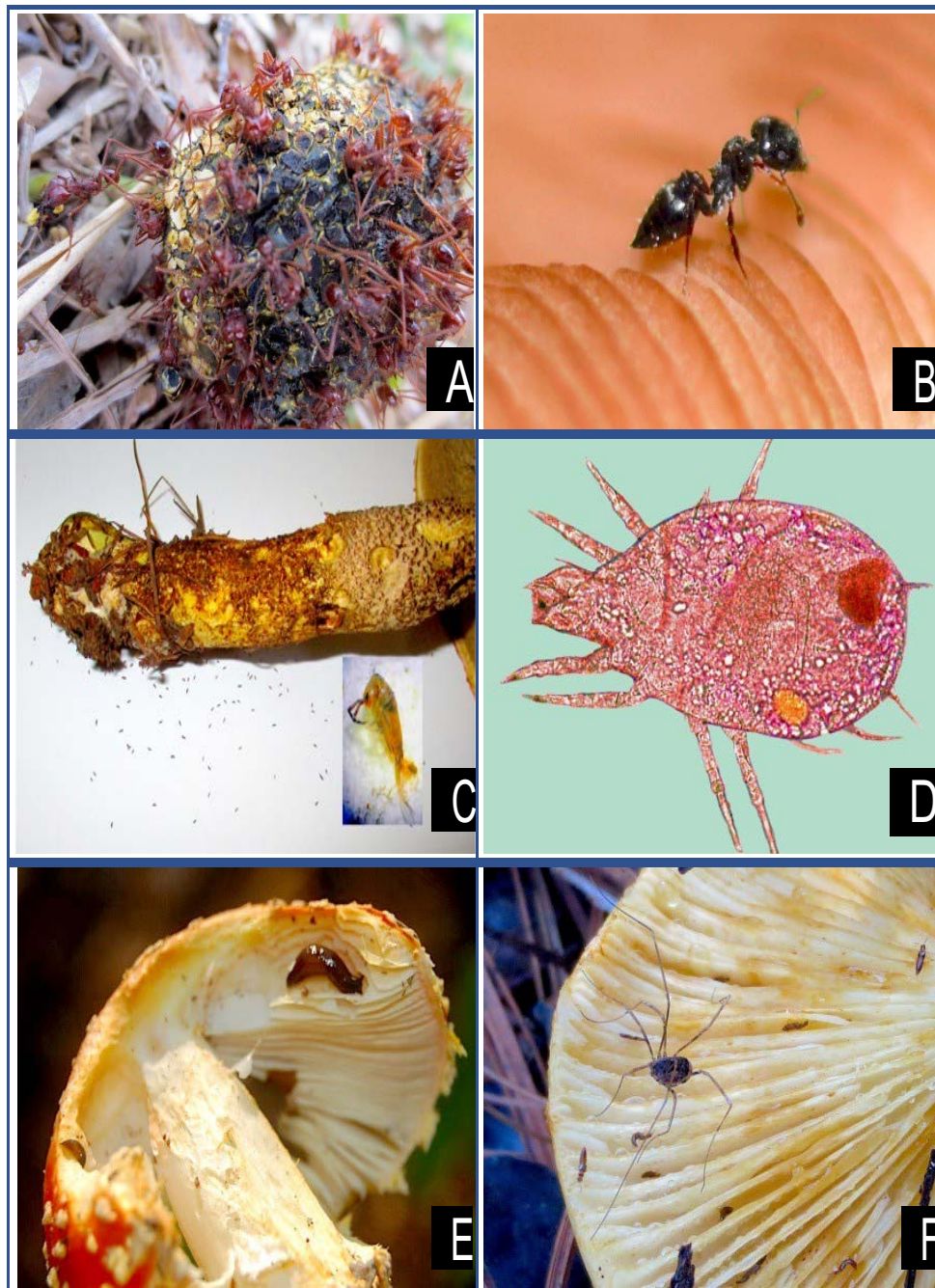


Fig. 6. Interactions of animals and ectomycorrhizal fungi at both Sierras: *Pisolithus arhizus* and *Atta Mexicana* (A); *Agaricus campestris* gills with *Crematogaster* sp. Ant (B); *Leccinum insigne* with springtails *Lepidocyrtus* sp. (C); Mite (D), *Amanita muscaria* var. *flavivolvata* and *Milax gigates* slugs (E); *Lactarius* sp. with Staphilinidae insects in the gills and the spider *Leiobunum* sp. (F).

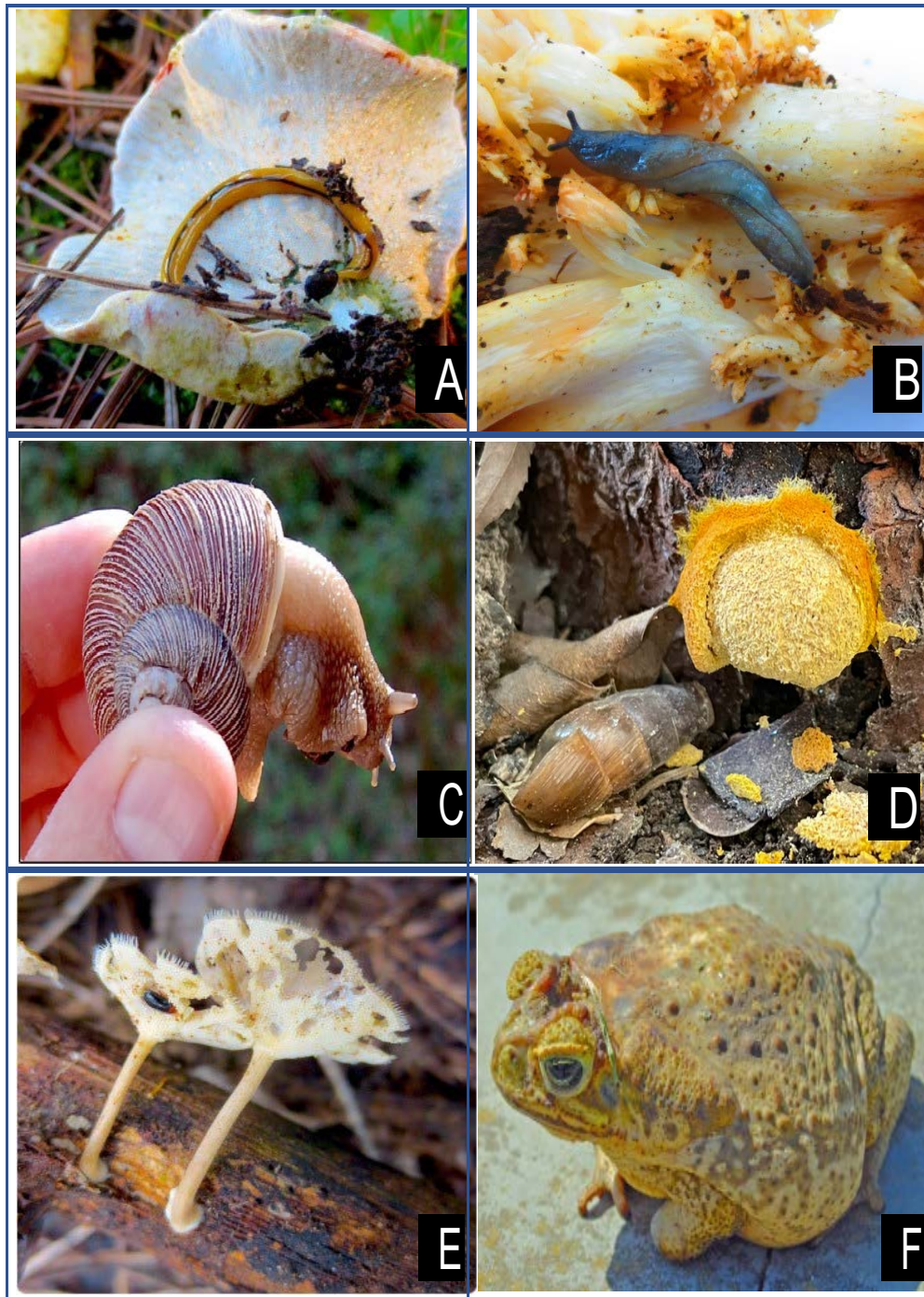


Fig. 7. Interactions of animals and ectomycorrhizal fungi at both Sierras: Hammer flat worm *Bipallium adventium* on *Hypomyces lateritius* (A); Bluish slug *Milax gagates* on *Ramaria flava* (B); *Helix* sp. feeds on many mushroom species (C); *Rumina decollata* eating *Fuligo septica* (D); Insect feeding of *Lentinus arcularius* (E); *Rhinella marina* toad (F).

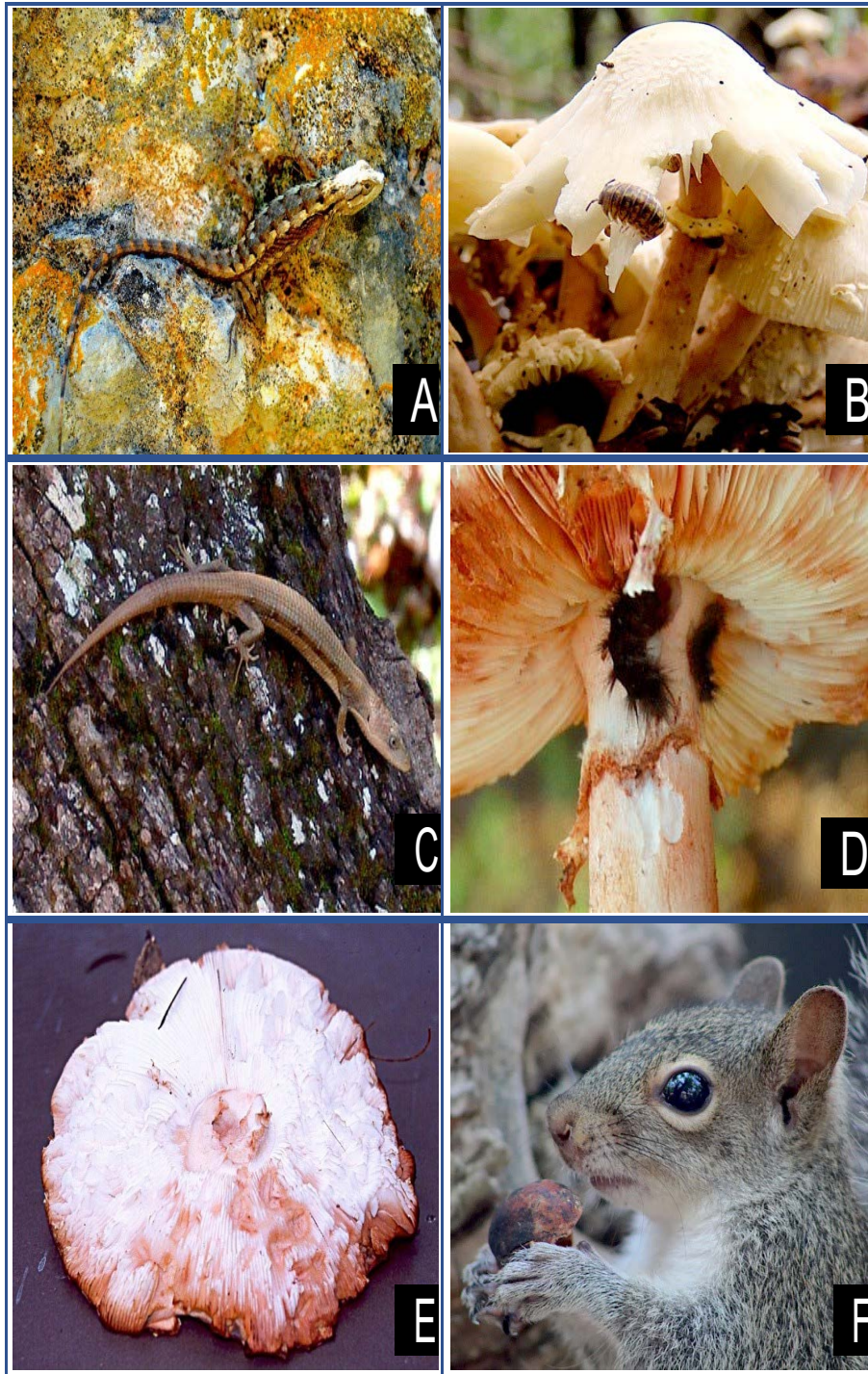


Fig. 8. Interactions of animals and ectomycorrhizal fungi at both Sierras: *Sceloporus olivaceus* lizard (A); *Armadillidium vulgare* (B); Forest caiman lizard *Gerrhonotus ophiurus* (C); Woolly bear carterpillar *Pyrrhactia isabella* feeding on *Amanita novinupta* (D); *Amanita rubescens* gills eaten by rodents (E); Forest grey squirrel *Sciurus caroliniensis* (F).

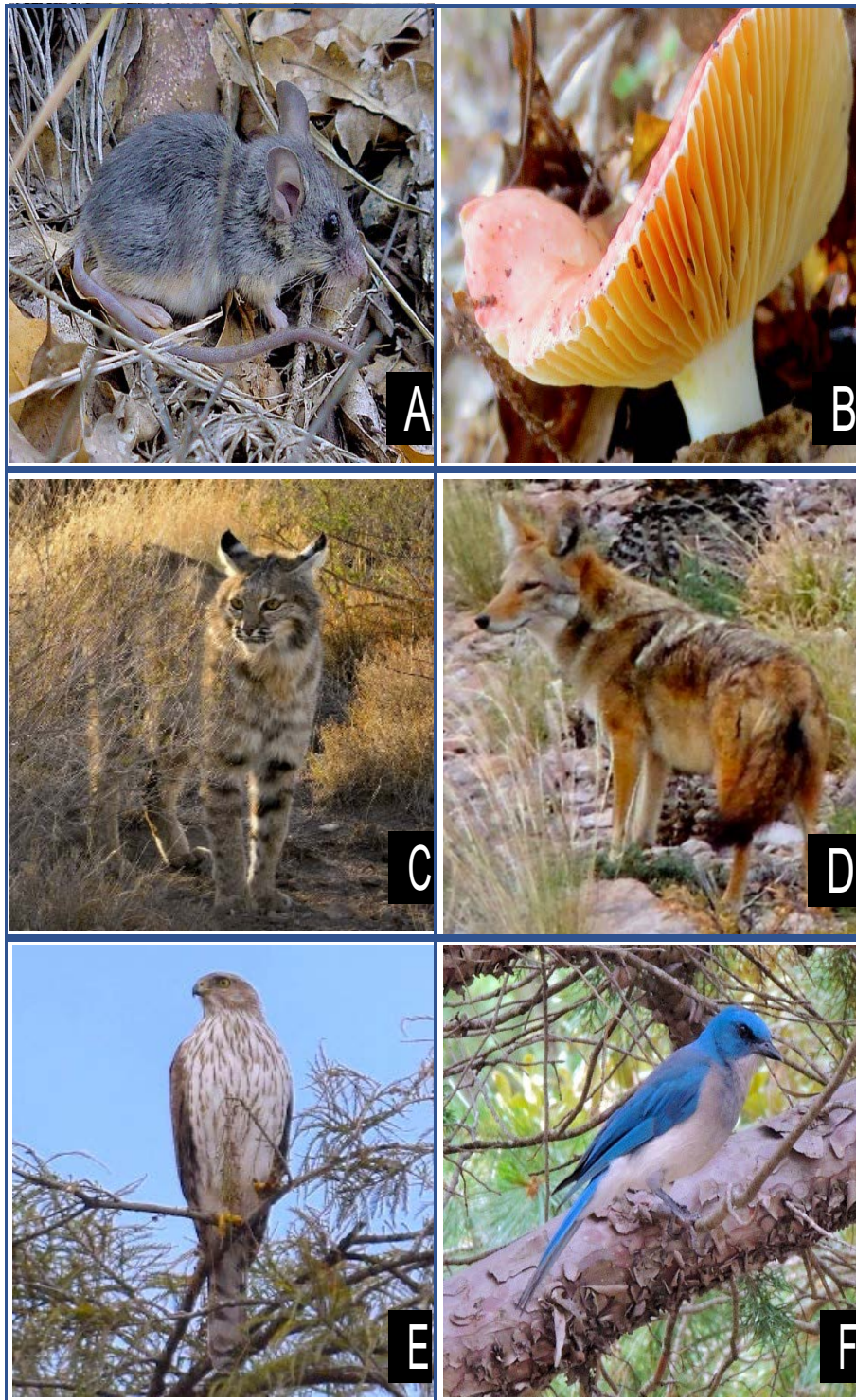


Fig. 9. Interactions of animals and ectomycorrhizal fungi at both Sierras: Mouse *Peromyscus maniculatus* (A); *Russula* sp., with Staphilinidae insects (B); *Lynx rufus* (C); Coyote *Canis latrans* (D); *Accipiter cooperi* hawk (E); Forest blue bird *Apelocoma wollweberi* (F).

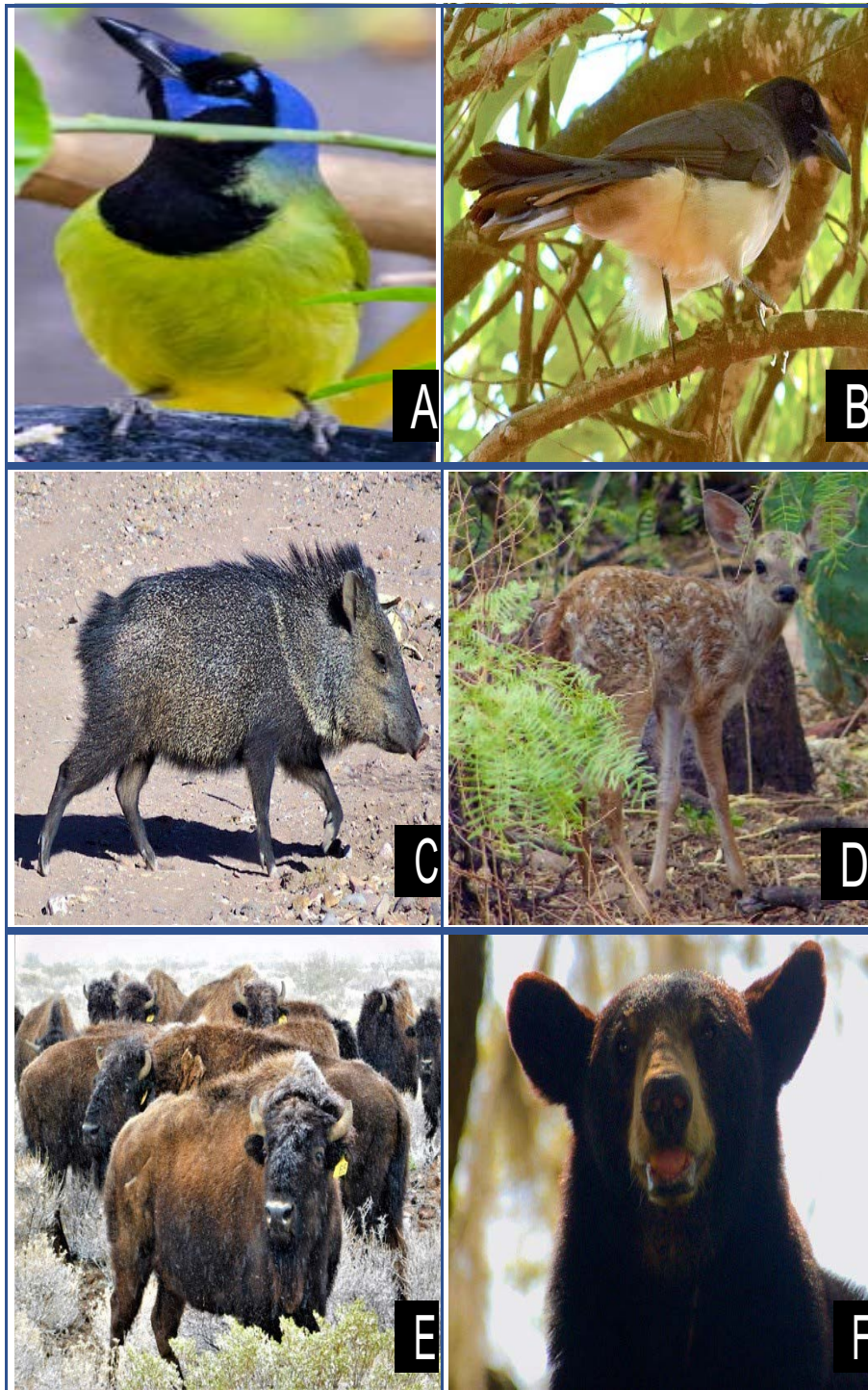


Fig. 10. Interactions of animals and ectomycorrhizal fungi at both Sierras: *Cyanocorax yncas* Chara (A); *Psilorhinus morio* chara papán (B); Wild pig *Pecari tajacu* (C); White tailed deer *Odocoileus virginianus* (D); North American *Bison bison* (E); Black bear *Ursus americanus* (F).

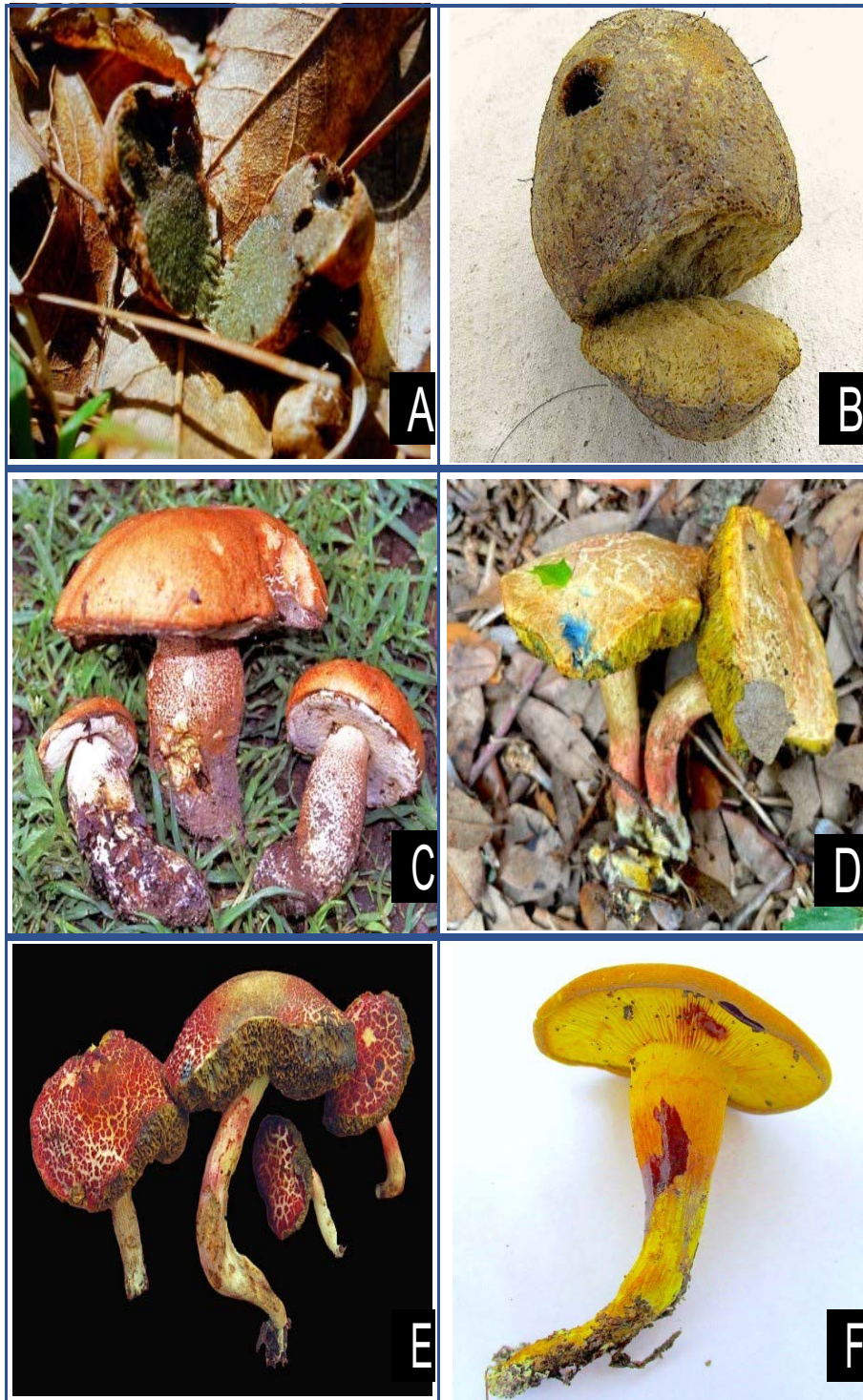


Fig. 11. Rare species found at both Sierras (SMW and SME) in the north of México: *Sclerogaster* sp. (A); *Rhizopogon* sp. (B); *Leccinum aeneus* (C); *Xerocomus* sp. (D); *Xerocomellus carmenae* a new species recently described (E) (Garza et al., 2022); *Paxillus* sp. (F).

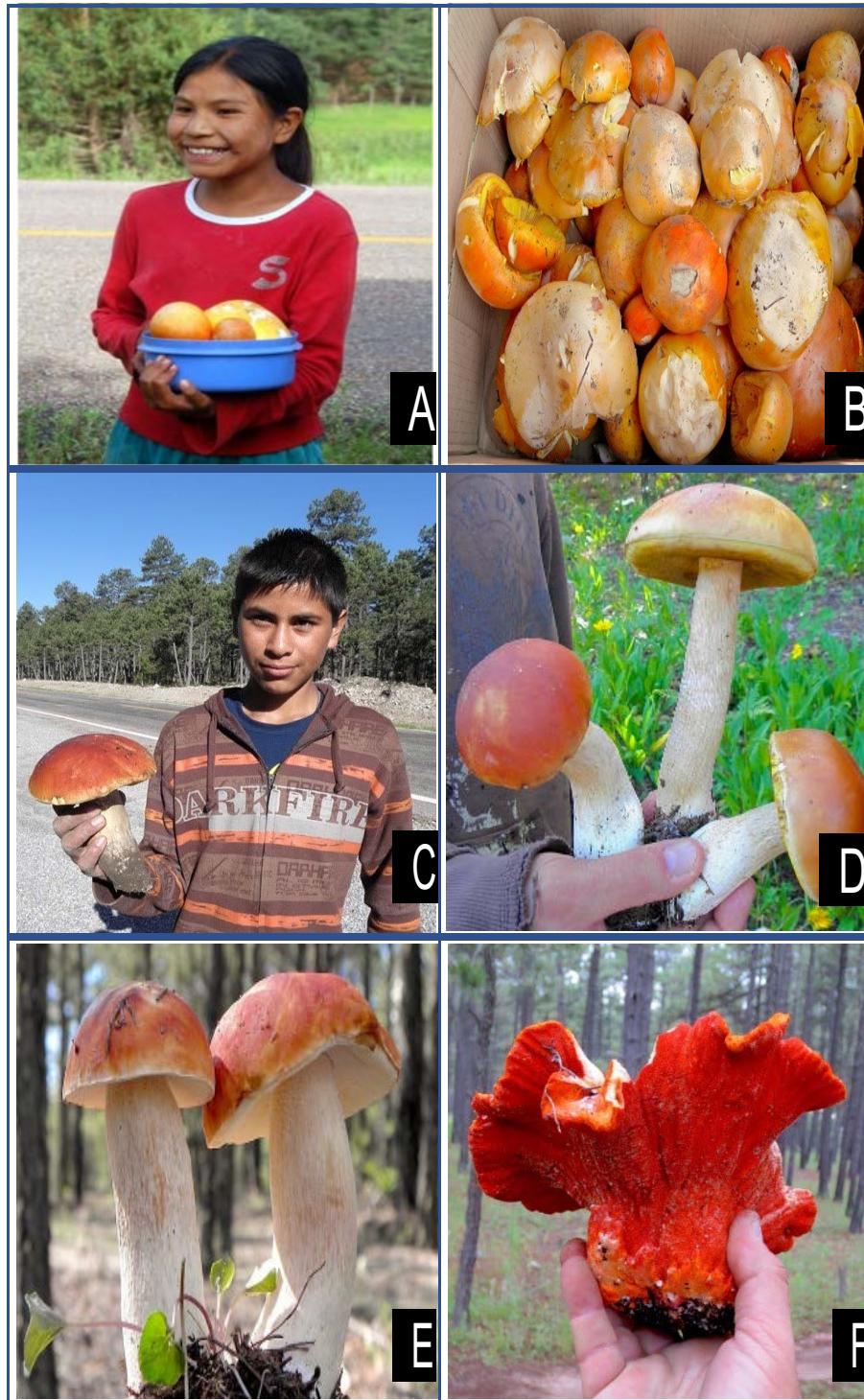


Fig. 12. Edible species and people at the Sierra Madre Occidental (SMW): Girl selling *Amanita cochiseana* by the road (A); *A. cochiseana* (B); Boy showing *Boletus rubriceps* (C); Different *Boletus* species of the *edulis* complex collected for food at SMW (E); *Boletus rubriceps*; *Hypomyces lactifluorum* (F) (Quiñones et al., 2014).

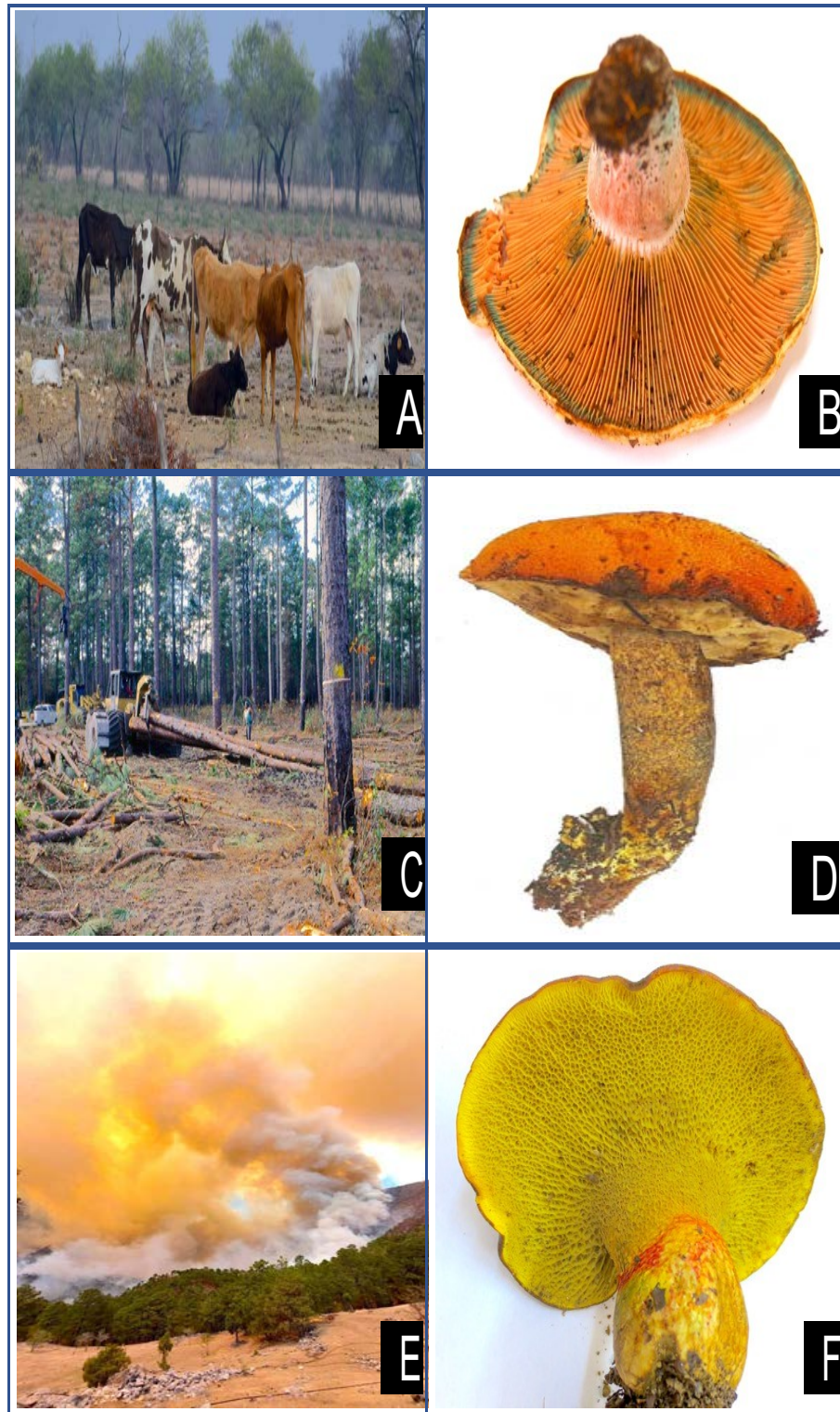


Fig. 13. Some of the activities that threat biodiversity in forests: Cows introduced at forests (A); *Lactarius deliciosus* (B); Lumber activities (C); *Leccinum versipelle* (D); Forest fire (E); *Boletinus merulioides* (F).

9. Discussion

Current knowledge on the diversity of ectomycorrhizal fungi from the north of Mexico is increasing and molecular methods will help to solve some taxonomic problems with some species (Garza et al., 2022). Diversity of oak and conifer species is high in both the SMW and SME and together with soil, climate, and altitudinal variables they help to understand how the establishment of macromycetes species in different locations is going on (Garza et al., 2019; Sridhar and Deshmukh, 2019). Oak diversity can reach more than 70 species and that of pines can be of more than 50 species (García, 2016; Frank et al., 2007; Olimpia et al., 2017). So far results show that all oak and conifer species form ectomycorrhizas with a high diversity of macromycetes and they are widely dispersed in the geographic panorama in the north of Mexico (García and Garza, 2001; García et al., 2014; de la Fuente et al., 2020). The distances from one locality to another are huge and the phenology of fruiting bodies production varies from one place to another and from one Sierra to another, many fungal species have been found either in the pacific or Atlantic coast of the USA, Canada, and Mexico (Barron, 1999; Cripps et al., 2016; McKenny and Stuntz, 1987). Others have not been studied so far (e.g., truffles) and molecular studies are required to carry out identification studies. Phylogenetic studies are solving many taxonomic problems and help the understanding of fungal distribution in some geographical regions (de la Fuente et al., 2020). However, even when correct identification has been carried out still many other data (e.g., mycophagy) are required to understand a bit more about how they are surviving in different locations (Maser et al., 2008; Elliot et al., 2018, 2022). Thus, it is well known that animal dispersion (e.g., mycophagy) occurs and many species are involved in these interesting ecological interactions. Thus, chipmunks, squirrels, rats, and mice are actively involved in eating mushrooms, deer, peccary, bear, and other big game species eat mushrooms or eat mushrooms eater species! and, in this way, they also contribute to dispersing spores in the forests (Maser et al., 2022). Thus, close relationships between animal spore dispersers and ectomycorrhizal fungi may explain to a certain extent the survival in an almost isolated condition that some species might have (e.g., *Pinus monophylla*) in Baja California. If the animal dispersers are varied and different species occur in each of the big Sierras and their locations in the North of Mexico, this information could be very helpful to try to understand a little bit more how important these ecological relationships are for the functioning of forest ecosystems (Elliot et al., 2022). This may also explain to a certain extent how, many ectomycorrhizal fungal species are associated with *Pinus cembroides* throughout its distribution in the north and central parts of Mexico as well as in some locations from Arizona. This condition also happens with many other species of ectomycorrhizal fungi that form associations with other conifers (e.g., *Pinus arizonica* or oaks *Quercus fusiformis*) in eastern and western North America and they also grow in the north of Mexico in both Sierras. Perhaps future studies of ectomycorrhizal fungi could elaborate a little more on ecological interactions of these fungal associations (e.g., mushrooms dispersion by animal species), local climate and soil conditions, altitudinal ranges, geologic substrates, phenology of fruiting bodies and their associated hosts' species. The latter could help to generate more information on the multiple relationships and interactions occurring between ectomycorrhizal fungi species in the forests (Elliot et al., 2022). Both small and big animals (e.g., insects, mites, earthworms, slugs, snails, nematodes, spiders, birds, snakes, deer, peccary, bear, rats, mice, squirrels, and chipmunks) and several species play important roles either individually or together in the nourishment, recycling, and dispersion of

ectomycorrhizal fungal species in the forests (Maser et al., 2008; Pacheco et al., 2014; Santos and Gatica, 2014; Schigel, 2012). Mushroom dispersion is an active process, and it has been like that for millions of years up to the present day. Thus, studies considering a more complete analysis could show a different panorama as the mutualistic symbiosis is in fact part of multiple symbioses occurring in the forest ecosystems of the world. The loss of ectomycorrhizal diversity in the forests can be translated into a degenerated ecosystem that has very different from the original condition and its functionality will be affected and, this condition will bring new challenges for all interacting species (e.g., from the fruit body to the squirrel and up to the wolf) to stay alive.

Conclusion

Temperate forests in the north of Mexico have a great diversity of ectomycorrhizal associations, pines, oak, and other hosts are abundant and many species of animals are nutritionally linked and associated through the mycophagy interactions during the rainy season. These associations are generally overlooked but they play important roles in the distribution of species in the forests. Soil, hosts, climate conditions, altitude and slope also play an important part in the distribution of the different species. Human-related activities (e.g., forest fires, illegal logging, cattle ranchers, and forest fragmentation) together with climate change are threatening the temperate forests and all their associated species. Some species are common in both Sierras as well as in the south of the USA and Canada and they might have shared a common origin in the past.

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