Original Research Article
BIODIVERSITY AND CLIMATE CHANGE IN MEXICO

ABSTRACT

During the last 150 years, the increase in the average temperature of the atmosphere and oceans has been documented due to the increase in the concentration of greenhouse gases produced by the burning of fossil fuels, deforestation, excess production and reduced capacity to capture pollution. The consequences have been radical changes in the distribution of ecosystems and species, rise in sea level, disappearance of glaciers and corals, unpredictable and extreme climates such as droughts and storms. Climate change affects all organisms on the planet, many of them are already responding to this new dynamic through changes in their distribution and migrations. All these factors are the product of human activities and their social, economic and political causes. The effects of human activities, which were previously small-scale, have turned into large-scale events, affecting the climate of the entire planet. Climate change has become one of the main threats to biodiversity. In Mexico, a large number of endemic species of highly restricted distribution are susceptible to be affected by the indicated factors. **Aims:** The objective of this study is to present a set of regional projections of temperature, rainfall, humidity and drought index for Mexico under the IPCC AR6 climate change scenarios, and to evaluate their impact on biodiversity in Mexico by the end of the century. **Methodology and results**: Regional models for Mexico show temperature increases between 0.5 to 5 °C, while % precipitation will range from -20.3 to 13.5% depending on the scenario and period of analysis. The low soil moisture, vegetation changes and drought indices show that the North, West and Bajío areas presented reductions in precipitation and temperature increase that caused soil moisture deficit, water stress, presence of scarce vegetation and semi-permanent meteorological drought. Under these scenarios, it is expected that the entire country will be subjected to moderate to extremely strong droughts that will last and worsen between now and the end of the century. The results of the scenario projections and forecasts made by the IPCC show that the effects on biodiversity associated with climate change have been manifested for several decades in Mexico and are expected to worsen by the end of the century, increasing the number of threatened and endangered species. Based on the probable temperatures by the end of the century (from 0.5 to 5 ° C) it is estimated that the risk of extinction ranges from 3 to 48% in terrestrial ecosystems, in ocean and coastal ecosystems the risk of biodiversity loss will go from moderate to very high; and for endemic species it is estimated that the risk of extinction is very high with the possibility of increase by more than ten times. **Conclusion:** Thus, the vulnerability of biodiversity in Mexico is high to very high, which puts a very high number of species and ecosystems at risk.

Keywords: Biodiversity, climate change, flora, fauna, fungi and microorganisms.

1. INTRODUCTION

Increased greenhouse gas (GHG) emissions are increasing the planet's temperature and causing anthropogenic climate change. The consequences include melting glaciers, rising sea levels, increasing/decreasing precipitation depending on the area of the planet and high frequency of extreme weather events with changes in the weather seasons. The accelerating pace of climate change, coupled with population growth, threatens climate and the health of the world's ecosystems and species.

Climate change is currently an important component of environmental health, as its effects have a direct and indirect impact on ecosystems and their component species (biological, environmental, physical, social, lifestyle and cultural conservation). The effects of climate change are causing an accelerated deterioration of environmental health, which in turn gradually encourages the increase in the threat and disappearance of species and alteration of ecosystems or biomes.

Vulnerability to climate change is the degree to which a natural or social system could be affected by environmental changes. Thus, a vulnerable system is one that is very sensitive to small changes in climate, including the possibility of suffering very harmful effects, or one whose ability to adapt is seriously limited. Vulnerability is framed in a scenario of inequalities, due to the enormous gaps between rich and poor countries, which further accentuates the problem of confronting climate change. All populations will be affected by climate change, but the most vulnerable regions will feel the effects to a greater degree. Thus, poor countries are the area's most vulnerable to the risks resulting from climate change and will also be exposed for a longer time to the consequences of it. Thus, megadiverse countries are the ones that will have the most difficulties in responding to the problems of biodiversity loss due to climate change [1].

This research aims to highlight the impacts of climate change on biodiversity in Mexico, such as the influence of extreme temperatures that contribute to the threat and extinction of species and ecosystems. The present analysis uses regional modelling of climate variables under climate change conditions, using two scenarios to simulate future climate.

BACKGROUND

Biodiversity or biological diversity is the variety of life. This concept includes several levels of biological organization. It covers the diversity of species of plants, animals, fungi and microorganisms that live in a given space, their genetic variability, the ecosystems of which these species are part and the landscapes or regions where the ecosystems are located. It also includes the ecological and evolutionary processes that occur at the level of genes, species, ecosystems and landscapes [2].

Humans have taken advantage of genetic variability and "domesticated" through artificial selection to various species; In doing so we have created a multitude of breeds of corn, beans, pumpkins, chili peppers, horses, cows, sheep and many other species. The varieties of domestic species, the processes used to create them and the oral traditions that maintain them are part of cultural biodiversity [2].

At each of the levels, from genes to landscape or region, we can recognize three attributes: composition, structure, and function. Composition is the identity and variety of elements (includes which species are present and how many are present), structure is the physical organization or pattern of the system (includes relative abundance of species, relative abundance of ecosystems, degree of connectivity, etc.) and function is ecological and evolutionary processes (includes predation, competition, parasitism, dispersal, pollination, symbiosis, nutrient cycling, natural disturbances, etc.) [2].

The biodiversity crisis is the accelerated loss of genetic variety, species and ecosystems due to human activities. It is considered that since the XVII century at least 778 animal species and 124 plant species have been recorded as extinct. If we include human-caused extinctions before 1600, the number rises to more than 2000 extinct species. Currently, more than 41459 plants and animals are under threat and at risk of the same fate (IUCN Red List) [3].

Globally, the sixth IPCC AR6 report (2022) reported that widespread impacts on ecosystems, people, settlements and infrastructure have resulted from observed increases in the frequency and intensity of climate and extreme weather events, including warm extremes on land and in the ocean, heavy rainfall events, drought and fire weather. Impacts such as bleaching and mortality of warm-water corals and increased drought-related tree mortality. Increases observed in areas burned by wildfires have been attributed to human-induced climate change in some regions. The adverse effects of tropical cyclones, with associated loss and damage, have increased due to rising sea levels and increased heavy rainfall. The impacts on natural and human systems of slow-evolving processes such as ocean acidification, sea level rise or regional decrease in precipitation have also been attributed to anthropogenic climate change (IPCC AR6: B.1.1, 2021) [4].

For AR6, climate change has caused substantial damage and increasingly irreversible losses to terrestrial, freshwater and marine coastal and offshore ecosystems. There has been widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, as well as changes in the seasonal calendar due to climate change, with adverse socio-economic consequences. About half of the globally assessed species have moved poleward or, on land, to higher elevations as well. Hundreds of local species losses have been driven by increases in the magnitude of heat extremes, as well as mass mortality events on land and in the ocean and loss of kelp forests. Some losses are already irreversible, such as the first species extinctions driven by climate change. Other impacts approach irreversibility such as the impacts of hydrological changes resulting from glacier retreat, or changes in some mountain and Arctic ecosystems driven by thawing permafrost (IPCC AR6: B.1.2, 2021) [4].

The vulnerability of ecosystems and people to climate change differs substantially between and within regions, driven by patterns of intersectional socio-economic development, unsustainable use of oceans and land, inequity, marginalization, historical and continuing patterns of inequality such as colonialism and governance. A high proportion of species are vulnerable to climate change. Human and ecosystem vulnerability is interdependent. Current patterns of unsustainable development are increasing the exposure of ecosystems and people to climate hazards (IPCC AR6: B.2, 2021) [4].

Since the IPCC AR5, there is growing evidence that human degradation and destruction of ecosystems increases people's vulnerability. Unsustainable land use and land cover change, unsustainable use of natural resources, deforestation, biodiversity loss, pollution and their interactions negatively affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change. The loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for indigenous peoples and local communities that depend directly on ecosystems, to meet basic needs (IPCC AR6: B.2.1, 2021) [4].

Human-induced non-climatic factors exacerbate the current vulnerability of ecosystems to climate change. Globally, and even within protected areas, unsustainable use of natural resources, habitat fragmentation and damage to ecosystems by pollutants increase the vulnerability of ecosystems to climate change. Globally, less than 15% of land, 21% of freshwater and 8% of the ocean are protected areas. In most protected areas, there is insufficient management to contribute to reducing damage or increasing resilience to climate change (IPCC AR6: B.2.2, 2021) [4].

The future vulnerability of ecosystems to climate change will be strongly influenced by the past, present and future development of human society, including from unsustainable consumption and production in general, and increasing population pressures, as well as persistent unsustainable use and management of land, oceans and water. Projected climate change, combined with non-climatic factors, will cause the loss and degradation of much of the world's forests, coral reefs and low-lying coastal wetlands. While agricultural development contributes to food security, unsustainable agricultural expansion, driven in part by unbalanced diets, increases human and ecosystem vulnerability and leads to competition for land and/or water resources (IPCC AR6: B.2.3, 2021) [4].

In Mexico, several species of freshwater fish have disappeared such as the Potosí cub (Cyprinodon alvarezi), the Trinidad puppy (Cyprinodon inmemoriam) of Nuevo León; birds restricted to islands such as the Socorro Island pigeon (Zenaida graysoni) and the Guadeloupe Island petrel (Oceanodroma macrodactyla); and some large mammals such as the Caribbean monk seal (Monachus tropicalis), the brown bear (Ursus arctos horribilis) and the Mexican wolf (Canis lupus baileyi) of northern and central Mexico [2].

Mexico is considered a "megadiverse" country (Figure 1 and Table 1), since it is part of the select group of nations with the greatest diversity of animals and plants, almost 70% of the world's diversity of species (considering the best known groups: amphibians, reptiles, birds, mammals and vascular plants) [2].

Fig. 1 Map of megadiverse countries

The direct factors that impact and threaten species are five:

Habitat loss
Habitat loss and deterioration is the main cause of biodiversity loss. By transforming forests, forests, scrublands, grasslands, mangroves, lagoons, and reefs into agricultural fields, ranchers, shrimp farms, dams, roads, and urban areas, we destroy the habitat of thousands of species. Many times, the transformation is not complete but there is deterioration of the composition, structure or function of ecosystems that impacts species and the goods and services we obtain from nature. The latest estimates indicate that around 50% of natural ecosystems have been lost in Mexico. The main transformations occurred in wet and dry forests, grasslands, cloud forests, mangroves and to a lesser extent in scrub and temperate forests. The most accessible, productive ecosystems, with better soils and in flat places have been the most transformed. The main remnants are in inaccessible or unproductive places. Habitat loss occurs due to the "change of land use" from natural ecosystems (forests, jungles, pastures, etc.) to agricultural, livestock, industrial, tourism, oil, mining activities [3].

Invasive species
The introduction of non-native (exotic) species that become invasive (pests) is a very important cause of biodiversity loss. These species that come from distant places accidentally or deliberately, prey on native species, compete with them, transmit diseases, modify habitats causing environmental, economic and social problems. Some well-known are the rats and mice of Asia, the water lily of South America and the lionfish of the Western Pacific and Oceania [3].

Table 1. Mexico's position with respect to other megadiverse countries [5].

Country	Vascular plants	Mammals	Poultry	Reptiles	Amphibians

Place of Mexico	5	3	11*	2	5
Brazil	56,215	648*	1,712	630	779
Colombia	48,000	456	1,815	520	634
China	32,200	502	1,221	387	334
Indonesia	29,375	670*	1,604	511	300
Mexico	21,989 - 23,424*	564*	1123-1150*	864*	376*
Venezuela	21,073	353	1,392	293	315
Ecuador	21,000	271	1,559	374	462
Peru	17,144	441	1,781	298	420
Australia	15,638	376	851	880	224
Madagascar	9,505	165	262	300	234
Congo	6,000	166	597	268	216

Overexploitation

Overexploitation is the extraction of individuals from a population at a rate greater than that of their reproduction and when this happens the population decreases. This has been the history of many of the species that have been exploited for different reasons: whales, fish, deer, cacti, orchids, among others; so many of them are in danger of extinction. Some species are more vulnerable than others due to their biological characteristics such as: restricted distribution, low abundance, high mortality rate, low reproductive rate, high congregation of the population, among others. The activities of hunting, logging, fishing, illegal trade of species, affect the species by overexploiting their populations. Buyers of illegal organisms and products are complicit in overexploitation. Regulations on the use of Mexican species are found in various types of regulations [3].

Contamination

The increase in the presence of chemicals in the environment resulting from human activities has serious consequences for many species. Industrial, agricultural, livestock and urban activities contribute substantially to air, water and soil pollution. Initially pollution was a problem of small spatial scale, however currently the production of pollutants affects the entire planet. Some pollutants have weakened the ozone layer that protects living beings from ultraviolet radiation, while others have caused global warming. Water, soil and air pollution directly affects many organisms even in remote locations. In addition to chemical substances, excess energy (sound, heat or light) is also considered a pollutant, and transgenic organisms [3].

Climate change

During the last 150 years, the increase in the average temperature of the atmosphere and oceans of the planet has been documented due to the increase in the concentration of greenhouse gases (carbon dioxide, methane, nitrogen oxides, ozone, chlorofluorocarbons and water vapor) produced by the burning of fossil fuels and deforestation, a combination of excess production and reduced capacity to capture pollution. The consequences are radical changes in the distribution of ecosystems and species, rise in sea level, disappearance of glaciers and large areas of coral, unpredictable and extreme climates such as droughts and floods. Climate change affects all organisms on the planet, many of them are already responding to this new dynamic through changes in their distribution and migrations. All these factors are due to human activities and their causes are social, economic and political. The effects of our activities, which for a long time had been small-scale, have become large-scale, affecting the climate of the entire planet. Climate change has become one of the main threats to biodiversity. In Mexico, a large number of endemic species of highly restricted distribution are susceptible to being affected by these factors. Thus, the objective of this research is to evaluate the vulnerability of biodiversity in Mexico as a result of anthropogenic climate change during the present century [3].

2. MATERIAL AND METHODS

Climate change scenarios at the regional level provide the information needed to estimate the potential impacts of extreme weather on the environment and human activities (IPCC AR6, 2021)[4]. Scenarios should not be interpreted as predictions or forecasts, but as consistent visualizations of possible future climates, responding to the increase in radiative forcing. This is very important since the climate at the regional level can be affected by other variables that are not included in global models such as the effects of land use change, tropical cyclones, among others.

Ocean-Atmosphere Global Circulation Models (AOGCM) do not have sufficient spatial resolution to represent some atmospheric processes of relevance to the regional climate of tropical areas (e.g., tropical cyclones) or land surface processes that determine the unique regional heterogeneity of Mexico's climate. Thus, biases in simulations and the limited number of spatial and temporal high-resolution experiments, either with nested models or statistical techniques, affect confidence regarding regional and local precipitation and temperature scenarios. Thus, the approach of obtaining regional scenarios focuses on reducing the errors of the AOGCM to make an adequate estimate of the expected changes due to the increase in radiative forcing, product of GHG concentrations.

Due to the thick scale at which AOGCMs operate, geographic locations of coasts or mountain ranges may be distorted, inducing systematic discrepancies in regional climate simulations. These discrepancies can propagate in regional climate change scenarios if simple linear interpolation is used as a downscaling tool. Therefore, AOGGMs need to be adjusted so that they can be interpolated at the regional level. CMIP6 (CCKP, 2022) [6] was developed by the World Bank to statistically reduce discrepancies in climate model production from seasonal and regional climate predictions for regional model validation. The spatial resolution fields of the coarse climate model of temperature and precipitation are approximately 300 × 300 km and can be reduced to finer spatial scales of the order of 100 × 100 km, comparable to observed analyses of the regional climate.

Downscaling techniques (global to regional) calibrate statistical transfer functions through historical relationships between modeled and observed fields to reduce systematic errors in model output. The identification of such errors is best achieved when not only grid points but also patterns and modes of variability are correlated [7]. CMIP6 scenarios form the database of the IPCC Assessment Reports and were therefore used to develop regional projections.

The IPCC's integrations for climate change studies span from 1900 to 2100, allowing transfer functions to be built using the high spatial resolution of the observed temperature and precipitation fields for the period 1900-2020. In the present analysis, the stability and ability of the transfer function are assessed using data from 1995-2014 as the reference period. As with any method of bias correction, the quality of observational datasets limits the quality of bias correction. In addition, it is assumed that the bias behavior of the model does not change over time; therefore, in downscaling, relationships are assumed to be stable in a changing climate. This is important in downscaling climate change scenarios [8].

Various statistical approaches have been proposed to scale AOGCM climate change scenarios for Mexico, to project medium and extreme event activity [9-10]. However, most of these are based on few models and lack the benefit of a multi-model overview such as that presented at the IPCC AR6. AOGCM climate change scenarios used in the IPCC AR6 model projections of temperature and precipitation are available from the IPCC Data Distribution Centre. The multiassembly model output fields for the radiative forcing scenarios of SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 have been reduced with the CMIP6 scenarios. CMIP6 reference scenarios for each AOGCM were used to construct projected changes in regional climate.

In the downscaling process, the monthly observed temperature and precipitation fields of the Climate Research Unit (CRU) of the University of East Anglia were used, with a spatial resolution of 50 x 50 km for the period 1901-2020 [11]. CMIP6 data capture Mexico's low-frequency variability and temporal temperature and precipitation trends.

In the present study, climate projection data are modeled data from global climate model compilations from Coupled Model Intercomparison Projects (CMIP) phase 6. The data presented are CMIP6, which form the database of the IPCC Assessment Reports. This climate predictability tool, used as a statistical method of downscaling, allows the preparation of regional climate change projections to estimate the spread between models as a measure of uncertainty in projected changes in climatological variables. In this way, changes in temperature, precipitation, relative humidity and annual drought index for this century are obtained and together with vulnerability projections, the potential impacts on biodiversity in Mexico are estimated. The projection data is presented with a resolution of 1.0ºx1.0º (100km x 100km).

The ability to generate scenarios over a long period allows to reproduce climate parameters and the response of regional climate to large-scale forcing, such as increased radiative forcing, resulting from increased GHG concentrations. Thus, the estimated trend of temperatures, relative humidity, precipitation and annual drought index SPEI was obtained on a regional scale for Mexico between 2020 and 2099.

Other analyses were used to determine environmental health impacts such as the Normalized Difference Vegetation Index (NDVI), which was taken from NASA's data archive [12]. The NDVI is used to assess the impact of abnormal climatic conditions on vegetation and is a measure of the amount and vigor of vegetation on the soil surface. The index ranges from −1.0 to 1.0, with negative values and positive values close to zero, indicating bare soil, and higher ranging from sparse vegetation (0.1−0.5) to dense green vegetation (0.6 and above). Because NDVI is an indicator of the amount and vigor of vegetation greenness, positive anomalies correspond to healthy vegetation conditions and negative anomalies to stressed vegetation. Likewise, Standardized Precipitation Evapotranspiration Indices (SPEI) were used, which is an indicator of precipitation-derived drought, which calculates drought based on the average accumulated rainfall in the long term, including evapotranspiration. Positive values indicate positive water balance (wet conditions) and negative values indicate negative water balance (dry conditions). This indicator shows the frequency and intensity of droughts observed lasting 6 and 12 months. Longer periods can be used to indicate risks associated with prolonged hydrological drought, such as reduced reservoir recharge and water availability. Temperature increases generally increase moisture and precipitation losses and therefore increase the risk of drought. This indicator should be used with caution in typically arid regions and dry seasons. The reference period for calculating the SPEI indicator is 1981-2010. Soil moisture (metre^3/metre^3) was also estimated, showing the average water content of the topsoil (0 to 5 cm deep) and used as an indicator of the extent and duration of drought. There is a strong interrelationship between soil moisture, vegetation and climate in the short and long term. Soil moisture influences the type and condition of vegetation and, in turn, evapotranspiration. The change in soil moisture can have considerable impacts on the environmental health of ecosystems and consequently on the threat and extinction of species. Soil moisture data can be used to anticipate and manage risks related to drought and secondary hazards (e.g., wildfires), and guide long-term resilience programming for biodiversity conservation. Maps of drought episodes in Mexico in recent decades were also used.

3. RESULTS AND DISCUSSION

Figure 2 presents the climatology for Mexico in the period 1991-2020, the data present a resolution of 0.5º x 0.5º (50 km x 50 km) for a) average annual temperature (21.3±4.1°C), b) accumulated annual precipitation (898.5±45.2 mm), c) minimum temperatures (13.7±4.0°C), maximum (28.9±4.0°C), monthly precipitation (74.9±41.5mm) and d) relative humidity (58.0±6.4%), as a reference to evaluate the changes between now and the end of the century.

The trend to change in temperature, relative humidity and precipitation are a measure of climate sensitivity to increased radiative forcing that has increased in recent years, forcing warmer weather (IPCC, AR6 2021)[4]. The regional linear trend over Mexico in the period 1991-2020 is captured by the CMIP6 regional set of climate change scenarios.

Regional climate change scenarios

Most studies agree that the temperature will increase in the coming decades, affecting the hydrological cycle on a global and regional scale.[4, 13, 14]. The impacts of climate change are estimated to have a large number of consequences, including biodiversity loss in countries where climate disasters have also occurred in recent decades. The IPCC (2007, 2021) has concluded that Mexico will be among the regions where the water deficit will be exacerbated due to increases in temperature, reduced relative humidity and rainfall, increasing drought, extreme events. affecting species development and consequently the problems of threat and extinction of the same [4, 13]. The regional scale climate change scenarios obtained through CMIP6 are able to show the contrasts in projected climate changes between regions of Mexico.

Regional models for Mexico show that the average annual surface temperature can experience a wide variety of increases ranging from 0.5 to 5 °C depending on the selected scenario and period and that can reach values above 40 ° C, while the percentages of change in rainfall from -20.3% to 13.5% according to scenario and analysis period with decreases of up to -180 mm/year. It is estimated that it is unlikely to limit GHGs and radiative forcing to scenarios SSP1-1.9 and SSP1-2.6, on the other hand it is expected that the actions taken to mitigate GHG emissions allow the worst scenario (SSP5-8.5) not to be reached, based on this it is estimated that the two most likely scenarios are the intermediate scenario SSP2-4.5 and the high scenario SSP3-7.0, which will be described and discussed. For changes in average, maximum and minimum temperatures, annual and monthly precipitation, relative humidity and SPEI, the period 1995-2014 will be taken as a reference, and with which the impacts on the biodiversity will be evaluated.

For the SSP2-4.5 scenario, the average annual temperature for Mexico in the period 2020-2039 is estimated at 22.1±4.1°C, for 2040-2059 of 22.7±4.1°C, the period 2060-2069 of 23.2±4.2°C and at the end of the century (2080-2099) of 23.6±4.2°C (Table 2). It must be remembered that the values are differentiated according to the region, state and municipality. In the SSP3-7.0 scenario, the average annual temperature between 2020-2039 is estimated at 22.0±4.1°C, between 2040-2059 of 22.9±4.2°C, the period 2060-2069 of 23.8±4.2°C and in 2080-2099 of 24.8±4.2°C (Table 2 and Figure 3).

However, it must be remembered that extreme events develop with maximum and minimum temperatures, rather than with averages. Thus, for the SSP2-4.5 scenario, the minimum annual temperature for Mexico in the period 2020-2039 is estimated at 14.4±4.1°C, for 2040-2059 of 15.0±4.1°C, between 2060-2069 of 15.5±4.1°C and at the end of the century (2080-2099) it will reach a value of 15.8±4.1°C (Table 2). In the SSP3-7.0 scenario the minimum annual temperature between 2020-2039 is estimated at 14.4±4.0°C, for 2040-2059 of 15.2±4.1°C, between 2060-2069 of 16.0±4.1°C and in 2080-2099 it will reach 17.0±4.2°C (Table 2).

It is very likely that the maximum temperature is one of the variables that impacts the most. The maximum annual temperature for the SSP2-4.5 scenario in the period 2020-2039 is estimated at 29.9±4.0°C, for 2040-2059 of 30.5±4.0°C, for the period 2060-2069 of 31.0±4.1°C and for 2080-2099 of 31.3±4.1°C (Table 2). In the SSP3-7.0 scenario, the maximum annual temperature between 2020-2039 is estimated at 29.7±4.0°C, for 2040-2059 of 30.6±4.0°C, the period 2060-2069 of 31.6±4.1°C and in 2080-2099 of 32.6±4.1°C (Table 2 and Figure 4).

Mexico's regional relative humidity projections estimate that for the SSP2-4.5 scenario in the period 2020-2039 it is estimated at 57.2±6.5%, while for 2040-2059 of 56.6±6.8%, between 2060-2069 of 56.0±6.9% and at the end of the century (2080-2099) it will reach 55.6±7.0% (Table 2). In the SSP3-7.0 scenario, the relative humidity between 2020-2039 is estimated at 57.4±6.6%, between 2040-2059 of 56.6±6.6%, between 2060-2069 of 55.4±7.0 and in 2080-2099 it will reach 54.7±7.3% (Table 2).

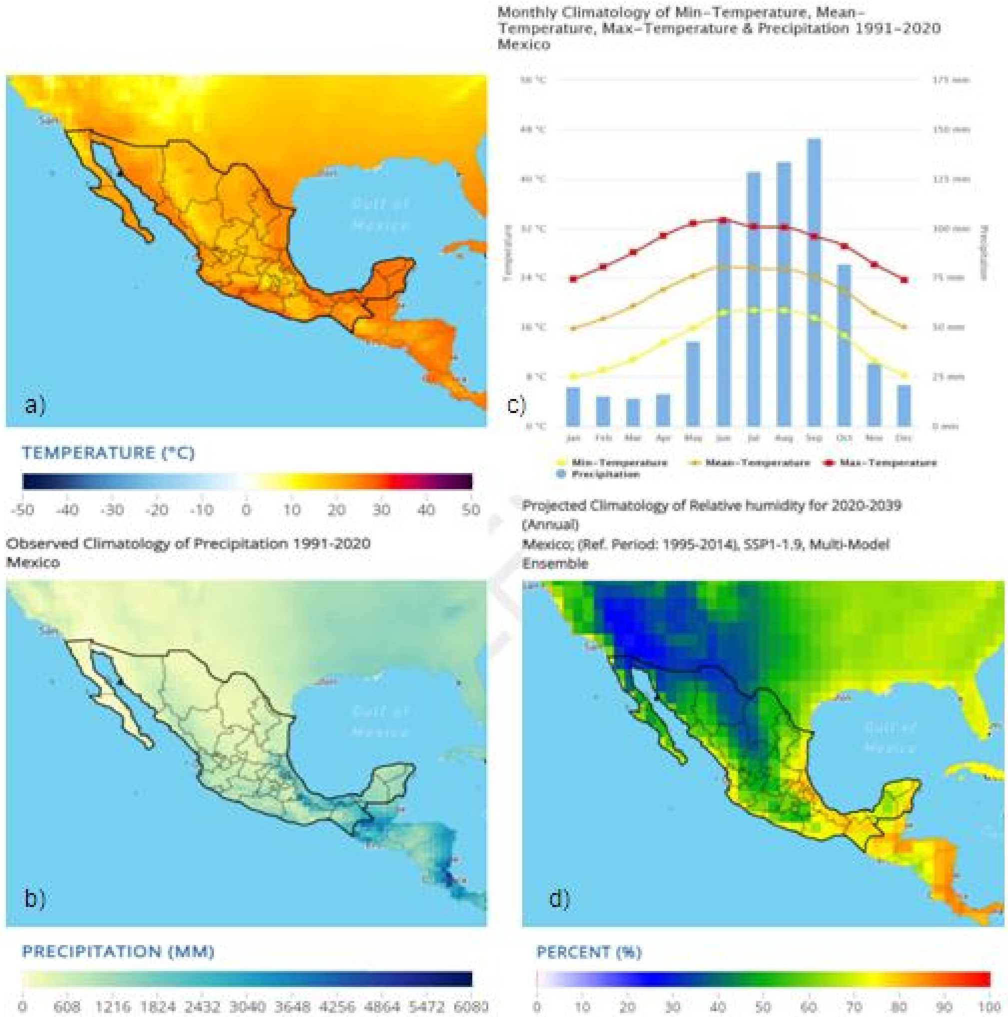

Fig. 2. Climatology with CRU data (50 × 50 km) (base period 1991-2020) observed of a) average annual surface temperature, (b) average annual precipitation (mm), (c) minimum, maximum, average and monthly precipitation; and (d) relative humidity (CCKP, 2022).

The regional precipitation projections showed negative and positive changes depending on the period analyzed and/or the region of the country. The most important changes are in the North, Central and South of Mexico; with decreased rainfall in almost the entire country. For the SSP2-4.5 scenario, the average annual precipitation (mm) in the period 2020-2039 is estimated at 900.0±43.1, for 2040-2059 of 887.3±43.2, between 2060-2069 of 873.1±42.8 and at the 2080-2099 of 857.8±42.3 (Table 2). In the SSP3-7.0 scenario, the average annual precipitation (mm) in the period 2020-2039 is estimated at 886.9±41.6, for 2040-2059 of 856.4±40.8, between 2060-2069 of 827.5±39.5 and in 2080-2099 it will reach 805.3±39.1 (Table 2 and Figure 5).

Table 2. Average, minimum, maximum temperatures, relative humidity, precipitation and SPEI drought index for Mexico according to the different scenarios of the IPCC (2021) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5 during the present century, obtained from regional models (Own elaboration with data from CCKP, 2022).

Average temperatures in °C				
	2020-2039	**2040-2059**	**2060-2079**	**2080-2089**
SSP1-1.9	22.0±4.2	22.1±4.2	22.0±4.2	21.9±4.2
SSP1-2.6	22.1±4.1	22.4±4.1	22.6±4.2	22.5±4.2
SSP2-4.5	22.1±4.1	22.7±4.1	23.2±4.2	23.6±4.2
SSP3-7.0	22.0±4.1	22.9±4.2	23.8±4.2	24.8±4.2
SSP5-8.5	22.2±4.1	23.2±4.1	24.4±4.1	25.8±4.1
Minimum temperatures in °C				
	2020-2039	**2040-2059**	**2060-2079**	**2080-2089**
SSP1-1.9	14.4±4.1	14.5±4.1	14.5±4.1	14.3±4.1
SSP1-2.6	14.4±4.1	14.7±4.1	14.8±4.1	14.7±4.1
SSP2-4.5	14.4±4.1	15.0±4.1	15.5±4.1	15.8±4.1
SSP3-7.0	14.4±4.0	15.2±4.1	16.0±4.1	17.0±4.2
SSP5-8.5	14.6±4.1	15.5±4.1	16.7±4.1	18.0±4.2
Maximum temperatures in °C				
	2020-2039	**2040-2059**	**2060-2079**	**2080-2089**
SSP1-1.9	29.6±4.0	29.7±4.1	29.6±4.1	30.0±4.1
SSP1-2.6	29.8±4.0	30.2±4.0	30.3±4.0	30.2±4.1
SSP2-4.5	29.8±4.0	30.5±4.0	31.0±4.1	31.3±4.1
SSP3-7.0	29.7±4.0	30.6±4.0	31.6±4.1	32.6±4.1
SSP5-8.5	29.8±4.0	30.9±4.0	32.1±4.0	33.6±4.1
Relative humidity in %				
	2020-2039	**2040-2059**	**2060-2079**	**2080-2089**
SSP1-1.9	57.3±6.9	58.0±6.9	57.2±6.9	57.7±6.6
SSP1-2.6	56.9±6.6	56.9±6.5	56.3±6.6	56.6±6.6
SSP2-4.5	57.2±6.5	56.6±6.8	56.0±6.9	55.6±7.0
SSP3-7.0	57.4±6.6	56.6±6.6	55.4±7.0	54.7±7.3
SSP5-8.5	57.3±6.6	56.2±6.8	55.2±7.1	53.6±7.5
Precipitation in mm				
	2020-2039	**2040-2059**	**2060-2079**	**2080-2089**
SSP1-1.9	917.4±45.9	929.5±46.2	925.8±45.3	917.5±45.2
SSP1-2.6	912.0±43.6	901.9±42.8	890.8±41.9	899.5±42.6
SSP2-4.5	900.0±43.1	887.3±43.2	873.1±42.8	857.8±42.3
SSP3-7.0	886.9±41.6	856.4±40.8	827.5±39.5	805.3±39.1
SSP5-8.5	877.2±42.3	858.7±41.4	831.0±40.8	786.0±40.2
SPEI Annual Drought Index				
	2020-2039	**2040-2059**	**2060-2079**	**2080-2089**
SSP1-1.9	-0.06±0.03	-0.05±0.06	-0.06±0.05	-0.05±0.04
SSP1-2.6	-0.02±0.01	-0.03±0.01	-0.05±0.02	-0.05±0.02
SSP2-4.5	-0.03±0.02	-0.07±0.02	-0.14±0.05	-0.17±0.07
SSP3-7.0	-0.02±0.01	-0.09±0.04	-0.25±0.07	-0.40±0.13
SSP5-8.5	-0.04±0.03	-0.22±0.13	-0.45±0.11	-0.82±0.14

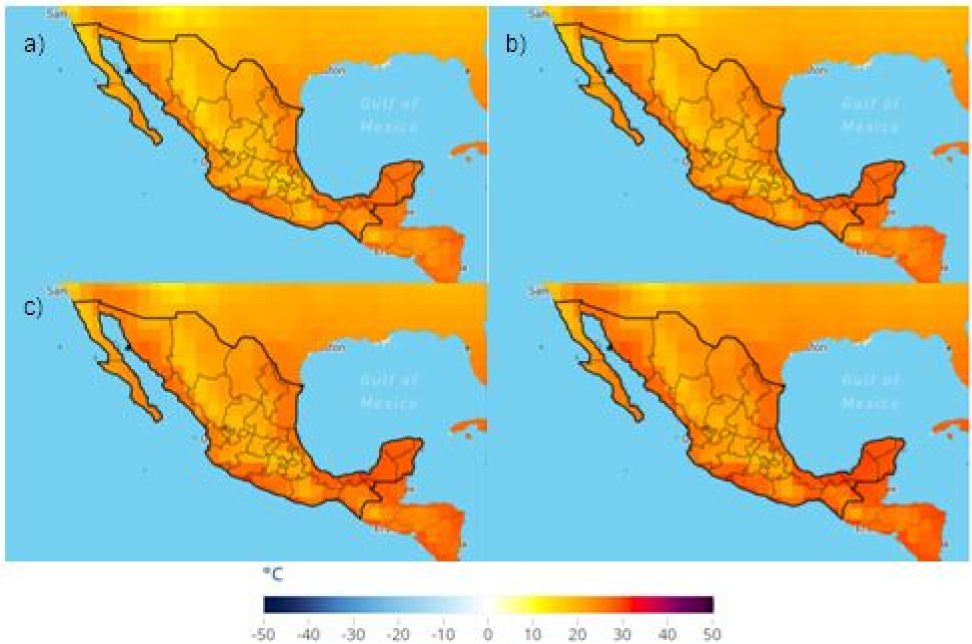

Fig. 3. Average (Annual) temperature projected for Mexico under scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

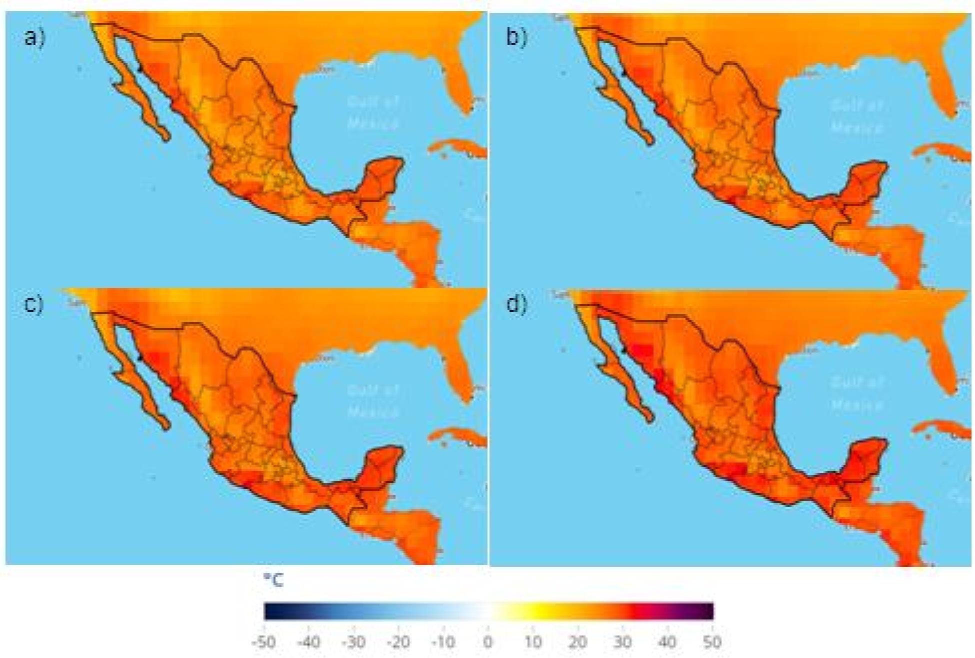

Fig. 4. Maximum (Annual) temperature projected for Mexico under scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

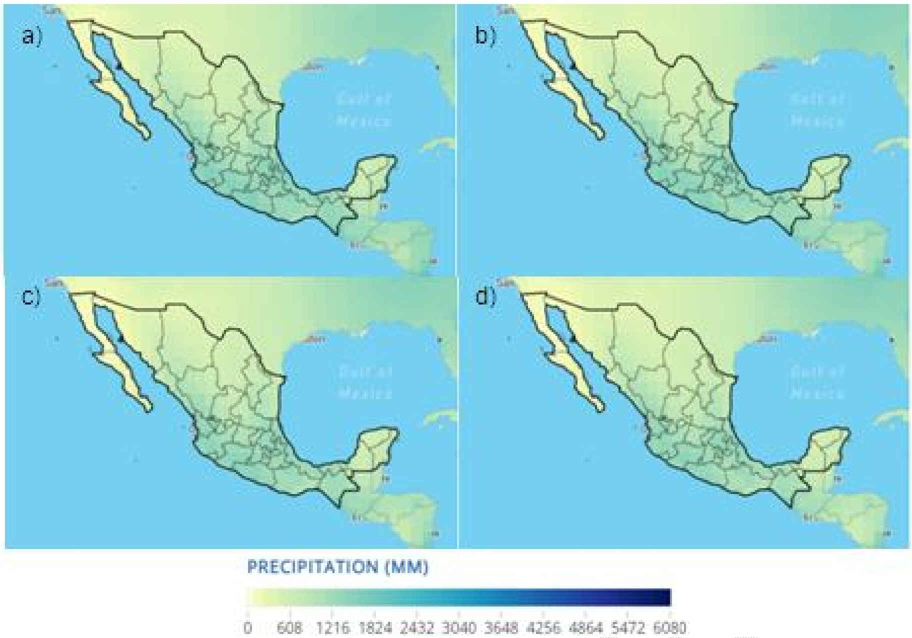

Fig. 5. Projected precipitation (Annual) for Mexico under scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

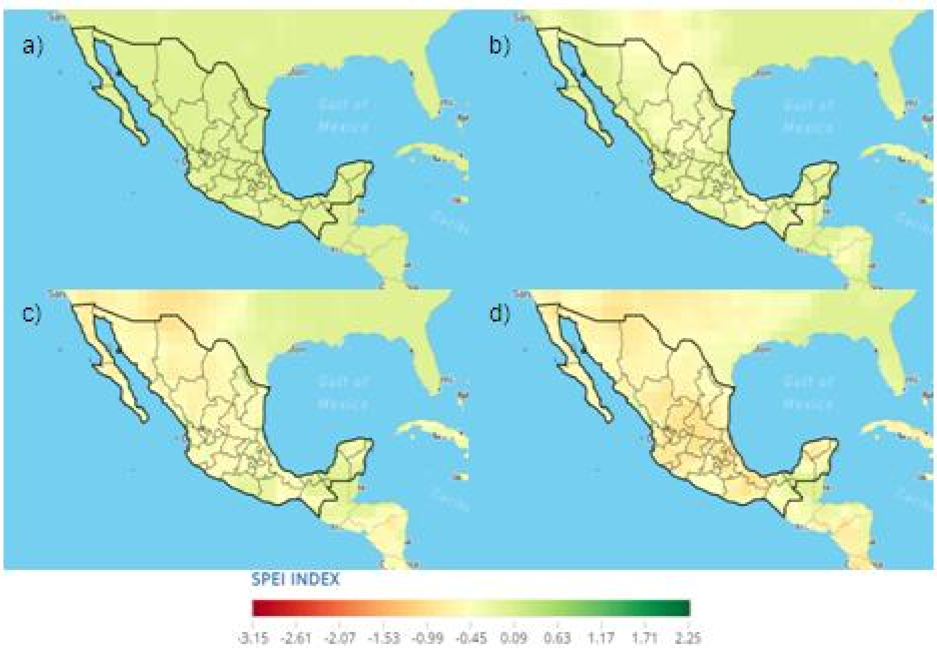

Fig. 6. Annual SPEI drought index of the projected climatology for Mexico under scenario SSP3-7.0 a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 (CCKP, 2022).

The SPEI annual drought index presented for the SSP2-4.5 scenario, in the period 2020-2039 value of -0.03±0.02, for 2040-2059 of -0.07±0.02, between 2060-2069 of -0.14±0.05 and between 2080-2099 of -0.17±0.07 (Table 2). In the SSP3-7.0 scenario, the SPEI in the period

2020-2039 is estimated at -0.02±0.01, for 2040-2059 -0.09±0.04, between 2060-2069 of -0.25±0.07 and in 2080-2099 it will reach -0.40±0.13% (Table 2 and Figure 6).

Mexico is one of the regions of the world where rainfall is most likely to decrease under climate change (IPCC 2007) [4]. These reductions in precipitation combined with large increases in temperature imply a large increase in potential evapotranspiration and substantial reduction in water availability and soil moisture, affecting the development of many plant and animal species; and the ecosystem as a whole. Thus, in general, it is expected by the end of the century the temperature anomalies range between 0.6-4.5 °C and that in rainfall is between -45 and -115 mm, decrease in relative humidity by almost 5% and increases in drought as a consequence. Natural climate variability in some cases produces larger changes in annual precipitation than those estimated by climate change. However, if a large negative anomaly in precipitation due to natural variability is combined with the anomaly due to climate change, then the effect would be magnified and the availability of water for all uses would decrease, leading to decreased water availability, which aggravated the growth problems of the species its threat and extinction.

The temporal evolution of the projections indicates that increases in temperatures, decreases in relative humidity and precipitation are more likely to be more important during the second half of the twenty-first century, showing a clear negative trend in any of the CIMP6 scenarios. Add to these observations of soil moisture, the 12-month Standard Precipitation Index SPEI12 log (ERAS LAND), Normalized Difference Vegetation Index (NDVI) and drought events (Figure 6) and give us a more robust picture of how temperature and precipitation changes will affect Mexico's water resources, reproductive activities and threatening biodiversity. The soil moisture map (mm) allows us to show that the north, west and bajío areas have the lowest values of soil moisture with values below 0.1, which will be intensified with higher temperatures that will cause greater evaporation and with less rainfall that will not allow the ecosystem to recover and maintain the conditions of equilibrium; which will impact water stress on vegetation, crops, water supply, and ecosystem health [14]. The south, gulf and southeast areas, although they have a higher level of soil moisture (between 0.2 and 0.4 mm), will also be affected as a result of climate change (figure 7a). SPEI is a standardized version of precipitation anomalies and has been used to characterize the severity of meteorological drought [15]. SPEI12 allows to evidence the effects of persistent precipitation anomalies and estimate the potential trend to more meteorological droughts. The SPEI12 map shows prolonged drought such as those that occurred in the 1910s, 1930s, 1950s, 1970s, and those of the late 1990s to date throughout the country, with more intensity in the north (figure 7b). The magnitude of SPEI12 during the twentieth century ranged from -1 to −2 in episodes of prolonged drought, which corresponds to extremely dry conditions. The regional-scale multimodel precipitation projections for 2000−2099 do not include the magnitude of observed natural variability. However, a more definite trend towards negative SPEI12 values is observed in the SSP3-7.0 scenario than in the SSP2-4.5 scenario, with average values of -1, semi-permanent moderate meteorological drought conditions.

NDVI (figure 7c) is closely related to soil temperature and moisture [16]. Thus, the NDVI changes over Mexico are related to reductions in rainfall and increased temperatures. By the second half of the 21st century projected patterns give severe soil moisture deficit and water stress with terrible consequences. NDVI values indicate sparse vegetation. The projected changes in soil moisture and NDVI in SSP scenarios resemble those observed under conditions of intense ENSO events (1982-1983, 1986-1993, 1997-1998, 2014-2016). Most of the affected regions are semi-arid areas. Very low frequency climate variability over Mexico with temperature anomalies of 5 °C and decreased rainfall resulted in an increase in forest fires without considering the effect of climate change. If climate change anomalies are added to these conditions, it is possible that fires in forests and jungles will increase during the present century, and the dispersion of endemic flora and fauna communities.

Regional climate change scenarios suggest that by the end of the century, water availability in northern Mexico may be reduced by up to 30%, a consequence of reduced rainfall and temperature increase. High anomalous temperatures in northern Mexico persisted into the summers of 1998-2002 (around +2 °C) with below-normal rainfall (-20 to -30%), leading to prolonged drought. Such climatic anomalies resulted in a severe deficit of soil moisture and water stress that increased the potential for wildfires. The spring of 1998 was one of the seasons with the highest number of forest fires in recent decades, hydrological stress, agricultural slash and burn [17]. Vulnerability in northern Mexico has not been reduced [1 8] and the risk is still present [19] and will be complicated by climate change.

The drought map (figure 7d) shows that practically the entire country has suffered from moderate (central and south of the country) to extremely strong (north of the country) droughts. Under the climate change scenarios SSP2-4.5 and SSP3-7.0 with conditions of strong increase in temperatures, decrease in humidity and rainfall, the drought scenario in Mexico will last and worsen until the end of the century, with the implications in the water and agricultural sectors and will put at risk the survival of some endemic species due to changing climatic conditions.

On a global scale, it is expected that the effects of climate change on water and agricultural resources will be extensive, but differentiated from one region to another, according to latitude, altitude, biomes, orographic conditions, hydrography among others. In some regions of the planet, the symptoms of affectation in water resources and therefore in biodiversity are already registered. With the climatology, an increase in surface temperature of Mexico of approximately 1.8 °C for the year 2020 with respect to 1900 was already evident, above the global values of 1.09 for 2020 with respect to 1850 (IPCC AR6: A.3.1, 2021) [4].

Regional CIMP6 models for Mexico show that in most of the Mexican territory heat waves are more frequent and intense, while extreme cold events have decreased in frequency and intensity. This has led to very warm summers and less harsh winters, which is consistent with the global projections of the AOGCM (IPCC AR6: A.3.1, 2021) [4].

In the case of Mexico, the regional scenarios projected for Mexico's surface temperature will continue to increase from 2020 to 2100 in all GHG emission scenarios considered, exceeding the threshold of 2 °C increase and reaching values of almost 5 °C in average, maximum and minimum temperatures. This coincides with the projection of AOGCM models with increases above 1.5 - 2 °C during the twenty-first century (IPCC AR6: B.1, 2021) [4]. The projections show that Mexico will present the following increases with respect to the period of 1994-2014: between 2081-2099 for the SSP2-4.5 scenario, from 1.8 to 2.6 °C and for the SSP3-7.0 scenario from 2.8 to 3.8 °C. In the first case below the IPCC estimate (2.1 to 3.5 °C) and in the second case within the range projected by the IPCC (2.8 to 4.6 °C) globally (IPCC AR6: B.1.1, 2021) [4].

In Mexico, the projected regional scenarios will reach temperature levels higher than the global ones (1.8 °C), which is very likely to increase both in frequency and intensity of hot extremes (heat waves, intense rainfall, meteorological, agricultural and ecological droughts as never before observed), which coincides with what is estimated in the AR6 of the IPCC (IPCC AR6: B.2.2, 2021) [4].

Global assessments project that some mid-latitude and semi-arid regions will see the largest increase in temperature on the hottest days, about 1.5 to 2 times the rate of global warming (IPCC AR6:B.2.3, 2021) [4]. Mexico is located within these regions so regional projections coincide with the estimates with global projections with temperature increase on hot days in the global ranges of 1.5 to 2 times the rate of warming.

Global phenomena projected by regional models for Mexico where it is estimated that in the present century the frequency of extreme events (heat waves, recurrent droughts, forest fires and floods) will increase as a result of the increase in temperatures and decrease in relative humidity and rainfall, in agreement with the global estimates (IPCC AR6: A.3.5, 2021) [4].

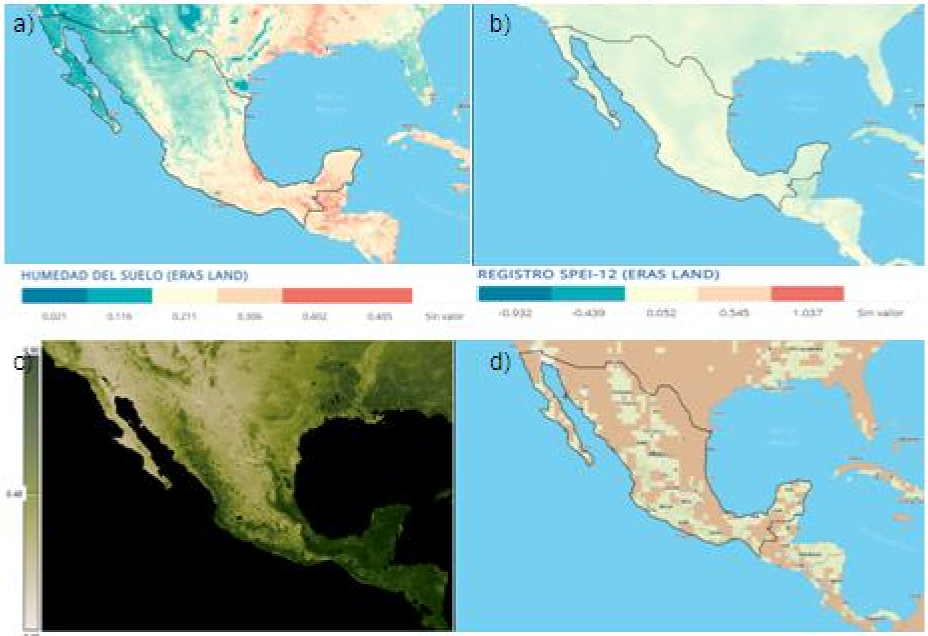

Fig. 7. (a) soil moisture (mm) and (b) SPEI12 log (ERAS land), c) normalized difference vegetation index (NDVI) changes and d) drought events in the SSP2-4.5 scenario for the second half of the 21st century. (CCPK and NASA 2022).

In terms of precipitation, the IPCC mentions that heavy rainfall events are very likely to intensify and become more frequent in most regions with additional global warming. On a global scale, global warming extreme daily precipitation events are projected to intensify by around 7% per 1°C (IPCC AR6:B.2.4, 2021) [4]. In Mexico, only slight increases in rainfall will occur in the first period (2020-2039) and in the very low and low scenarios. In the rest of the scenarios the tendency will be to decrease precipitation. However, in all cases the intensity of the rains will increase and the relative humidity will decrease its percentages for all of Mexico.

Continued global warming is also expected to further intensify the water cycle, including its variability, monsoon precipitation and the severity of wet and dry events (IPCC AR6:B.3, 2021) [4]. In Mexico, the initial period (2020-2039) will present increases in the amount of precipitation, but in the subsequent periods (2040-2059, 2060-2079 and 2080-2099) there will be a decrease in wet events and a greater presence of dry ones, intensifying the drought from moderate to prolonged.

There is evidence that the global water cycle will continue to intensify as global temperatures rise and precipitation and surface water flows become more variable within seasons and from year to year. On land, the global annual average precipitation is projected to increase between 0–5% in the very low scenario (SSP1-1.9), between 1.5–8% for the scenario (SSP2-4.5) and 1–13% in the very high scenario (SSP5–8.5) for 2081–2100 relative to 1995–2014. Precipitation is projected to increase in high latitudes, equatorial zone, Pacific and monsoon regions, but decreases in the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (IPCC AR6:B.3.1, 2021) [4]. The regional projections for Mexico coincide with the global forecasts of tropical areas with decreased rainfall in the SSP2-4.5 (-5.81±7.59%), SSP3-7.0 (-10.59±12.66) and SSP5-8.5 (-12.80±16.15) scenarios in the period 2080-2099.

It is estimated that a warmer climate will intensify very wet and very dry weather, events and weather seasons with implications for floods or droughts, but the location and frequency of these will depend on changes in regional atmospheric circulation. It is very likely that the variability of rainfall associated with ENSO will be amplified by the second half of the century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios (IPCC AR6:B.3.2, 2021) [4]. The regional projections for Mexico of soil moisture decline, the **SPEI12** index, NVDI and the large periods of drought of recent decades confirm for Mexico the global estimates of intensification of very dry weather and prolonged droughts.

The monsoon season is projected to have a late start in North America (IPCC AR6:B.3.3, 2021) [4]. Regional projections estimate that North America's monsoon will be delayed as the century progresses, along with declining precipitation, will cause storage problems in the country's water bodies.

Increases ≥2°C of global warming, the level of confidence and magnitude of change in droughts, and intense and medium rainfall are estimated to increase. Weather, hydrological, and agricultural droughts are projected to increase in North America (IPCC AR6:C.2.3, 2021) [4]. This has already manifested itself in Mexico during the first two decades of this century and is projected to intensify by the end of the century.

Many regions are expected to experience increased likelihood of compound events such as more frequent concurrent heatwaves and droughts; and will be more recurrent at 2°C compared to 1.5°C warming (IPCC AR6:B.2.2, 2021) [4]. The estimates for the end of the century in Mexico under the most likely scenarios will be above 2 °C (0.8-3.5 °C) which could mean effects from events composed of heat waves; decreased humidity, precipitation, water availability and presence of droughts.

In general, in mid-latitudes and subtropical zones (location of Mexico), significant decreases in precipitation and runoff are expected, which will cause an increase in scarcity conditions and greater pressure on diversified water resources in different regions. In various regions of the world and in Mexico, there are already conditions of scarcity of water resources and agricultural products; even without climate change, due to population growth, urban concentration, water pollution, overexploitation of water resources, particularly underground resources, coupled with a scarce water culture. To this scenario must be added the effects of climate change, which in Mexico will be a reduction in the natural availability of water as a result of the increase in temperature and decrease in rainfall, which together poses very great challenges for the management and sustainable use of water, which will endanger the survival of some species.

According to the IPCC (2007), in many regions current water management practices are inadequate or sufficient to meet the challenges of climate change. Mexico is one of the countries in which the public management policies implemented so far will not be sufficient to face the impacts of climate change [13].

On the other hand, a warmer climate will mean more intense precipitation events, even in places where the average annual precipitation is likely to be lower. What is already happening and will continue to happen in southern and southeastern Mexico. The average annual precipitation may even decrease, but the rains will be more intense, which will make it more difficult to control the flows through the current channels. These extreme events will be among the most difficult to forecast in future climate change scenarios, as they have a local character. Global warming impacts on runoff are expected to be detected first in the occurrence of extreme events than in availability.

In the case of Mexico, this effect of climate change will increase vulnerability in basins in southern and southeastern Mexico where flooding problems are already registered [20]. The existence of heavier rainfall is compatible with the forecast of lower annual runoff. On the other hand, the increase in the occurrence of droughts in the north of the Mexican territory is evident, which is consistent with the projections of decrease in precipitation and runoff and is expected to occur more frequently and intensely. If adaptation measures are not adopted, the availability of water resources in quantity and quality and the conservation of already threatened and endangered species could be at great risk.

Impacts of climate change on biodiversity in Mexico.

As already mentioned, Mexico belongs to the 17 megadiverse countries on the planet. It has between 21,989 - 23,424 vascular plants, ranking fifth worldwide; 564 different mammals being the third place in the world; between 1123-1150 species of birds, eleventh place in the world; 864 reptiles, second place; and 376 amphibians ranking fifth globally. However, anthropogenic climate change, together with habitat loss, invasive species, overexploitation and pollution are putting this megadiversity at risk, increasing the number of threatened, endangered and some already extinct species.

According to the IPCC AR6, global warming, which would reach 1.5°C in the short term, would cause inevitable increases in multiple climate hazards and present multiple risks to ecosystems. The level of risk will depend on simultaneous short-term trends in vulnerability, exposure, level of socio-economic development and adaptation. Short-term actions limiting global warming to about 1.5°C would substantially reduce projected climate change-related losses and damages to human systems and ecosystems, compared to higher levels of warming, but cannot eliminate them all (IPCC AR6:B.2.2, 2021) [4]. While it is true that limiting the temperature increase to 1.5 °C would minimize the threat and extinction of species, this objective would be practically unattainable for Mexico where increases greater than 2 ° C are projected in almost all of this century in the two most likely scenarios SSP2-4.5 and SSP3-7.0, so it is very likely that threats and extinctions of species cannot be minimized.

Short-term warming and increased frequency, severity and duration of extreme events will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risk of biodiversity loss. Short-term risks of biodiversity loss are moderate to high in forest, seaweed and seagrass ecosystems and high to very high in Arctic terrestrial and sea ice ecosystems and warm-water coral reefs. Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure and commit low-lying coastal ecosystems to submergence and loss. If urbanization trends in exposed areas continue, this will exacerbate impacts, with more challenges where energy, water and other services are limited. The number of people at risk from climate change and associated biodiversity loss will increase progressively. (IPCC AR6:B.3.1, 2021) [4]. Thus, for Mexico, the IPCC projections will fall short as a result of a greater increase in temperature, a decrease in precipitation and relative humidity and the increasingly recurrent frequency of extreme events; prolonged drought in the North and West and floods in the South and Southeast of the country.

In the short term, climate-related risks to natural and human systems depend more on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios. Regional differences exist, and risks are highest when species and people exist near their upper thermal limits, along coasts, in close association with seasonal ice or rivers. Risks are also high when multiple non-climatic factors persist or where vulnerability is high. Many of these risks are unavoidable in the short term, regardless of the emissions scenario. Several risks can be moderated with adaptation. Short-term actions limiting global warming to about 1.5°C would substantially reduce projected climate change-related losses and damages to ecosystems, compared to higher levels of warming, but cannot eliminate them all (IPCC AR6:B.3.2, 2021) [4]. As already mentioned, in the case of Mexico, there are non-climatic factors that increase the vulnerability of biodiversity loss, which will be difficult to stop and eliminate and that together with the consequences of climate change will significantly increase the number of threatened and endangered species, without having certainty of how many will become irretrievably extinct.

The IPCC estimates that beyond 2040 and depending on the level of global warming, climate change will generate numerous risks to natural systems. 127 key risks have been identified, the impacts assessed in the medium and long term are up to several times higher than those currently observed. The magnitude and rate of climate change and associated risks depend largely on short-term mitigation and adaptation measures, and projected adverse effects and associated loss and damage increase with increasing global warming (IPCC AR6:B.2.2, 2021) [4]. These estimates do not give much hope to countries like Mexico that are very vulnerable to climate change and associated non-climatic factors, so a higher rate of biodiversity loss is estimated.

Biodiversity loss and degradation, damage and ecosystem transformation are already key risks for all regions due to past global warming and will continue to increase with increasing global warming. In terrestrial ecosystems, 3 to 14 percent of assessed species are likely to face a very high risk of extinction at global warming levels of 1.5 °C, increasing to 3 to 18 percent at 2 °C, 3 to 29 percent at 3 °C, 3 to 39 percent at 4 °C, and 3 to 48 percent at 5 °C. In ocean and coastal ecosystems, the risk of biodiversity loss ranges from moderate to very high at a global warming level of 1.5 °C and is moderate to very high at 2 °C, but with more ecosystems at high and very high risk, and increases from high to very high in most ocean and coastal ecosystems at 3 °C. The very high extinction risk for endemic species in biodiversity hotspots is projected to double by at least 2% between 1.5°C and 2°C at global warming levels and to increase at least tenfold if warming increases from 1.5°C to 3°C (IPCC AR6: B.4.1, 2021) [4]. Based on the probable temperatures by the end of the century in Mexico (from 0.5 to 5 ° C) it is estimated that the risk of extinction ranges from 3 to 48% in terrestrial ecosystems, while in oceanic and coastal ecosystems the risk of biodiversity loss will go from moderate to very high; and finally for endemic species it is estimated that the risk of extinction is very high with the possibility of increasing by more than ten times.

The IPCC estimates that simultaneous and repeated climate hazards occur in all regions, increasing impacts and risks to ecosystems. Multiple risks interact, generating new sources of vulnerability to climate hazards and aggravating the overall risk. The increasing concurrence of heat and drought events is causing crop production losses and tree mortality. Above 1.5°C of global warming, increasing simultaneous weather extremes will increase the risk of simultaneous crop losses in major food-producing regions, and this risk will increase further with higher levels of global warming. Future sea level rise combined with storm surge and heavy rainfall will increase compound flood risks (IPCC AR6:B.5.1, 2021) [4]. Given these global projections and with the results of regional models, it is estimated that the dangers of crop loss, mortality of tree species will increase beyond those evidenced by the AOCGM, also floods could put at risk some animal and plant species in flooded areas, mainly in Southern and Southeastern Mexico.

The adverse effects of climate hazards and the resulting risks are cascading across sectors and regions, spreading impacts along coasts and urban centers and in mountainous regions. These cascading hazards and risks also trigger tipping points in sensitive ecosystems. Forest fires, in many regions, have affected ecosystems and species, people and their built assets, economic activity and health (IPCC AR6:B.5.2, 2021) [4]. Mexico is one of the countries that presents a real risk of increasing forest fires due to climatic and non-climatic factors with the risk of threat and danger of extinction of a significant number of plants, animal, fungal and chromista species that coexist in its different biomes.

In jungle regions and some mountainous regions, cascading impacts of climatic (e.g., heat) and non-climatic (e.g., land-use change) stressors will result in irreversible and severe losses of ecosystem services and biodiversity at a global warming level of 2°C and beyond. Inevitable sea level rise will bring cascading and compound impacts resulting in losses of coastal ecosystems and ecosystem services, salinization of groundwater, flooding and damage to coastal infrastructure that become risks to livelihoods, settlements, health, well-being, food and water security, and short- and long-term cultural values (IPCC AR6:B.2.2, 2021) [4]. Events that have already been happening for decades in the Mexican territory in the jungles of the Southeast, in the forested and mountainous areas of the entire country and in the coastal areas of the Gulf of Mexico and the Pacific Ocean.

There have also been risks arising from some responses aimed at reducing the risks of climate change, such as maladaptation and adverse side effects of some emission reduction and carbon dioxide elimination measures. The deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can exacerbate climate-related risks to biodiversity, water, food security, and livelihoods, especially if implemented on a large scale, especially in regions with insecure land tenure (IPCC AR6: B.5.4, 2021) [4]. Some of these practices are also already present in Mexico with maladaptation and mitigation strategies, which instead of contributing to the reduction of climate change have contributed to increasing the risk of threats to biodiversity in the country.

While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of the processes allow for assessing the impacts of overshoot. Further warming, for example above 1.5°C during an overshoot period this century, will lead to irreversible impacts on certain ecosystems with low resilience, such as mountain and coastal ecosystems (IPCC AR6:B.6.1, 2021) [4]. In Mexico, as already mentioned, it will be impossible to limit the temperature increase to 1.5 °C, so every tenth of a temperature increase and reduction in precipitation will increase the risk of biodiversity loss.

The risk of severe impacts increases with each additional increase in global warming. In high-carbon ecosystems (storing 3,000 to 4,000 GtC) such impacts are already observed and are projected to increase with each additional increase in global warming, such as increased wildfires, massive tree mortality, peatland drying and thawing permafrost, weakening the earth's natural carbon sinks and increasing GHG emissions. The resulting contribution to a possible amplification of global warming indicates that a return to a lower level of global warming would be more difficult (IPCC AR6:B.6.2, 2021) [4]. In this case these global estimates are exceeded by the estimates at the regional level for Mexico, so consequently the projections for Mexico are not encouraging, and the risk of biodiversity loss increases.

According to the Red List of threatened and endangered species of the International Union for Conservation of Nature and Natural Resources (IUCN), Mexico is one of the countries in Mesoamerica that presents the greatest risk in biodiversity loss. Data shows that Mexico has 2437 threatened species. Plants are the largest group, followed by fish, amphibians, other invertebrates, reptiles, mammals, birds and mollusks (Table 3).

Table 3. Number of threatened species in each major taxonomic group by country in Mesoamerica. IUCN Red List (2023)[3].

Name	Mammals	Birds	Reptiles	Amphibians	Fishes	Mollusks	Other Inverts	Plants	Fungi	Chromists	Total
Belize	10	8	8	2	67	0	27	90	0	0	**212**
Costa Rica	12	25	16	55	145	2	53	342	5	0	**655**
El Salvador	6	9	10	8	52	0	10	82	0	0	**177**
Guatemala	16	19	39	96	97	2	34	394	1	0	**698**
Honduras	10	18	60	69	89	0	36	196	2	0	**480**
Mexico	97	68	105	232	308	14	129	1,478	6	0	**2,437**
Nicaragua	9	19	11	11	97	2	33	121	0	0	**303**
Panama	18	19	16	77	128	0	39	262	2	0	**561**

The IUCN reports that Mexico is the country in Mesoamerica that reports the largest number of species in the kingdom animalia among EX - Extinct, EW - Extinct in the wild, CR - Critically endangered, EN - Endangered, VU - Vulnerable, LR/cd - Lower risk/dependent on conservation, NT - Near Threatened (LR/nt - Low Risk/Near Threatened), DD - Data Deficient, LC - Least concern (includes LR/LC - Low Risk/Minor Concern). with 6880 species in any of these categories (Table 4). 953 animals are considered at risk of threat.

Likewise, it reports for the kingdom Plantae, 4996 species in one of the risk categories already described, being again the one with the highest risk of biodiversity loss in Mesoamerica (Table 5). With 1478 plant species at risk of threat.

Table 4. Number of animal species (kingdom: Animalia) listed in each IUCN Red List Category by country in Mesoamerica. IUCN Red List (2023) [3].

Name	EX	EW	Subtotal (EX+EW)	CR(PE)	CR(PEW)	Subtotal (EX+EW+ CR(PE)+CR(PEW))	CR	IN	VU	Subtotal (threatened spp.)	LR/cd	NT or LR/nt	LC or LR/lc	DD	Total
Belize	1	0	1	0	0	1	26	33	63	122	0	60	2,093	90	2,366
Costa Rica	4	0	4	9	0	13	59	90	159	308	0	114	3,496	237	4,159
El Salvador	0	0	0	0	0	0	10	26	59	95	0	46	1,634	85	1,860
Guatemala	3	0	3	5	0	8	66	99	138	303	0	88	2,893	169	3,456
Honduras	4	0	4	10	0	14	84	83	115	282	0	92	3,082	153	3,613
Mexico	20	9	29	36	3	68	229	353	371	953	1	245	5,061	591	6,880
Nicaragua	1	0	1	0	0	1	44	38	100	182	0	85	2,986	157	3,411
Panama	2	0	2	8	1	11	73	91	133	297	0	125	3,618	297	4,339

IUCN Red List Categories: EX - Extinct, EW - Extinct in the Wild, CR - Critically Endangered (includes CR(PE) and CR(PEW)), EN - Endangered, VU - Vulnerable, LR/cd - Lower Risk/conservation dependent, NT - Near Threatened (includes LR/nt - Lower Risk/near threatened), DD - Data Deficient, LC - Least Concern (includes LR/lc - Lower Risk/least concern). CR(PE) & CR(PEW): The tags 'Possibly Extinct' and 'Possibly Extinct in the Wild' have been developed to identify CR species that are likely already extinct (or extinct in the wild), but require more investigation to confirm this. NOTE that these are not IUCN Red List Categories; they are tags that can be attached to the CR category to highlight those taxa that are possibly extinct. They are included in the above table to indicate a plausible upper estimate for number of recently extinct species on The IUCN Red List.

Table 5. Number of plant species (kingdom: Plantae) listed in each IUCN Red List Category by country in Mesoamerica [3].

Name	EX	EW	Subtotal (EX+EW)	CR(PE)	CR(PEW)	Subtotal (EX+EW+ CR(PE)+CR(PEW))	CR	IN	VU	Subtotal (threatened spp.)	LR/cd	NT or LR/nt	LC or LR/lc	DD	Total
Belize	0	0	0	0	0	0	4	45	41	90	0	16	1,093	6	1,205
Costa Rica	0	0	0	0	0	0	20	161	161	342	1	155	2,198	24	2,720
El Salvador	0	0	0	0	0	0	5	30	47	82	0	28	910	12	1,032
Guatemala	0	0	0	0	0	0	63	196	135	394	1	63	1,627	23	2,108
Honduras	0	0	0	1	0	1	44	92	60	196	1	54	1,542	14	1,807
Mexico	4	3	7	10	3	20	226	753	499	1,478	2	184	3,130	195	4,996
Nicaragua	0	0	0	0	0	0	7	62	52	121	1	61	1,638	10	1,831
Panama	0	0	0	1	1	2	20	96	146	262	1	99	2,251	120	2,733

IUCN Red List Categories: EX - Extinct, EW - Extinct in the Wild, CR - Critically Endangered (includes CR(PE) and CR(PEW)), EN - Endangered, VU - Vulnerable, LR/cd - Lower Risk/conservation dependent, NT - Near Threatened (includes LR/nt - Lower Risk/near threatened), DD - Data Deficient , LC - Least Concern (includes LR/lc - Lower Risk/least concern). CR(PE) & CR(PEW): The tags 'Possibly Extinct' and 'Possibly Extinct in the Wild' have been developed to identify CR species that are likely already extinct (or extinct in the wild), but require more investigation to confirm this. NOTE that these are not IUCN Red List Categories; they are tags that can be attached to the CR category to highlight those taxa that are possibly extinct. They are included in the above table to indicate a plausible upper estimate for number of recently extinct species on The IUCN Red List.

In the case of the Fungi kingdom, the IUCN 44 species in one of the risk categories, with 6 species under threat, being again the one with the highest risk of biodiversity loss in Mesoamerica (Table 6). These data provided by the IUCN Red List differ somewhat from those described in the Official Mexican Standard NOM-059-SEMARNAT-2010, Environmental Protection-Native species of wild flora and fauna of Mexico - Risk categories and specifications for their inclusion, exclusion or change-List of species at risk, described below [21].

The risk categories of NOM-059-SEMARNAT-2010 are the following:

Probably extinct in the wild (E): That native species of Mexico whose specimens in free life within the National Territory have disappeared, as far as the documentation and studies carried out prove it, and of which the existence of live specimens is known, in confinement or outside the Mexican Territory.

In danger of extinction (P): Those whose distribution areas or size of their populations in the National Territory have drastically decreased putting at risk their biological viability in all their natural habitat, due to factors such as destruction or drastic modification of habitat, unsustainable use, diseases or predation, among others.

Threatened (A): Those that could be in danger of disappearing in the short or medium term, if the factors that negatively affect their viability continue to operate, by causing the deterioration or modification of their habitat or directly reducing the size of their populations.

Subject to special protection (Pr): Those that could be threatened by factors that negatively affect their viability, so the need to promote their recovery and conservation or the recovery and conservation of populations of associated species is determined.

Table 6. Number of fungus species (kingdom: Fungi) listed in each IUCN Red List Category by country in Mesoamerica [3].

Name	EX	EW	Subtotal (EX+EW)	CR(PE)	CR(PEW)	Subtotal (EX+EW+ CR(PE)+CR(PEW))	CR	IN	VU	Subtotal (threatened spp.)	LR/cd	NT or LR/nt	LC or LR/lc	DD	Total
Belize	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Costa Rica	0	0	0	0	0	0	0	0	5	5	0	7	7	0	19
El Salvador	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3
Guatemala	0	0	0	0	0	0	0	0	1	1	0	0	2	0	3
Honduras	0	0	0	0	0	0	0	0	2	2	0	0	2	0	4
Mexico	0	0	0	0	0	0	1	1	4	6	0	3	34	1	44
Nicaragua	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Panama	0	0	0	0	0	0	0	0	2	2	0	1	3	0	6

IUCN Red List Categories: EX - Extinct, EW - Extinct in the Wild, CR - Critically Endangered (includes CR(PE) and CR(PEW)), EN - Endangered, VU - Vulnerable, LR/cd - Lower Risk/conservation dependent, NT - Near Threatened (includes LR/nt - Lower Risk/near threatened), DD - Data Deficient, LC - Least Concern (includes LR/lc - Lower Risk/least concern). CR(PE) & CR(PEW): The tags 'Possibly Extinct' and 'Possibly Extinct in the Wild' have been developed to identify CR species that are likely already extinct (or extinct in the wild), but require more investigation to confirm this. NOTE that these are not IUCN Red List Categories; they are tags that can be attached to the CR category to highlight those taxa that are possibly extinct. They are included in the above table to indicate a plausible upper estimate for number of recently extinct species on The IUCN Red List

Thus, according to data from NOM-059-SEMARNAT-2010, Mexico has 2606 species at risk with 49 species extinct in the wild, 475 in danger of extinction, 1186 threatened and 896 subject to special protection. Plants (987) are the most threatened, followed by reptiles (443), birds (392), mammals (291), fish (204), amphibians (194), invertebrates (49) and fungi (46). However, amphibians have the highest number of extinctions, followed by fish and mammals. The most endangered species are plants, followed by birds, fish and mammals, while the most threatened species are plants, reptiles, birds, amphibians and mammals (Table 7).

If currently the population in Mexico is 128 million Mexicans (2020), making a simple exercise of population growth to 2050 of 25% (160 million Mexicans) and to 2100 of 20% (153 million) (Figure 8). Under this scenario, both 2050 and 2100 would have a population that would demand greater exploitation of natural resources and animal and plant species, which will put the country's biodiversity at risk. Estimating that in the same proportion the demand for agriculture and livestock in Mexico would grow without reducing poverty, nor significantly increasing total GDP and per capita, 26 million hectares of crops would be needed; However, the land suitable for cultivation is only 24.6 million, so there would be a deficit of 1.5 million hectares without considering climate change. Averaging all the decreases in the productivity of the main crops these would give approximately -22%, which would represent a deficit of 4.84 million hectares, which if we add the deficit due to lack of arable land of 1.5 million hectares, would give a total deficit of 6.4 million hectares of crops, which would represent a very important decrease in the production of food for both human and livestock use, which would put at risk other plant species that are not currently part of the country's food system.

As for the livestock sector according to the Agrifood Atlas, in 2018, in Mexico an area of 109.8 million hectares (ha) is dedicated to livestock, more than half of the national territory (55.9%). Estimating that in that same proportion the demand for livestock in Mexico would grow, 137.25 million hectares (70.5% of the national territory) dedicated to livestock would be needed, which is unfeasible. Therefore, it is likely that the use of non-traditional animal species will be used, which would increase the risk of threat, danger of extinction and extinction of these species.

Table 7. Species under special protection, threatened, endangered and extinct in the wild according to NOM-059-SEMARNAT-2010 [20]. Own elaboration.

Category	Amphibians	Birds	Invertebrates	Mammals	Reptiles	Fishes	Fungal	Plants	Total
Pr	44	126	12	124	142	80	28	340	896
To	143	152	17	104	274	30	8	458	1186
P	7	95	20	52	27	81	10	183	475
And	0	19	0	11	0	13	0	6	49
	194	392	49	291	443	204	46	987	2606
Pr=Special protection, A=Threatened, P=Danger of extinction, E=Extinguished									

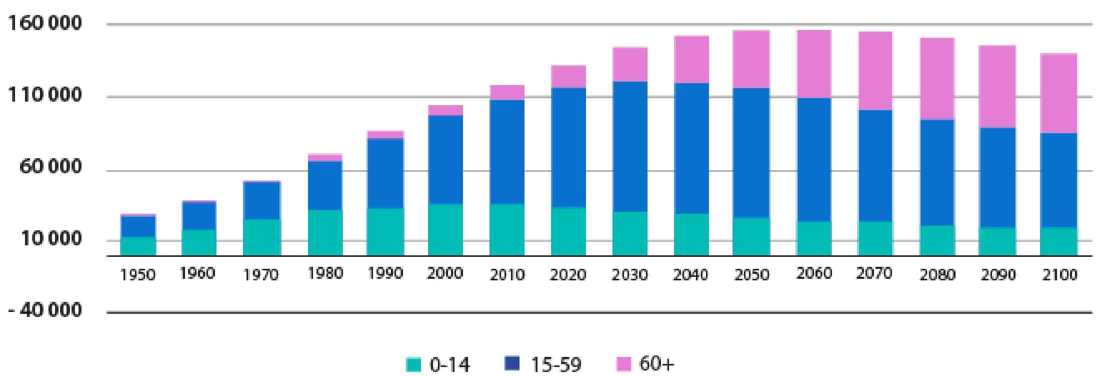

Figure 8 Total population (thousands) and projected age groups for Mexico during the twenty-first century. Source: world population survey data 2012, UN.

Since the regional models for Mexico show that temperature increases ranging from 0.5 to 5 °C, and % precipitation change will range from -20.3% to 13.5% depending on scenario and period of analysis. The low soil moisture (mm), the negative changes of NDVI and SPEI12 show that the whole country will present reductions in precipitation and temperature increase, flooding of lands emerged by sea level rise, disappearance of agricultural land and therefore biodiversity since many species could not migrate (mainly plants) and could become extinct and many others increase their danger of extinction and threat. Also, the large number of extreme hot events such as heat waves, intense rainfall, meteorological, agricultural and ecological droughts, decrease in wet events and greater presence of dry periods, intensifying moderate drought to prolonged drought, storage problems in water bodies and moving from having meteorological droughts to hydrological and agricultural and more forest fires, decrease in food productivity, malnutrition and scenarios of greater vulnerability to disappearance and exacerbation of threat to species already at risk of extinction and threatened status.

The results show that it is unsustainable to maintain the megadiversity of Mexico under current conditions, so it is imperative to take adaptation and mitigation measures to reduce the risk of biodiversity loss, thus, the integral management of soils, water resources, training on climate change, the promotion of good practices in the management of species, diversification of food sources, including resistant varieties are possible routes.

For its part, it has also been shown that the impacts of climate change on the conservation of biodiversity, through the impact of variations in temperature, relative humidity and precipitation will be intensified by the presence of extreme weather effects such as frost, drought, hurricanes and extreme rains (floods) in the different geographical regions of Mexico. Species with developmental constraints have a high vulnerability to climate hazards. Between 2010 and 2020, biodiversity risk could be 10 times higher in highly vulnerable regions, compared to regions of low vulnerability.

Climate change puts increasing pressure on biodiversity, increases in the frequency, intensity and severity of droughts, floods and heat waves, and continued sea level rise will increase the risks of species loss in vulnerable regions from moderate to high between 1.5-2°c global warming level, with zero or low levels of adaptation. At a level of global warming of 2°c or more in the medium term, the risks to biodiversity due to climate change will be more severe. Global warming will weaken soil health and pollination, increase pest and disease pressure, and reduce marine animal biomass. At global warming of 3 °C or more in the long term, areas exposed to climate-related hazards will expand substantially, exacerbating regional disparity in biodiversity risks. Mexico is already experiencing these ravages where in many regions the population of threatened species is being compromised.

Climate change and related extreme events will significantly increase ecosystem health and species disappearance in the short and long term. Species risks that are sensitive to climate are projected to increase at all levels of warming without additional adaptation. In Mexico, the increase in the number of species at risk and threatened is already evident; and these are expected to increase significantly with the increase in temperature, decrease in precipitation and the increasingly recurrent presence of extreme weather events.

The risks of climate change for aquatic ecosystems will increase rapidly in the medium and long term with further global warming, especially in places already exposed to high temperatures, along coasts or with high vulnerabilities. The population potentially exposed to coastal flooding is projected to increase by approximately 25% if mean sea level rises by 0.15 m compared to 2020; the exposed population doubles with a 0.75 m rise in sea level and triples to 1.4 m with no population change and further adaptation. In the case of Mexico, the risks occur on the coasts of the Gulf of Mexico and the Caribbean Sea where the greatest increases in sea level are expected, and to a lesser extent on the coasts of the Pacific Ocean.

In the medium and long term, species movements will increase with intensified heavy rainfall and related flooding, tropical cyclones, drought and sea-level rise. At progressive levels of warming, there would be involuntary migration of species from regions with high exposure and low adaptive capacity and those that cannot migrate are doomed to disappear. Problems that are already occurring in the North of Mexico (due to drought) and in the Southeast (due to floods), which will affect significant losses of species throughout the territory. In summary, the consequences of climate change on Mexico's biodiversity will worsen from high to very high as the century goes by and temperatures continue to increase, rainfall decreases and extreme weather events increase.

4. CONCLUSION

Thus, in view of the results of the projections of regional scenarios for Mexico by the end of the century, the forecasts made by the IPCC, the IUCN Red List and the species reported in NOM-059-SEMARNAT-2010, it is estimated a strong to very strong increase in the risk of threatened species, in danger of extinction and extinct, considerably decreasing the biodiversity of Mexico. It is also clear that all the estimates predicted by the IPCC have already been present for several decades in Mexico and the risk of biodiversity is expected to worsen as a result of climate change. Based on the probable temperatures by the end of the century (from 0.5 to 5 °C) it is estimated that the risk of extinction ranges from 3 to 48% in terrestrial ecosystems, while in ocean and coastal ecosystems the risk of biodiversity loss will go from moderate to very high; and finally for endemic species it is estimated that the risk of extinction is very high with the possibility of increasing by more than ten times. Thus, the vulnerability of biodiversity in Mexico is high to very high, which puts a very high number of species and ecosystems at high risk.

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