Impacts of Climate Change on Forest Resources in Mexico: Regional Projections and Vulnerabilities

ABSTRACT

Anthropogenic climate change can affect forest ecosystems and is one of the causes of deforestation, which leads to desertification. Deforestation is one of the main drivers of climate change due to the release of large amounts of CO_2 stored in forests and jungles. Rising temperatures, decreased rainfall and drought have negative impacts on the diversity of forest species, as well as on forest ecosystem goods and services. Thus, this research focuses on climate change and its impact on Mexico's forests, evaluating deforestation and its effects on climate change and, subsequently, the effects of that climate change on forests; and the role of forests in carbon sequestration.

Aims: The objective of this study is to present a set of regional temperature, precipitation, and drought projections for Mexico under the IPCC's AR6 climate change scenarios, and to estimate the potential impacts on Mexico's forest resources.

Methodology: The methodology consists of obtaining a set of regional projections of temperature, precipitation, vegetation, drought and soil moisture under the conditions of the IPCC AR6 climate change scenarios for Mexico, with the changes of the aforementioned variables the vulnerability of the forestry sector in Mexico will be evaluated through models of the influence of these factors.

Results: Regional models for Mexico show temperature increases ranging from 0.5 to 5 °C, while the percentage change in precipitation will range from -20.3% to 13.5% depending on the scenario and period of analysis. The low soil moisture (mm), the negative changes of the NDVI and the SPEI12 show that the North, West and Bajío zones will present reductions in precipitation and temperature increase that will cause a severe deficit of soil moisture and water stress in the plants, considering these areas with scarce vegetation and the presence of semi-permanent meteorological drought. Under these scenarios, it is expected that practically the entire country will be subject to moderate droughts (Central and South) to extremely severe droughts (North) that will last and worsen between now and the end of the century. These conditions have already been recorded in Mexico's main forest areas and if adaptation and mitigation measures are not adopted, the country's forest resources are at risk. Likewise, in addition to the decrease in rainfall, it is estimated that it will be more intense with the presence of extreme events, which will increase the vulnerability of some basins throughout the country, in the Central and Northern areas with extreme drought events, while in the Southeast with floods.

Conclusion: Temperate and cloud forests, xerophilous scrub and grasslands will be the most affected forest ecosystems in Mexico, to reduce the effects of climate change on forest resources, it is necessary to design and prioritize adaptation actions and implement mitigation measures that prevent the effects of climate change from intensifying in the most vulnerable regions of the country.

Keywords: Forest resources, Climate change, regional scenarios, forests.

1. INTRODUCTION

The deep interdependence that exists between forest ecosystems and their inhabitants marks the need to keep the environment healthy to achieve social, cultural and economic stability, as well as the positive impact that communities have on the regeneration and care of ecosystems. The relationship between people and forest ecosystems can be positive or negative. When it is negative, due to activities such as illegal logging, overgrazing, induced forest fires, mining activities or deforestation, the consequences are the release of Greenhouse Gases (GHG), loss of biodiversity and ecosystems, as well as scarcity of natural resources. Globally, the forest sector is responsible for 11% of carbon dioxide (CO_2) emissions, mainly due to deforestation (IPCC, 2022b), caused by the establishment of agricultural and livestock areas, urban expansion and natural resource extraction. On the other hand, when the relationship is positive, the forestry sector plays a decisive role in combating climate change, since it is the only sector that, in addition to emitting, also reduces GHGs. Globally, it reduces human CO_2 emissions by 29% (FAO, 2022a), making it especially important in the fight against climate change.

31% of the Earth's surface is covered by wooded forest ecosystems (FAO, 2022a). If we consider the areas of scrub and grassland, this area would be much larger. Forest ecosystems reduce the amount of CO_2 available in the atmosphere and store it in their structure. For their growth, plants carry out the process of photosynthesis in which they capture CO_2 and release oxygen. Plants use carbon from CO_2 to enlarge their trunk, roots and leaves, that is, they convert it into biomass. Thus, plants function as a large store of carbon for long periods, while reducing the amount of carbon in the atmosphere, and regulate the local climate by capturing rainwater. During photosynthesis, plants transpire to regulate their temperature, which releases water vapor into the atmosphere, but when it cools and accumulates it will form the clouds that will later precipitate. In this way, plants help us regulate the local climate and lessen the effects of climate change (Smith, et al. 2023).

In addition to storing CO_2 and regulating the climate, forest ecosystems also help us combat the current climate crisis, through the following natural processes: *Soil conservation*, *Continuity in the water cycle*, *Biodiversity conservation, Provision of products, Provision of cultural services.*

Due to the close relationship between forest ecosystems and humans, it is important to develop mitigation and adaptation policies and strategies that seek sustainable forest management. When climate change adaptation and mitigation measures are not carried out, or conservation or sustainable management, there is a loss of forest ecosystems due to deforestation and forest degradation, as well as a decrease in the capacity to regulate the planet's climate. Climate change creates environmental variations that affect forest ecosystems, making them vulnerable. In the face of changes in temperature and local precipitation, some plant species are more favored than others, while some ecosystems such as forests and jungles are reduced in extension. The number of forest fires and pests and diseases have also increased, which threatens the extension of ecosystems, the health and well-being of their inhabitants, as well as the benefits they provide us. Human beings have had a direct impact on forest ecosystems by needing spaces where livestock can develop or our food can be grown. According to the FAO, during the last three decades (1990-2020) 420 million hectares of forest ecosystems have been deforested (twice the size of Mexico) (FAO, 2020).

Deforestation and forest degradation are the main causes of GHG emissions in forest ecosystems. The carbon that was stored in the trunks, roots, leaves or soil is released into the atmosphere when trees are lost or burned, or organic matter decomposes, thus contributing to global warming. Forest ecosystems, in addition to contributing to the problem, are also vulnerable to climate change. The negative effects on these ecosystems are: Less water availability for vegetation growth, due to droughts and changes in rainfall patterns; greater vulnerability of young plants due to the lack of moisture due to droughts; reduced capacity of species to capture carbon from the atmosphere, due to the increase in CO_2; greater vulnerability to forest pests and diseases favored by changes in temperature and precipitation; changes in the distribution of biodiversity, less frequent pollination process; increased vulnerability of forest ecosystems to disturbances such as hurricanes, droughts, landslides and floods; greater frequency of forest fires due to the increase in temperature and prolonged droughts; loss of leaves due to increased frost, among others (Thilagam et al.,2022).

1.1 Forest Resources in Mexico

Mexico is located between two great oceans (Pacific and Atlantic) and in the Nearctic and Neotropical regions of our planet. This geographical position has allowed the development of various natural ecosystems. Each of these ecosystems has a high biological diversity and endemic species, that is, living beings that only live in a certain place. Due to these characteristics, Mexico is positioned as the fifth most megadiverse country worldwide. (CONABIO, 2020b; Llorente-Bousquets, et al., 2008). Currently, Mexico has a population of 126 million people, according to the 2020 Population and Housing Census of the National Institute of Statistics and Geography (INEGI, 2020), making it the eleventh most populous country in the world.

Mexico ranks thirteenth among the countries that emit the most GHGs worldwide (1.4% of global emissions) and second place in Latin America, after Brazil. According to the National Inventory of Greenhouse Gas and Compound Emissions 1990-2019, prepared by the National Institute of Ecology and Climate Change (SEMARNAT-INECC, 2020), 736.6 million tCO_2e were emitted in Mexico in 2019, with the energy sector being the country's main emitter (64%), followed by the agricultural (19%), industrial (10%) and waste (7%) sectors. On the other hand, in the same year, 188 million tCO_2e were reduced in forest ecosystems, which means that the forestry sector is capable of capturing 25% of the country's emissions.

Climate change is a global problem that has differentiated impacts on nations. Due to its geographical and social conditions, Mexico is a country vulnerable to the effects of climate change. Some of the impacts that have already been observed are: an increase in average temperature by 0.85°C in the last 50 years; an increase in extreme hot days and a decrease in extreme cold days and frost; increase in the intensity of tropical cyclones; and, changes in the distribution of precipitation. These events put biodiversity at risk, and vulnerable the population, as it is estimated that 68% of the national population and 71% of the Gross Domestic Product (GDP) are exposed to the effects of climate change (SEMARNAT, 2022).

In recent years, the depletion and degradation of Mexico's natural resources have had an economic cost greater than its growth and public spending on environmental protection (INEGI, 2021a). The occurrence of extreme events due to climate change generates greater exposure and/or vulnerability of ecosystems. Between 1999 and 2017, 91% of disaster declaration resources were allocated to climatic events. For each geological disaster, 13 climate disasters occurred with a cost 10 times higher (INECC, 2021b).

According to the FAO, Mexico is the twelfth country with the largest area of forested land in the world, with more than 66 million hectares (FAO, 2020). However, if we consider the areas covered by shrubs and grasslands, this area would be more than 138.7 million hectares, which represents 71% of the national area (CONAFOR, 2022a) (Figure 1). The forest ecosystems that exist in our country are divided into 6 large groups: forests, jungles, mangroves, xerophilous scrub, other associations and other forest areas. The largest ecosystems in the country are xerophilous scrub with 56 million hectares, followed by forests and jungles with 34 million and 30 million hectares, respectively. The other forest areas are grasslands, prairies, tulars, among others, with an area of almost 16 million hectares, mangroves with an area of almost 940 thousand hectares. And, finally, other associations (savannahs, palm groves or petenes), with more than 540 thousand hectares.

The country's forest ecosystems are vulnerable to climate change, as they show a rapid rate of loss, mainly mangroves, cloud forests and humid jungles. The impacts of climate change on forest ecosystems are different due to the different climates that exist, distribution of natural resources, demographic concentration, social conditions and economic activities. This rapid loss increases the vulnerability of biodiversity, human communities and productive activities to climate change, as many of the ecosystem services are lost. This vulnerability is also differentiated, human settlements near forest areas are also vulnerable, as are coastal areas to water deficit, geographically, the most vulnerable areas of .the country are the south and northwest (INECC, 2022b).

The country's forestry sector faces a variety of threats and pressures; On the one hand, there are the productive and commercial activities that are carried out on forest land (agriculture, livestock, illegal logging, extraction of land from the mountains or open-pit mining) that transform ecosystems. On the other hand, events such as fires, pests, and forest diseases that affect the health of forest ecosystems. Social, economic and political contexts such as inequality, marginalization, poverty, lack of appreciation of ecosystem services and the supply and demand of forest products also exert pressure on forest ecosystems. Finally, climate change is a threat that the forest sector faces and constantly transforms it, causing deforestation and environmental degradation in forest ecosystems. Through degradation processes, biomass decreases and, with it, carbon stocks, so there are more GHG emissions. The main causes of forest degradation are illegal timber extraction, land removal, collection of firewood for fuel and grazing of animals, which impedes the regeneration of forest ecosystems. It was estimated that the average emissions associated with forest degradation for the period 2007-2016 was 886 thousand tCO_2e per year. The most deforested ecoregions are the warm-humid jungles located mainly in the Yucatan Peninsula, Chiapas, Tabasco and Veracruz; followed by the warm-dry forests with presence in the coastal plains and hills of the west, Gulf of Mexico and South Pacific, and the temperate mountain ranges located in the Sierra Madre Occidental, Oriental, del Sur, Eje Neovolcánico Transversal and the Altos de Chiapas.

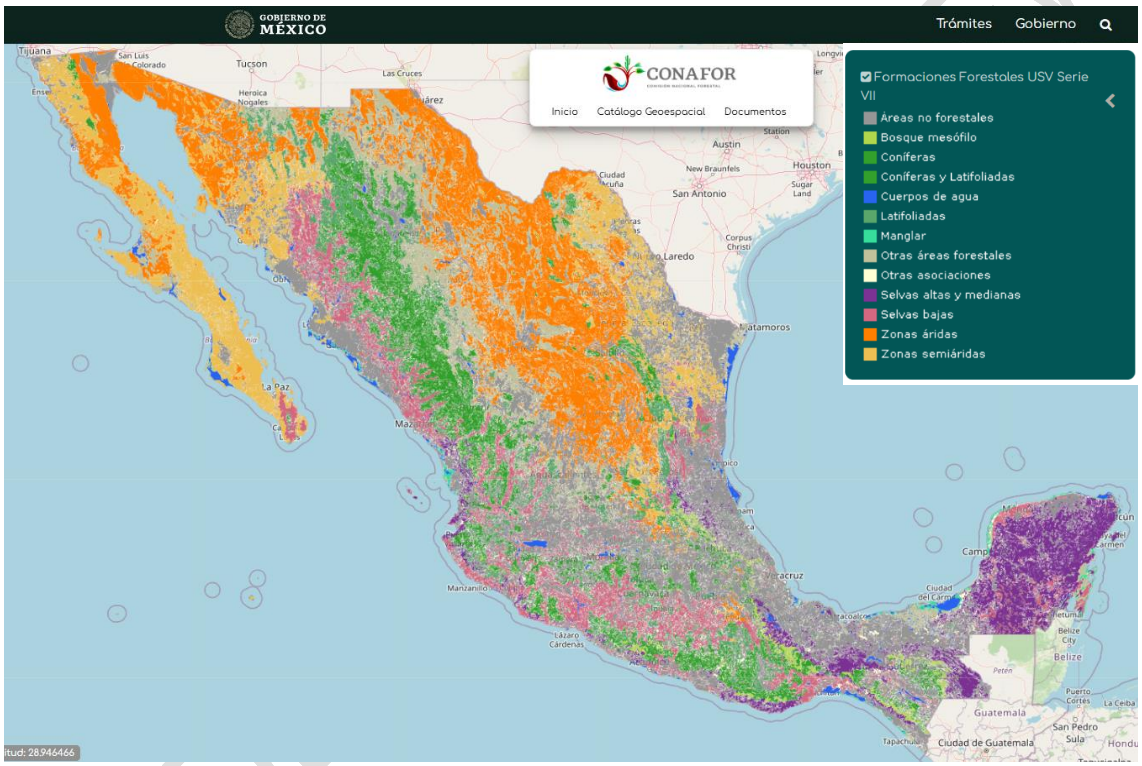

Fig. 1. Map of Forest Resources of Mexico. Source: General Coordination of Planning and Information. CONAFOR 2024. Report of Results of the INFyS 20152020. Based on the INEGI Land Use and Vegetation Charter, Series VII-2020.

However, the main cause of deforestation in our country is changes in land use, that is, the transformation of forest land to use the land for other purposes. Livestock and agricultural activities (in that order) are the main driver of these changes in land use (livestock accounts for 74% and agriculture for 21%), followed by the expansion of urban, industrial and tourist areas. The deforested area in Mexico is 208,850 ha on average from 2001 to 2021, which implies the deforestation of 0.15% of the national forest area each year. The year 2016 was the year with the highest annual deforestation rate with 350,298 ha (CONAFOR, 2022b).

During the period 2007-2016, the average emissions from deforestation was more than 19 million tonnes of CO_2e (tCO_2e) per year, with a peak in 2016, with more than 31 million tCO_2e. For the period 2017-2019, emissions decreased to more than 14 million tCO_2e (SEMARNAT, 2022). Thus, the forestry sector reduces more GHGs than it emits (it reduced 188 million tCO_2e in 2019).

Table 1 Forest Area of Mexico (CONAFOR 2020).

México forest area				
Ecosystem	**Forest area (ha)**		**Total**	
	Primary vegetation	**Secondary vegetation**	**has**	**%**
Forests	20,663,676	13,536,751	34,200,426	24.8
Jungles	10,167,721	19,858,784	30,026,505	21.8
Mangrove	842,975	96,660	939,636	0.7
Other associations	533,828	6,332	540,160	0.4
Xerophilous shrub	50,816,909	5,488,101	56,305,010	40.8
Other forest areas	11,488,048	4,345,353	15,833,401	11.5
Total	**94,513,157**	**43,331,980**	**137,845,138**	**100**

The biodiversity and ecosystem services of our country's forest ecosystems are threatened due to the effects of climate change. To design and focus conservation and adaptation actions on forest ecosystems, we must start with information on their vulnerability to climate change. The increase in forest fires in ecosystems not adapted to fire can cause considerable damage to forest cover. In recent years, the extent of cloud forest has decreased due to deforestation and increasingly warm, seasonal climates. This is causing local biodiversity to shrink, the size of coniferous forests, rainforests, halophilic and hydrophilic vegetation may decrease, while dry forests could increase. Currently, native and endemic species are being affected by climate change. 2956.4 hectares of mangroves have been lost, with one meter of sea level rise. The surface area of the soil with water available to plants will be reduced by 45% from their current surface.

The effects of global climate change are present in different regions of the world. Figure 2 shows the anomalies of a) temperature and b) global precipitation. The increase in temperature is especially important from the seventies onwards.

The World Meteorological Organization (WMO) indicates that the global average temperature over the continents and oceans during the year 2020 has been one of the three warmest. A positive anomaly of 1.2 °C, compared to the average temperature of the pre-industrial era, as shown in Figure 3. The average surface temperature over the last ten years has been the warmest. Thus, the decade between 2011 and 2020 has been the warmest on a global scale in the entire record.

According to AR6, compared to 1850-1900, the global surface temperature during 2081-2100 is very likely to be higher by 1.0 to 1.8 °C in the very low GHG emissions scenario (SSP1-1.9), by 2.1 to 3.5 °C in the intermediate scenario (SSP2-4.5), and by 3.3 to 5.7 °C in the elevated scenario (SSP5-8, 5). The scenarios that are considered most likely today are SSP2-4.5 and SSP3-7.0 (IPCC AR6, 2021). Temperature rise forecasts for these scenarios are shown in Table 2 (IPCC AR6, 2021). In the SSP2-4.5 scenario, the expected global average temperature at the end of the century will increase from 2.1 °C and may be as high as 3.5 °C. In the SSP3-7.0 scenario, considered one of the critical scenarios, the expected increase will be 2.8 to 4.6 °C. To the extent that GHG emissions continue to grow, even at an increasingly higher rate than expected (Table 2).

Mexico's climate presents regional differences due to its topography and geographical location. The country's average temperature varies from 15 to 20°C in the central highlands; 23 to 27°C in the coastal lowlands. Seasonal variations are minimal in the south, ranging from 10 °C to 30 °C in summer in the north of the country. The average annual temperature is 20.6 °C, with monthly averages between 15 °C (January) and 25 °C (June).

The average annual rainfall is 725 mm, with the most significant rainfall between June and October. In the far north, rainfall is less than 50 mm per month throughout the year, while the southern regions and central highlands experience a wet season with an average of 550 mm per month in the southernmost regions. From June to November, the Atlantic and Pacific coasts are vulnerable to hurricanes and the weather is heavily influenced by the ENSO event, which provides wet and cool weather in the winter, followed by warmer and drier conditions in the summer.

Mexico, this same pattern of temperature increase is observed, although with values higher than the world average, as shown in Figure 4 (CONAGUA, 2021) the anomalies for the period 1950-2000 and Figure 5 (CCKP, 2022) temperatures for the period 1901-2020. The average temperature growth rate in the last twenty years is 0.3 °C per decade, and 0.72 °C in the last decade, which confirms Mexico's high vulnerability to climate change. Historical rainfall records show 1943 as the driest year and 1958 as the rainiest. The year 2020 is the second consecutive year with below-average rainfall (Figure 6). The average annual and five-year rainfall in the period 1901-2020 is presented in Figure 7.

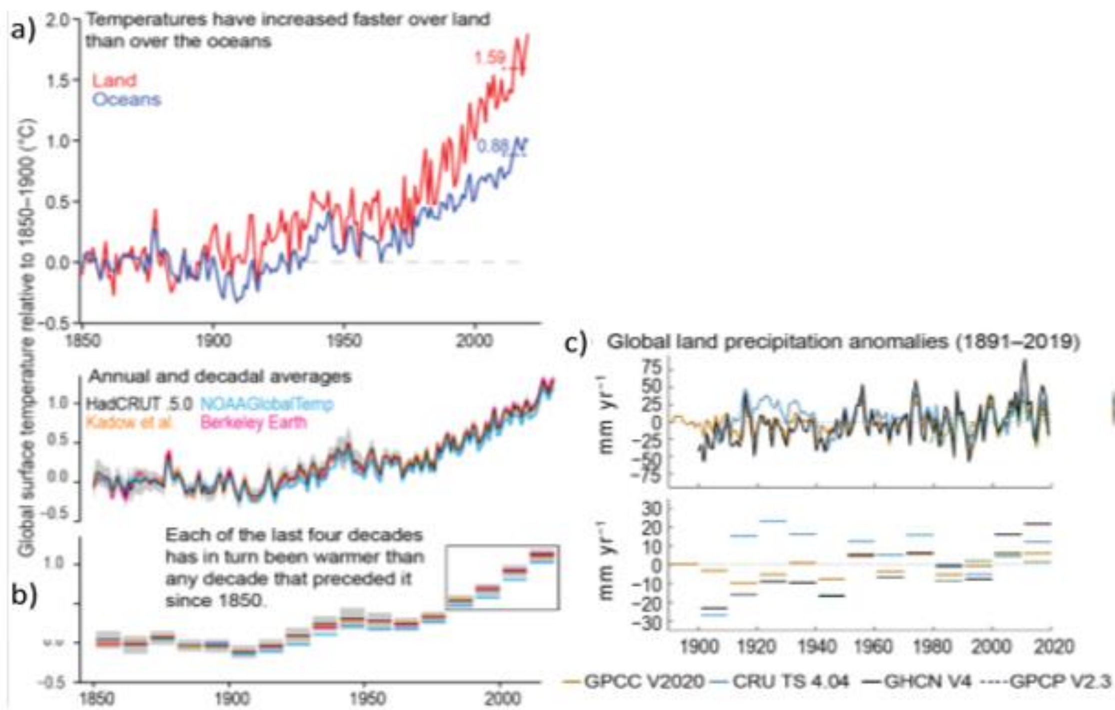

Fig. 2. Earth's surface temperature history with key findings annotated within each panel. (a) Temperature from instrumental data for 1850–2020; and b) annually and decadally resolved averages for the GMST datasets. c) Changes in observed precipitation. Annual time series and decadal means from 1891 to date relative to a 1981–2010 climatology (Gulev et al., 2021).

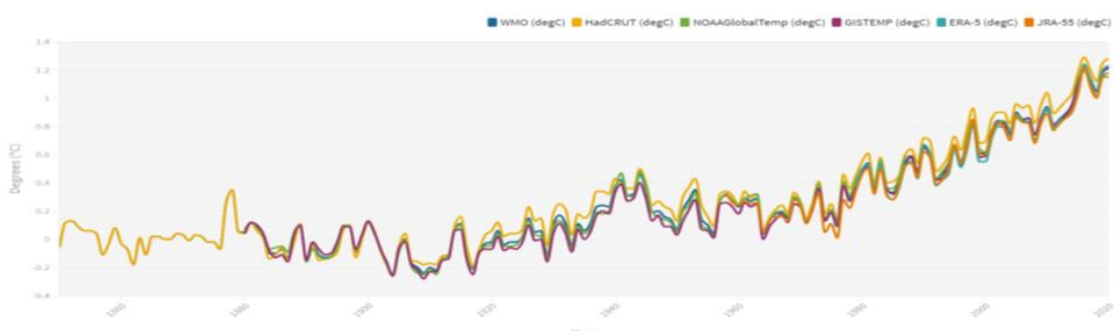

Fig. 3. Anomaly of average air temperature at two meters globally for 2020, from different research centers such as: ERA5 (ECMWF Copernicus Climate Change Service, C3S); GISTEMPv4

(NASA); HadCRUT4 (Met Office Hadley Center); NOAA GlobalTemp (NOAA), JRA-55 (JMA) and WMO (CONAGUA, 2021).

Future climate conditions will depend mainly on the amount of GHG emissions in the world, particularly carbon dioxide (CO_2). Thus, scientific predictions are made in terms of scenarios, which will depend on the ability to control their GHG emissions, as well as on the protection of biomes, which allows them to maintain jungle and forested regions, in which part of the CO_2 emitted into the atmosphere can be captured.

The objective of this study is to present a set of regional projections of temperature, precipitation, vegetation, drought and soil moisture under conditions of the IPCC AR6 climate change scenarios for Mexico. It also establishes the possible impacts of changes in temperature, precipitation, droughts, vegetation indices and soil moisture on Mexico's forest resources.

Table 2 Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. This includes the revised assessment of observed historical warming for the AR5 reference period 1986–2005, which in AR6 is higher by 0.08 °C than in AR5 (IPCC, 2021).

	Near term, 2021-2040		Mid-term, 2041-2060		Long term, 2081-2100	
Scenario	**Best estimate**	**Very likely range**	**Best estimate**	**Very likely range**	**Best estimate**	**Very likely range**
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

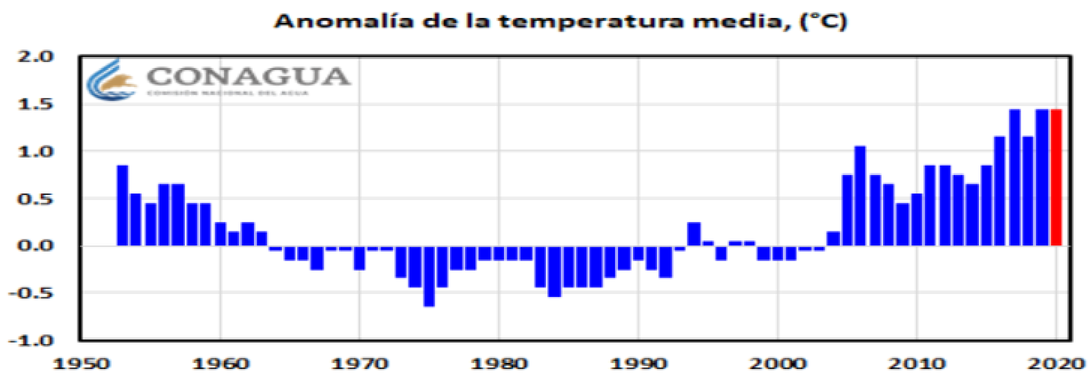

Fig. 4. Anomaly of the average annual temperature in degrees Celsius (°C), the red bar corresponds to the national anomaly estimated in 2020. Prepared based on estimates since 1953 of the National Meteorological Service (CONAGUA, 2021).

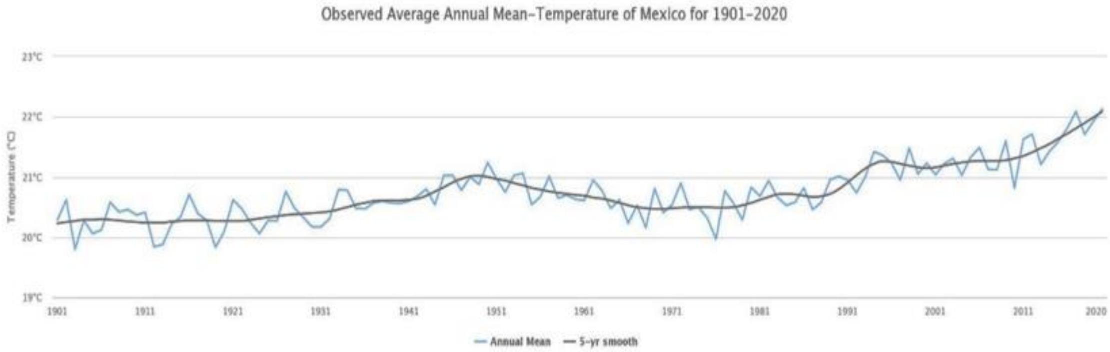

Fig. 5. Mean annual and five-year temperature in the period 1901-2020 (CCKP, 2022).

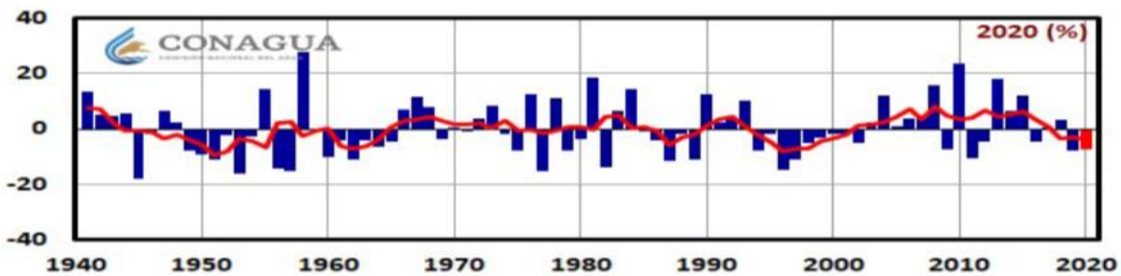

Fig. 6. Annual Nationwide Precipitation Anomalies (Blue Bars), Five-Year Moving Average (Red Line) (CONAGUA, 2021).

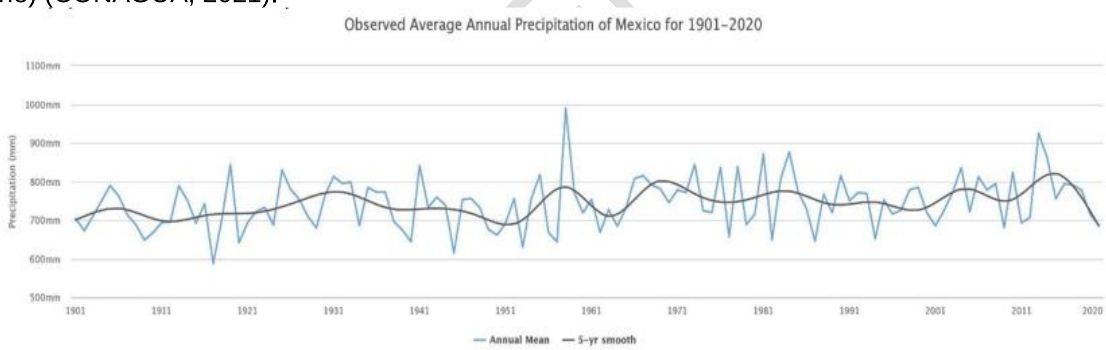

Fig. 7. Average annual and five-year rainfall in the period 1901-2020 (CCKP, 2022).

2. MATERIAL AND METHODS

Climate change scenarios at the regional level provide the necessary information to estimate the potential impacts of extreme weather on the environment and human activities (IPCC AR6, 2021). Scenarios should not be tacitly considered as predictions or forecasts, but as consistent visualizations of possible future climates, responding to increased 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 and climate projections such as the effects of land use change, tropical cyclones, among others.

The Global Ocean-Atmosphere Circulation Models (AOGCM) do not have sufficient spatial resolution to represent some atmospheric processes of relevance to the tropical regional climate or land surface processes that give regional climate heterogeneity to Mexico. Due to the coarse scale at which AOGCMs operate, it produces systematic discrepancies in regional climate simulations. Therefore, it is necessary to adjust the AOGGMs so that their production can be interpolated at the regional level. CMIP6 allows to statistically reduce discrepancies in the production of the climate model from seasonal and regional climate predictions to perform the validation of the regional model (CCKP, 2022). The spatial resolution fields of the coarse climate model of 300×300 km can be reduced to finer spatial scales of 100×100 km, comparable to observed analyses of regional climate.

Various statistical approaches have been proposed to reduce the scale of the AOGCM climate change scenarios for Mexico to project the activity of medium, and even extreme, events (Magaña et al. 1997, Cueto et al. 2010). However, most are based on few models and lack a multi-model overview perspective, such as the one presented in IPCC AR6. The output fields of multi-assembly models for the SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 radiative forcing scenarios have been reduced with the CMIP6 scenarios. The CMIP6 baseline scenarios for each AOGCM were used to construct the projected regional climate changes. In the downscaling process, the monthly observed temperature and precipitation fields of the Climate Research Unit (CRU) of the University of East Anglia, spatial resolution of 50×50 km for the period 1901-2020 (Mitchell et al. 2004), were used. CMIP6 data capture Mexico's low-frequency variability and temporal trends in temperature and precipitation.

Complementary impact analyses were used, such as the Normalized Difference Vegetation Index (NDVI), which is used to assess the impact of abnormal climatic conditions on vegetation and measures the quantity and vigor of vegetation (Tucker et al. 2005). NDVI images make it easy to distinguish green vegetation from bare soils. The index has values ranging from −1.0 to 1.0, with negative values indicating clouds and water, positive values close to zero, indicating bare soil, and positive values ranging from sparse vegetation (0.1−0.5) to dense green vegetation (0.6 and above). Thus, the positive anomalies correspond to healthy vegetation conditions and the negative ones to stressed vegetation. Standardized Precipitation Evapotranspiration Indices (SPEI) were also used, which is an indicator of drought derived from precipitation, which calculates drought based on long-term accumulated precipitation, including evapotranspiration. Positive values indicate a positive water balance (wet conditions) and negative values indicate a negative water balance (dry conditions). This indicator shows the frequency and intensity of droughts observed with a duration of 6 and 12 months. SPEI12 can be used to indicate risks associated with prolonged hydrological drought, such as reduced reservoir recharge and water availability. Increases in temperature usually increase moisture losses, therefore increasing the risk of drought. This indicator should be used with care in typically arid regions and dry seasons. Soil moisture (m^3/m^3) or average topsoil water content (0 to 5 cm depth) was also estimated as an indicator of the extent and duration of drought. Soil moisture influences the type and condition of vegetation and evapotranspiration. Change in soil moisture can have considerable impacts on ecosystem health. Soil moisture is used to anticipate and manage drought risks such as wildfires, crop insurance, and long-term forest resilience programming. Finally, this information was completed with drought maps in Mexico during the last two decades.

With the results of the projections of temperature, precipitation, droughts, vegetation indices and soil moisture, the vulnerability of the forestry sector in Mexico will be evaluated through models of the influence of these factors on forest growth and regeneration, composition and diversity of species; and forest habitat and ecosystems.

Initially, a base map of the current vegetation of Mexico and its relationship with the climate was created, with a correspondence between the climate classification of Köppen-García (1988) and the typology of vegetation made by Rzedowski (1978, 1992). For the generation of prospective scenarios, three models were applied that take into account the increase in CO_2 concentration in the IPCC SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.

García's (1989) climate classification was mapped on a 0.5x0.5° grid. Meteorological stations that represented the climatic characteristics of the country at this resolution and that had availability of average temperature and total precipitation data at the monthly level, for a period of 30 years, between 1980 and 2020, were evaluated. Thus, each grid table was associated with a climate database, with the average of the required 30 years. The climatic types defined by García were rearranged into 16 groups, in order to make the correspondence between them and the nine types of vegetation delimited by Rzedowski more balanced, and to facilitate their interpretation.

The map of the vegetation that should cover the territory without human impact (Rzedowski, 1992) was superimposed with each of the climate parameters, to recognize the climatic conditions in which each type of vegetation is preferentially distributed, the superimpositions were made in the IDRISI geographic information system and the corresponding vegetation was assigned to each type of climate. With the data from the climatological stations, a climate map was generated at the end of the century, to which the temperature and precipitation modifications indicated by the scenarios used were applied, and three climate maps were obtained, according to each of the proposed scenarios. With this information, maps of the possible distribution of vegetation were generated, according to climate-vegetation correspondences, and the vegetation that these new climatic conditions could potentially have been assigned to each area.

By superimposing the maps of climate scenarios with those of the current climate, the areas of the country that would present modifications in the climate type, according to each scenario, and those that would remain unchanged (climate variation maps) were obtained. Subsequently, each of the three maps of climate variation were superimposed on the current potential vegetation, in order to spatially indicate the vegetation areas that would be affected, according to each of the climate change scenarios.

Because SSP scenarios predict a change in temperature and precipitation, depending on the geographical area of the country (increases in temperature, and increases or decreases in precipitation), and that these variations do not necessarily imply a change in the type of climate and, therefore, the presence of a different type of vegetation than the current one, only the proportion of each type of vegetation that would be exposed to climatic variations was quantified. Finally, the climate variation maps of the three scenarios were superimposed on the vegetation and current land use maps, in order to evaluate the impact of climate change considering the state of conservation that the ecosystems currently present.

3. RESULTS AND DISCUSSION

Figure 8 presents the climatology of the period 1990-2020 at a resolution of 0.5ºx0.5º (50x 50 km) for a) average annual temperature, b) accumulated annual precipitation and c) minimum, maximum, average and monthly precipitation temperature of the period 1991-2020, which will serve as a reference to compare the changes in the regional models.

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

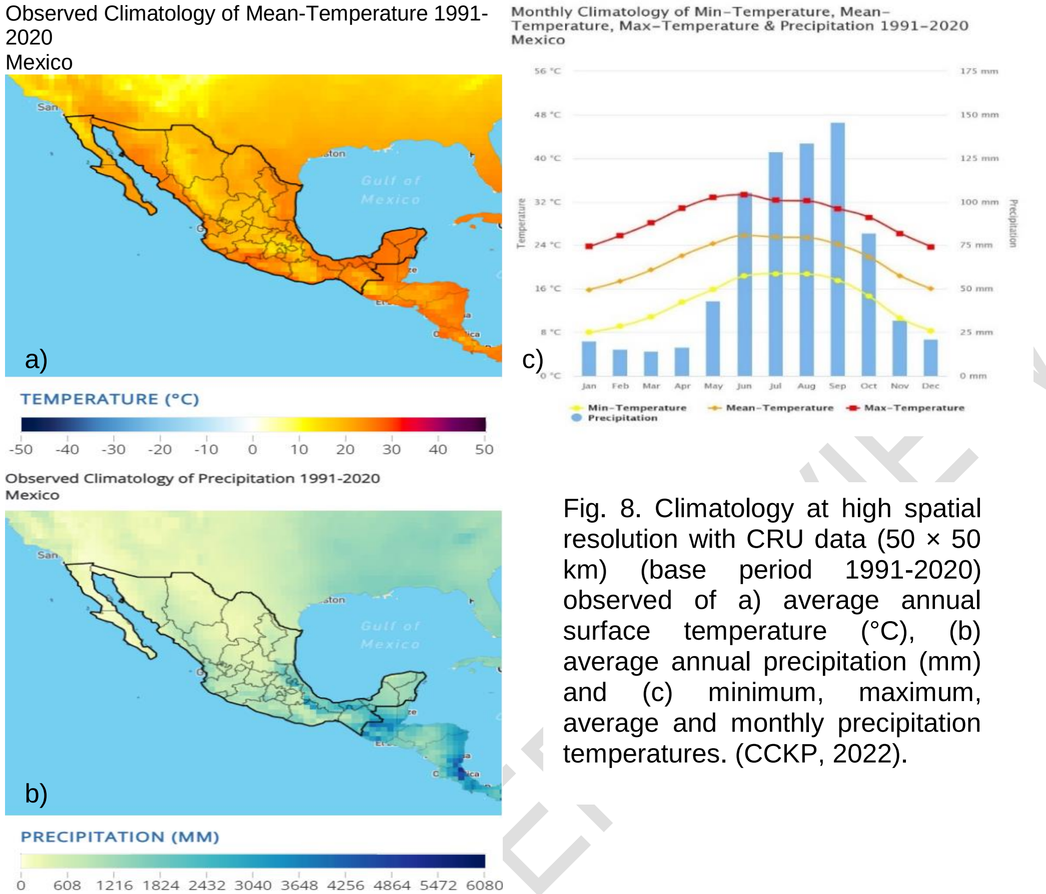

Fig. 8. Climatology at high spatial resolution with CRU data (50 × 50 km) (base period 1991-2020) observed of a) average annual surface temperature (°C), (b) average annual precipitation (mm) and (c) minimum, maximum, average and monthly precipitation temperatures. (CCKP, 2022).

3.1 Regional climate change scenarios

Most studies agree that the temperature will increase in the coming decades and will affect the hydrological cycle and forestry sector on a global and regional scale (IPCC, 2007, 2021). The impacts of climate change are expected to have a large number of socio-economic consequences, particularly in regions where climate disasters have 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 the increase in temperature and reduction in rainfall. The regional-scale climate change scenarios obtained through CMIP6 are able to show the contrasts in projected climate changes between regions of Mexico. Variations in temperature increase are expected because the mechanisms that control climate variability are related to processes in the Pacific and Atlantic oceans (Magaña et al. 2003, Méndez & Magaña 2010).

Regional models for Mexico show that the average annual surface temperature can experience increases ranging from 0.5 to 5 °C depending on the selected scenario and period, while the percentages of change in precipitation from -20.3% to 13.5% depending on the scenario and period of analysis. It is estimated that it is unlikely to limit GHGs and radiative forcing to the SSP1-1.9, SSP1-2.6 scenarios, while the actions that are carried out to mitigate GHG emissions allow the SSP5-8.5 scenarios not to be reached, based on this it is estimated that the two most likely scenarios are the SSP2-4.5 and SSP3-7.0 scenarios. For the anomalies of temperature, precipitation and changes in the percentage of rainfall, the period 1995-2014 was taken as a reference. They will also be the scenarios with which the impacts on forest resources in Mexico will be evaluated.

For the SSP2-4.5 scenario, the annual mean temperature anomalies for Mexico in the period 2020-2039 are estimated at 0.83±0.06 °C, while for 2040-2059 with a value of 1.46±0.06 °C, the period 2060-2069 of 1.96±0.09 °C and at the end of the century (2080-2099) it will reach a value of 2.35±0.12 °C with respect to the reference period 1995-2014 (Table 3). It must be remembered that the values are differentiated according to the region, state and municipality. In the SSP3-7.0 scenario, the annual mean temperature anomaly in the period 2020-2039 is estimated at 0.75±0.04 °C, the period 2040-2059 of 1.59±0.06 °C, the period 2060-2069 of 2.49±0.11 °C and in 2080-2099 of 3.49±0.14 °C (Table 3 and Figure 9).

Table 3. Anomalies of temperature, precipitation and change in % of precipitation for Mexico according to the different scenarios of the IPCC (2014) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5 during this century, obtained from regional models (CCKP, 2022).

Temperature anomalies in °C				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	0.68±0.09	0.81±0.08	0.70±0.1	0.61±0.10
SSP1-2.6	0.82±0.06	1.19+±0.07	1.32±0.06	1.25±0.09
SSP2-4.5	0.83±0.06	1.46±0.06	1.96±0.09	2.35±0.12
SSP3-7.0	0.75±0.04	1.59±0.06	2.49±0.11	3.49±0.14
SSP5-8.5	0.94±0.04	1.93±0.05	3.14±0.08	4.54±0.15
Precipitation anomalies in mm				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	1.57±5.41	2.58±5.83	2.27±5.98	1.58±5.28
SSP1-2.6	1.12±3.39	0.28±3.75	-0.65±3.38	0.08±3.75
SSP2-4.5	0.12±3.71	-0.93±4.45	-2.12±5.00	-3.40±6.31
SSP3-7.0	-0.97±2.13	-3.51±4.64	-5.92±8.35	-7.77±11.18
SSP5-8.5	-1.78±2.56	-3.32±5.82	-5.63±8.49	-9.38±14.07
Changes in % precipitation in mm				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	-2.60±5.84	-1.64±5.57	-1.36±4.94	-2.90±3.84
SSP1-2.6	0.42±3.45	-0.21±3.62	-1.27±4.38	-0.35±4.54
SSP2-4.5	-0.98±4.48	-3.10±6.71	-5.1±6.49	-5.81±7.59
SSP3-7.0	-1.46±3.60	-4.94±6.15	-8.78±8.94	-10.59±12.66
SSP5-8.5	-1.65±4.76	-4.28±7.57	-7.63±11.18	-12.80±16.15

Regional precipitation projections tend to produce negative and positive changes depending on the period analyzed and/or the region of the country. However, most are a decrease in rainfall in almost the entire country. For the SSP2-4.5 scenario, the average annual precipitation anomalies (mm) in the period 2020-2039 are estimated at 0.12±3.71, the period 2040-2059 of -0.93±4.45, the period 2060-2069 of -2.12±5.00 and at the end of the century 2080-2099 it will reach -3.40±6.31 (Table 3). In the SSP3-7.0 scenario, the average annual precipitation anomalies (mm) in the period 2020-2039 are estimated at -0.97±2.13, the period 2040-2059 of -3.51±4.64, the period 2060-2069 of -5.92±8.35 and in 2080-2099 of -7.77±11.18 (Table 3 and Figure 10). Precipitation anomalies in mm are difficult to interpret, so they were reported in % of precipitation change for a simpler interpretation. For the SSP2-4.5 scenario, the changes in the % average annual precipitation in the period 2020-2039 is estimated at -0.98± 4.48%, the period 2040-2059 with a value of -3.10±6.71%, the period 2060-2069 of -5.1± 6.49% and at the end of the century 2080-2099 of -5.81±7.59% (Table 3). In the SSP3-7.0 scenario, the changes in the average annual rainfall % in the period 2020-2039 is estimated at -1.46±3.60%, the period 2040-2059 of -4.94±6.15%, between 2060-2069 of -8.78±8.94 and in 2080-2099 it will reach -10.59±12.66% (Table 3 and Figure 11).

Mexico is one of the regions of the world where rainfall is most likely to decrease under climate change (IPCC 2007). These reductions combined with large increases in temperature imply a large increase in potential evapotranspiration and a substantial reduction in water availability and soil moisture, affecting agriculture in Mexico and with it forest growth and regeneration, species composition and diversity; and forest habitat and ecosystems. Thus, in general, the expected magnitude of negative changes in rainfall is expected to be between -5 and -10% by the end of the century.

The temporal evolution of the projections indicates that it is more likely that the decreases in rainfall will be significant during the second half of the twenty-first century, showing a clear negative trend in any of the CIMP6 scenarios. If we add to this the observations of soil moisture (mm), Standard Precipitation Index of 12 months SPEI12 Log (ERAS LAND), the normalized difference vegetation index (NDVI) and drought events gives us a more robust picture of how temperature and precipitation changes will affect Mexico's water and forest resources. Thus, the soil moisture map (mm) allows us to show that the North, West and Bajío areas have lower values of soil moisture < to 0.1, which will be intensified with higher temperatures that will cause greater evaporation and less rainfall that will not allow the soil to recover its moisture. 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 12 a). The SPEI is a standardized version of precipitation anomalies and has been used to characterize the severity of meteorological drought (Méndez & Magaña 2010). SPEI12 allows to evidence persistent precipitation anomalies and estimate the potential trend for more meteorological droughts. The SPEI12 map shows the prolonged droughts that occurred in the 1910s, 1930s, 1950s, 1970s and 1990s to date throughout the country, with more intensity in the northern zone (Figure 12 b). The magnitude of SPEI12 during the 20th century ranged from −1 to −2 when prolonged droughts occurred, which corresponds to extremely dry conditions. The corresponding projections of precipitation in the multimodel set at the regional scale for 2000−2099 do not have the magnitude of the observed natural variability. However, there is a trend towards negative values of SPEI12 under the SSP3-7.0 scenario than under the SSP2-4.5 scenario, with values of around -1. Conditions of moderate semi-permanent meteorological drought over Mexico, which will affect forests and jungles.

NDVI (Figure 12 c) is closely related to soil temperature and moisture (Ichii et al. 2002). Thus, the negative changes of the NDVI over Mexico are related to reductions in rainfall and the increase in temperatures. The projected patterns for the second half of the 21st century correspond to a severe deficit of soil moisture and water stress in plants. NDVI values are considered sparse vegetation. The projected scenario could be analyzed with the conditions of previous droughts. For example, the projected changes in soil moisture and NDVI in SSP scenarios resemble the anomalies observed under intense ENSO event conditions (1982-1983, 1986-1993, 1997-1998, 2014-2016). Most of the affected regions are semi-arid areas, where natural vegetation is a niche of very rich biodiversity. Very low frequency climate variability over Mexico with surface temperature anomalies close to 5 °C and water stress (decreased rainfall) has resulted in a greater number of forest fires, without considering the effect of climate change. If positive temperature anomalies and negative rainfall anomalies are added to these conditions, it is possible that this exacerbated the increasing presence of fires in forests and jungles in Mexico, a situation that could worsen until the end of the century.

Regional climate change scenarios suggest that by the end of the century, water availability in northern Mexico may be reduced by up to 30% due to global warming, due to possible reductions in rainfall and rising temperatures. Historically, droughts have had serious consequences on primary activities such as agriculture, livestock, forestry and the environment. To examine the impact of climate change, conditions during a similar anomalous hot and dry period can be analyzed. High anomalous temperatures in northern Mexico persisted during the summers of 1998-2002 (around +2 °C) with below-normal rainfall (-20 to -30%), leading to prolonged drought. This resulted in a severe deficit of soil moisture and water stress in crops and vegetation that increased the potential for forest fires. The spring of 1998 turned out to be the season with the highest number of forest fires in Mexico in recent decades, not only due to hydrological stress on vegetation, but also due to slash and burn in the agricultural sector (Magaña 1999). Vulnerability in northern Mexico has not been reduced (Liverman 2001) and consequently, the risk of an environmental disaster is still present (Wilder et al. 2010) and will be complicated by the effects of climate change.

The drought map (Figure 12 d) shows the current droughts, where practically the entire country has suffered from moderate droughts (center and south) to extremely strong (north). Under the

SSP climate change scenarios with conditions of strong increase in temperatures and decrease in rainfall, the drought scenario in Mexico will be prolonged and exacerbated between now and the end of this century, with damage to agriculture, livestock, forestry and forest ecosystems in Mexico, affecting the associated social, economic, political and cultural activities.

3.2 Impacts of climate change on water resources

On a global scale, it is expected that the effects of climate change on water resources will be extensive, but of different sign and magnitude from one region to another, according to latitude, altitude, biomes, orographic conditions, hydrography, among others. In some regions of Mexico, the first symptoms of damage to water resources are already being recorded. In the case of the results of this study, an increase in the surface temperature of Mexico of approximately 1.8 °C by 2020 compared to 1900 was evidenced, remaining above global values. The CIMP6 regional models show a similar behavior to the global projection where 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 hot summers and less harsh winters.

In the case of Mexico, the regional scenarios show that Mexico's surface temperature will continue to increase proportionally from the period 2020 to the period 2080-2099 in all the scenarios considered and exceeding the threshold of 2 °C increase. Projections show that Mexico will present the following increases with respect to the period 1994-2014: in the period 2081-2099 for the most likely scenarios SSP2-4.5, from 1.78 to 2.58 °C and for the SSP3-7.0 scenario it will reach 2.75 to 3.84 °C. The first below the IPCC and the second above the IPCC at a global level.

In the regional projections for Mexico, the threshold of 2 °C in the period 2040-2059 would be exceeded in all scenarios except for the SSP1-1.9 scenario. which is in line with the global scenarios. In Mexico, the projected regional scenarios will reach temperature levels higher than the global ones (1.8°C) with which it is very likely that both in frequency and intensity of hot extremes (heat waves, intense rainfall, meteorological, agricultural and ecological droughts will increase as never before. Regional models for Mexico estimate that this century will see an increase in the frequency of extreme events such as heat waves, recurrent droughts, forest fires, and floods. Rainfall for Mexico will increase only in the first projection period (2020-2039) and in the very low and low scenarios. In the rest of the scenarios, the tendency will be to decrease the amount of precipitation. However, in all cases the intensity of the rains will increase. The initial period (2020-2039) will present increases in the amount of precipitation, but in the following 3 periods (2040-2059, 2060-2079 and 2080-2099) there will be a decrease in wet events and a greater presence of dry events. The regional projections for Mexico meet the global forecasts for 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.

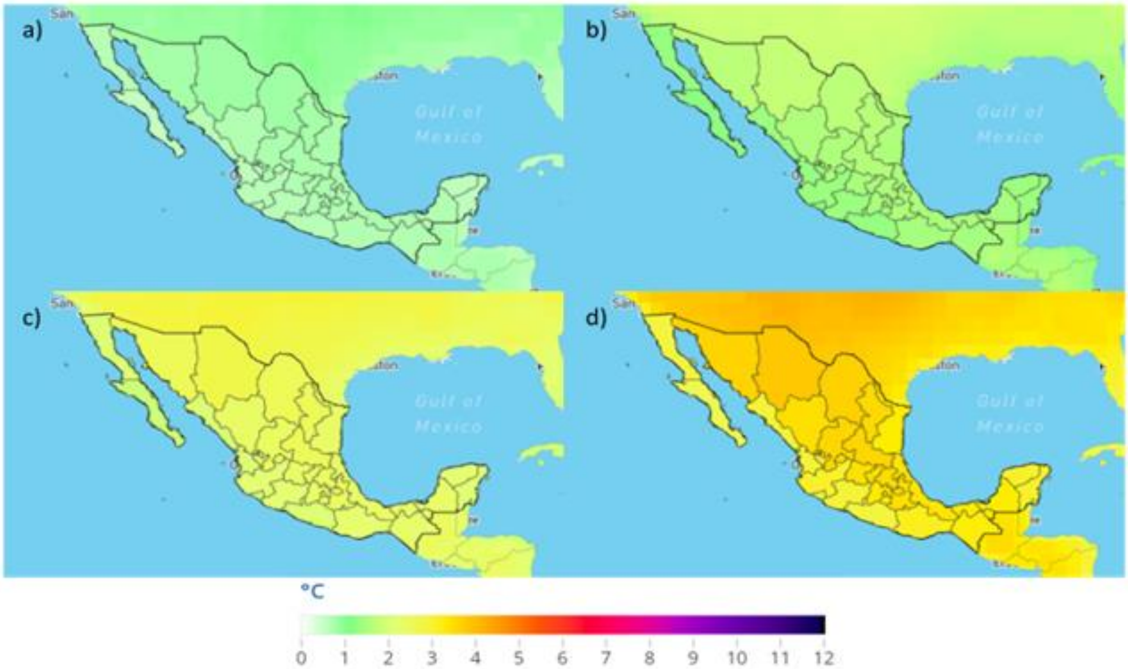

Fig. 9. Projected Mean Temperature Anomaly (Annual) for Mexico under the SSP3-7.0 scenario a) 2020-2039; b) 2040-2059; c) 2060-2079 and d) 2080-2099 (CCKP, 2022).

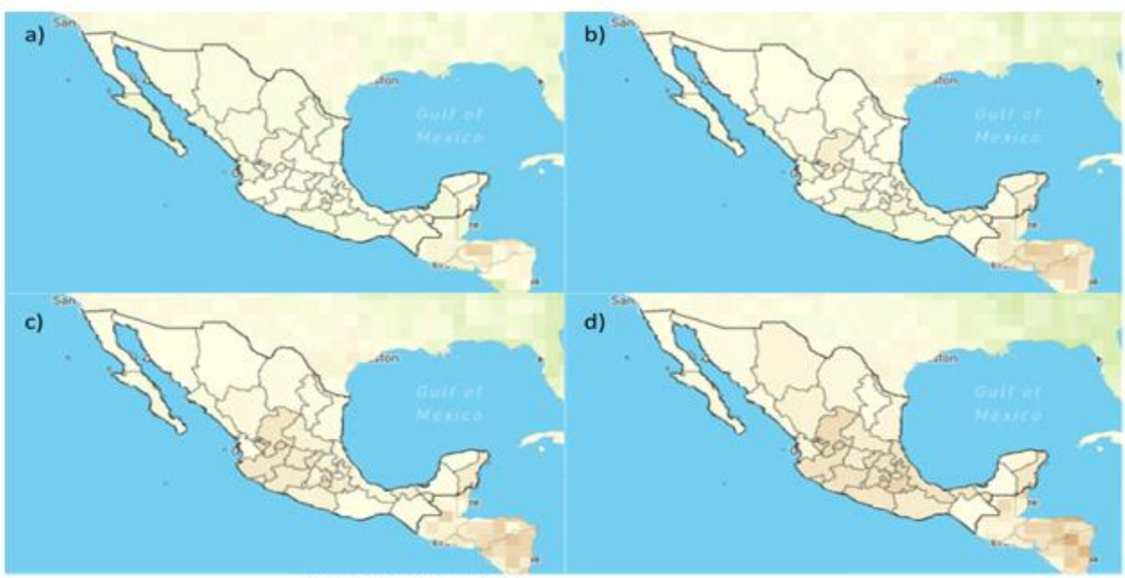

Fig. 10. Projected Precipitation Anomaly (Annual) for Mexico under the SSP3-7.0 scenario a) 2020-2039; b) 2040-2059; c) 2060-2079 and d) 2080-2099 (CCKP, 2022).

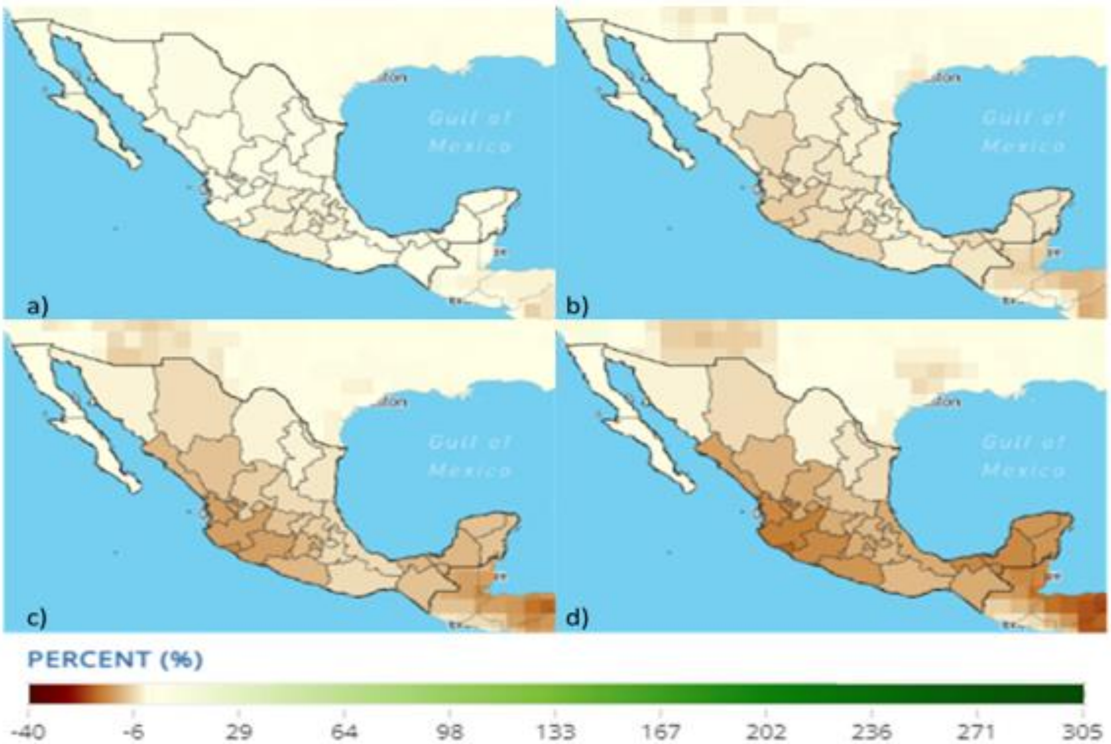

Fig. 11. Projected Precipitation Percent Change Anomaly for Mexico under the SSP3-7.0 scenario a) 2020-2039; b) 2040-2059; c) 2060-2079 and d) 2080-2099 (CCKP, 2022).

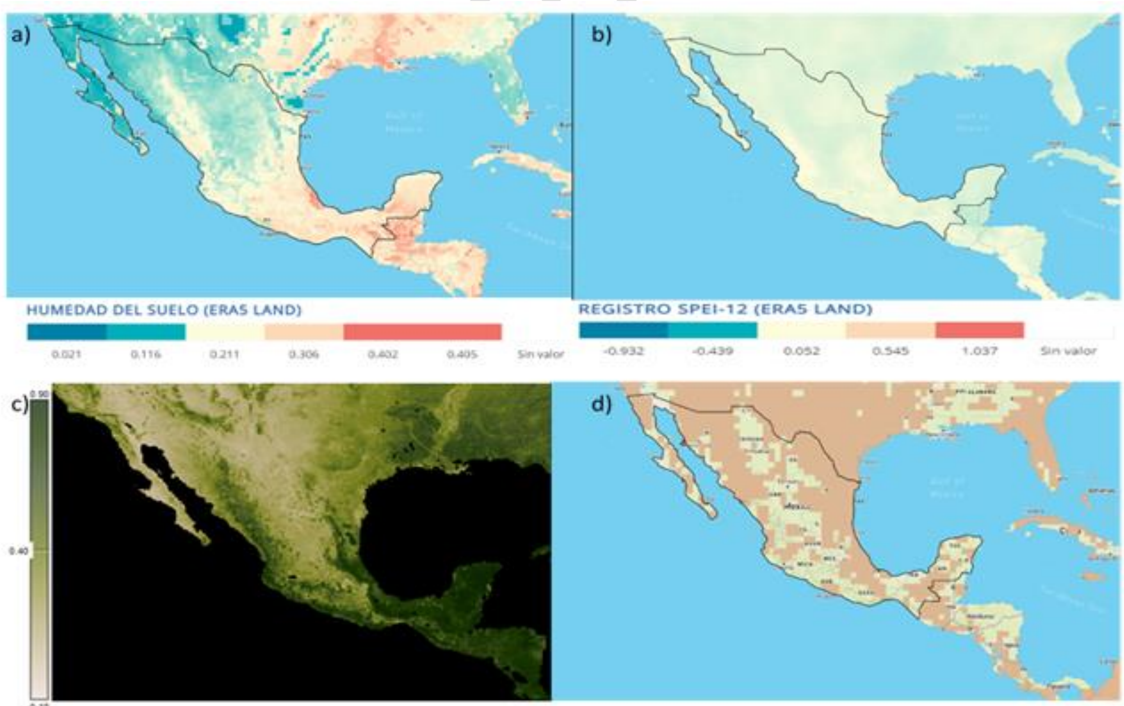

Fig. 12. (a) Soil moisture (mm) and (b) SPEI12 Log (ERAS LAND), c) normalized difference vegetation index (NDVI) changes and d) Droughts events in SSP2-4.5 scenario for the second half of the 21st century (CCPK and NASA 2022).

Regional projections of soil moisture decline, the SPEI12 index, NVDI, and the major periods of drought in recent decades confirm for Mexico global estimates of intensification of very dry weather and prolonged droughts. Given the conditions presented in the regional projections, it is estimated that the North American monsoon will be delayed as the century progresses and, together with the decrease in precipitation, will cause major storage problems in the northern bodies of the country. 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 conditions of scarcity and greater pressure on diversified water resources in the different regions.

On the other hand, a warmer climate will mean more intense precipitation events, even in places where average annual precipitation is likely to be lower. What is happening and will continue to happen in the south and southeast of Mexico. In fact, the average annual rainfall may even decrease, but more intense rains will be recorded, which will make it more difficult to control flows through the current channels. These extreme events will be the most difficult to predict in future climate change scenarios, as they are eminently local in nature. It is expected that the impacts of global warming on runoff will be detected first in the occurrence of extreme events rather than in annual availability, which has important natural variations.

In the case of Mexico, this effect of climate change will increase vulnerability in basins in southern and southeastern Mexico, such as the Grijalva-Usumacinta systems in Chiapas and Tabasco, and Papaloapan in Veracruz, which are already experiencing flooding problems (Martínez-Austria and Patiño-Gómez 2012). 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 predictions of decreased precipitation and runoff and is expected to occur more frequently and intensely. If important adaptation measures are not adopted, the availability of water resources in quantity and quality could be at major risk and, consequently, the food security and health of the population of Mexico.

3.3 Impacts of climate change on forest resources in Mexico

Cold and semi-warm temperate forests are the types of vegetation most sensitive to climate change and would tend to disappear as temperatures increase. Dry, very dry and thorny tropical forests, with warm affinities, would tend to occupy larger areas than at present, with the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios. SSP2-4.5 projects an increase in the distribution of humid and subhumid tropical forests, which would be favored by the increase in precipitation only in the first third of the century, however the rest of the century will be affected by a decrease in their surface area and a tendency to disappear due to decreased precipitation, soil moisture and the presence of permanent droughts.

The ecosystems most affected by human impact are tropical forests and grasslands, in contrast to temperate forests and xerophilous shrubland, which have a lower degree of anthropogenic deterioration, where the impact of climate change would be greater. In contrast, tropical ecosystems would be more sensitive to changes in precipitation (Emanuel, et al., 1985, Kauppi & Posch, 1985 and Bolin, et al., 1986). For the generation of prospective scenarios, three scenarios were applied that take into account the increase in CO_2 concentration as a function of the radiative forcing of the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios between now and the end of the century (IPCC, 2020). The sensitivity to climate change in these scenarios was estimated in the range of an increase in the country's temperature of between 0.5 and 2º C and a decrease of up to 30% to the current precipitation, depending on the period and scenario analyzed (Table 4).

The SSP3-4.5 scenario (2.35°C and -13% precipitation), predict an increase in the distribution of warm climates and a decrease in humidity; These changes would have an impact on the distribution of vegetation. The tropical evergreen, subevergreen and deciduous forests found in warm humid and subhumid climates of type 1 (average annual temperature > 22ºC and a precipitation/ temperature ratio between 43 and 55), would slightly increase their distribution; in the first third of the century, and they could settle in areas with higher altitudes than those of today. According to the scenarios, the increase in temperature would favor the establishment of tropical communities, taking away land from temperate oak and coniferous forests established in temperate and semi-cold climates; the latter would tend to disappear in the regional scenarios of SSP2-4.5. In the case of thorny forests, they would move southwards, mainly on the Pacific slope, favored by the conditions of greater aridity, in states such as Sonora and Sinaloa, or in the Balsas Basin and Isthmus of Tehuantepec where their distribution would be expanded. On the Gulf slope, these forests would have a greater distribution in Tamaulipas and Nuevo León.

According to the SSP3-7.0 model, the increase in the average annual temperature in the country would be 3.5°C and there would be a 23% decrease in annual precipitation. This model predicts a trend of decline, in the case of tropical evergreen, subevergreen and deciduous forests. The latter would tend to occupy areas of higher altitude than the current one, especially in the states of Jalisco and Guerrero, however, due to the significant increase in temperature and decrease in precipitation and humidity in the environment and in soils, these would tend to be supplanted by arid vegetation. Dry warm and semi-warm climates would increase their surface area covering areas such as the Balsas basin, the Isthmus of Tehuantepec, the state of Oaxaca, as well as Tamaulipas, which would favor the establishment of thorny forests or tropical deciduous forests in their driest forms in these areas. In the states of San Luis Potosí, Guanajuato and Zacatecas, they would also increase where temperate climates would be displaced by warmer ones, so that the plant communities in these areas would be xerophilous shrublands exposed to warmer conditions.

Table 4. Percentages of current potential vegetation, according to the current climate and according to SSP scenarios at the end of the century.

Type of climate (Köppen, modified by García)	Type of vegetation (Rzedowski)	Potential current	SSP2-4.5	SSP3-7.0	SSP5-8.5
Warm humid	Evergreen tropical forest	5.9	6.4	5.0	4.5
Warm Subhumid 2	Subevergreen tropical forest	3.7	4.0	1.7	1.5
Warm Subhumid 1	Tropical deciduous forest and subevergreen	17.7	15.0	10.0	7.0
Semi-warm humid	Cloud Forest	2.1	0.3	0.5	1.3
Semi-warm sub-humid 2	Subevergreen tropical forest and cloud	0.4	0.9	0.1	2.0
Semi-warm sub-humid 1	Tropical deciduous forest	6.6	4.6	5.0	6.0
Wet tempering	Coniferous and *Quercus* forest	0.6	0.3	0.3	0.3
Sub-humid temperate 2	Coniferous and *Quercus* forest	2.7	1.3	1.3	2.1
Sub-humid temperate 1	Coniferous and *Quercus* forest	3.1	1.5	2.1	2.3
Semifreddo	Coniferous forest	2.3	0.0	0.0	0.0
Dry warm	Thorny forest and xerophilous scrub	11.0	20.0	20.0	20.0
Dry semi-warm	Xerophilous shrubland and thorny forest	10.5	13.2	14.0	17.0
Dry tempered	Xerophilous grassland and shrubland	11.6	7.1	13.5	14.4
Warm aggregate	Xerophilous shrub	6.1	10.5	11.1	10.1
Semi-warm aggregate	Xerophilous shrub	11.3	11.5	11.8	11.5
Temperate aggregate	Grassland	4.6	3.4	3.5	0.0

The SSP5-8.5 scenario poses the most severe of the three analyzed. The model predicts an average temperature increase of almost 5°C and a decrease in precipitation of 30%. These increases reflect very important and drastic changes at the climatic level. There is an increase in the presence of warmer climates, in most of the country's surface. This would harm tropical forests, which could decrease their distribution to areas further north and south of the country than those currently occupied. Arid temperate and semi-warm climates would increase, and would cover areas that today occupy grasslands and xerophilous shrubs would displace shrubs with affinities to higher humidity and higher temperature, or even thorny forests. Coniferous forests settled in semi-cold climates would be replaced by more temperate communities, such as holm oak forests, which, in turn, would tend to settle in places with higher altitudes. Although the trend at the end of the century is for them to be replaced by drier forests.

The change in the distribution of plant communities predicted by the models implies that vegetation should have the response capacity to adapt or migrate in less time than these processes normally require, which is unlikely (Markham, 1996). For this reason, it is important to assess the impact of climate change on current ecosystems, without considering a redistribution of vegetation. About 50% of the country will be affected by climate change: 55.5% in the SSP2-4.5 scenario, 58.6% in the SSP3-7.0 scenario, and 60.5% in the SSP5-8.5 scenario.

It is observed that, depending on the regional scenario, plant communities will be differentially affected. The most sensitive are those in temperate climates, such as coniferous and oak forests (temperate forests), cloud forests, grasslands and xerophytic shrublands. As can be seen, between 65 and 70% of the total area of temperate forests would be affected; cloud forests would be exposed to change between 46 and 58% of their extension. Grasslands, as well as xerophilous shrublands with temperate affinities, up to 93% of their total area would be affected by the change.

The climatic variations to which these types of vegetation would be subject are very wide, according to what the SSP scenarios predict. Increases in temperature vary from 0.5°C to almost 5°C, throughout the territory; variations in precipitation range from - 20% to -30%. These changes are distributed in such a way in the country that in areas such as northern Mexico the average temperature would rise more than 4ºC, in contrast to areas in the south where the thermal increase would be around 2 and 2.5ºC. With respect to precipitation rates, predicts that most of the country would be subject to decreases in precipitation. The different combinations in temperature and precipitation changes, proposed by these scenarios, imply that vegetation should tolerate drier and warmer conditions than today, in the case of the decrease in precipitation.

Each type of climate is defined by certain ranges of temperature and humidity (García, 1988); exceeding the limits implies a change in the climate type; however, if the changes are not important enough to move to a different climate type. Thus, when the temperature in an area increased, without exceeding the classification range, it was considered unchanged.

With the SSP2-4.5 scenario, the vegetation types most affected by these climatic variations are those that are exposed to drier and warmer conditions, and would correspond to the mountain cloud forest, which would have about 31% of its total area affected, followed by temperate forests (22%), thorny forest and tropical deciduous forest (10%). The most sensitive areas of temperate forests are: the Sierra Madre Occidental, in the states of Chihuahua and Durango, Jalisco, Michoacán, Morelos and the Sierra de Zongolica in Veracruz. The cloud forests that would be most affected are located in Oaxaca and Chiapas. Tropical evergreen and subevergreen forests conserve about 80% of their surface in areas that will maintain the same type of climate.

According to the SSP3-7.0 Scenario, almost all vegetation types would have about 10% of their surface affected by drier and warmer conditions than the current ones, which would represent a strong pressure for these areas. Xerophilous shrublands located in Chihuahua, Coahuila, Zacatecas and in San Luis Potosí would have a larger area exposed to warmer climates, mainly in grasslands, xerophytic scrub and temperate forests.

In the SSP5-8.5 scenario, it predicts a more drastic scenario, since much of the country would have quite significant increases in temperature and decreases in humidity. Thorny forests, tropical deciduous and tropical subevergreen, would have part of their distribution area exposed to a decrease in precipitation but with a constant temperature (between 11 and 17% of their surface), mainly in Oaxaca and its border with Guerrero. Similarly, temperate and mountain cloud forests would have about 10% of their surface exposed to decreases in precipitation, even though much of their area would show changes towards warmer climates. The latter also happens with xerophytic scrub and grassland.

Of the total area reported for each type of vegetation, the percentage conserved and the deteriorated percentage are indicated, the latter grouped into secondary vegetation. Conserved vegetation is considered to be that which contains the structural and floristic elements that define the type of native vegetation. In the category of secondary vegetation, a range of communities that have lost their original composition, either due to forest fragmentation, extraction of species, felling, burning, etc., is considered, but that the type of original vegetation from which it comes and that was altered can be identified. It should be noted that the results obtained are only a first approximation, and that they should be considered as possible projections.

Table 5 shows the area of each vegetation type that, in its current distribution, would be affected by climate change, according to each model, as well as the relative proportion of the total area of each type that is in acceptable conditions of conservation or in different degrees of deterioration. Thus, grasslands, temperate forests and xerophytic shrublands with temperate affinities are the most sensitive types of vegetation, mainly of the latter type of vegetation it is considered that between 88 and 90% of the area that would be exposed to climate change is still preserved. More than 60% of the temperate pine and oak forests would be affected, of which it is estimated that about 73% are still preserved. Of the pastures, between 66 and 86% would be affected, according to the models, but of this more than 50% is disturbed. In the case of tropical forests, areas exposed to change show very high proportions, and between 60 and 85% of this type of vegetation is secondary.

Table 5. Percentage of current vegetation affected by climate change by the end of the century according to the IPCC SSP scenarios, considering its conservation status.

Type of vegetation	SSP2-4.5			SSP3-7.0			SSP5-8.5		
	Affected	Preserved	Secondary	Affected	Preserved	Secondary	Affected	Preserved	Secondary
Evergreen tropical forest	**20**	19.5	80.5	**23**	12	88	**25**	15	85
Subevergreen tropical forest	**25**	28	72	**30**	22	78	**30**	32	68
Tropical deciduous forest	**50**	40	60	**45**	36	34	**50**	35	65
Thorny forest	**30**	75	25	**40**	76	24	**45**	73	27
Xerophilous shrub	**65**	90	10	**75**	90	10	**75**	88	12
Grassland	**65**	50	50	**80**	50	50	**80**	48	52
Temperate forest	**65**	65	35	**70**	65	35	**70**	60	40
Cloud Forest	**55**	60	40	**60**	58	42	**55**	50	50
Aquatic vegetation	**25**	95	5	**30**	95	5	**28**	99.5	0.5

In general, according to the different climate change scenarios, the increase in the concentration of atmospheric CO_2 promotes changes in vegetation cover in large areas of the country. The area occupied by all temperate climates decreases, likewise, semi-cold climates give way to more temperate zones, which would mean the displacement of some coniferous forests. The habitat of temperate forests, established along the country's mountain ranges, would be considerably reduced, which would imply the redistribution of these forests or the establishment of forms adapted to drier and warmer conditions, such as thorny forests and xerophytic shrublands.

This means that in the face of possible climate change, plant communities will have to face pressures such as increased aridity or lower ranges of precipitation, and they would have to respond in relatively short times. In addition, the capacity to respond would be affected by the state of conservation of vegetation and by factors such as deforestation.

The analysis of the impact on forest cover should be combined with the analyses of forest growth, forest regeneration, species composition and diversity, forest habitat and forest ecosystems.

Forest growth: The growth rate is strongly influenced by the availability of water, if there is sufficient water availability, a short and not very intense dry period, and high temperature, a high growth rate will be found (Toledo et al. 2011). Solar radiation is another factor that affects the growth rate of trees. However, the effect on the growth rate of trees is more significant if combined with the effect of temperature. The variation in solar radiation and temperature together affected the growth rate of the trees at the stand level. In tropical forests, the correlation between the variation in the growth rate of trees at the stand level and the variation in incoming solar radiation is positive (Dong and Moorcroft 2011). Wagner et al. (2014) showed that precipitation and solar radiation had a positive association with tree growth. Thus, in the case of Mexico, the combination of the combined impacts of decreased precipitation, intense solar radiation, increased temperature, and low soil water content will impact the growth of all forest ecosystems by 50% by the end of the century.

Forest regeneration: Climate changes, such as temperature change and variation in water availability, can limit the ability of tree species to regenerate because tree seedlings are highly susceptible to climate change. In eucalyptus forests, the regeneration of tree species will be affected in the coming decades by increasing the temperature of 1.0-4.5 °C and decreasing rainfall from 3 to 25% (Mok et al. 2012). In temperate zones, the seedling mortality rate was significantly affected by reduced rainfall and increased temperature (Parada and Lusk 2011). In addition, one of the consequences of climate change, fire, can affect seedling density. In tropical humid deciduous forest, burnt forest seedling density was 63% lower than that of unburned forest (Kodanadapani et al. 2008). Thus, in the case of Mexico, the increase in temperature between 0 and 5 °C, the decrease in precipitation by up to 30%, as well as the establishment of semi-permanent meteorological drought and the intensification of forest fires between now and the end of the century, will limit the regeneration capacity of tree species in all the country's forest ecosystems.

Species composition and diversity: The drought and heat impacts of climate change can cause tree mortality that alters species composition and diversity (Allen et al. 2010). Likewise, the distribution and migration of species are directly affected by fire responses to climate change. In humid forests, water deficiency increased the mortality rate of trees and this effect was severe as the frequency and rate of water deficiency increased (Nishimua et al. 2007). However, tropical rainforests have a greater tendency to resist water scarcity compared to tropical dry forests. Another factor that can change the composition of species and the structure of the stand is fire. In both tropical dry and dry deciduous forests, seedling and sapling densities decreased and species diversity decreased by 50% and 60% due to moderate and intense fire frequency, respectively, compared to low fire frequency (Kodanadapani et al. 2008; Massad et al. 2013).. The impacts of drought and heat due to the increase in temperature and decrease in humidity, together with the increased presence of forest fires, can cause tree mortality that alters the composition and diversity of species in Mexico's forest ecosystems between now and the end of the century.

Forest habitat and forest ecosystems: Most species in Mexico have an unbalanced species distribution, which means that a change in distribution could be found even in a stable climate. On the other hand, a long history of anthropogenic activities and a good forest management system should also be considered as one of the factors to increase the presence of species. Habitat losses of endemic species are a consequence of the displacement of species to other regions, in response to a warmer climate. Tree species make natural adjustments to respond to global warming by moving to higher latitudes for their survival (Chen et al. 2011). Therefore, in the case of Mexico, forest habitats and ecosystems are expected to suffer drastic changes as a result of climate change, such as the displacement mainly of forests, jungles and xerophilous scrubland.

3.4 Role of forests in climate change

The world's forests store more than 650 billion tons of carbon in various components: 44% in biomass, 45% in soil and 11% in dead wood and leaf litter (FAO 2010). The world's forests show substantial carbon sequestration potential, which will vary depending on the canopy forest cover. In the case of Mexico, the temperate forest of central Mexico, carbon storage ranges from 42.63 to 181.88 MgC/ha, while carbon storage in temperate grasslands ranged from 3.74 to 9.83 MgC/ha (Mendoza-Ponce and Galicia 2010). According to the IPCC, the global carbon cycle has been affected and will be affected in the future by climate change. Climate change can increase the potential for wildfires, and reduce forest carbon storage. Tropical forests have been found to be vulnerable to its impacts, although temperate, broadleaved and Mediterranean species are less affected. Tropical forests have shrunk significantly with an annual loss of 2101 km^2/year (Hansen et al. 2013). In Mexico, the main disturbances affecting forests are fires, drought, introduced species, outbreaks of insects and pathogens, hurricanes, windstorms, and landslides, among others. Seedlings are more susceptible to the impacts of climate change. In addition, the mortality rate of seedlings in forests burned by annual fires appears to be higher than that of forests without burning. However, natural disturbances always interact with anthropogenic activities in general.

4. CONCLUSION

Based on the results, the main conclusions are that the regional models for Mexico show annual surface temperature increases ranging from 0.5 to 5 °C, while the percentages of change in rainfall will range from -20.3% to 13.5% depending on the scenario and period of analysis. For the SSP2-4.5 scenario, the annual mean temperature (°C) anomalies are estimated to be between 0.83±0.06 °C (2020-2039) and 2.35±0.12 °C (2080-2099), while in the SSP3-7.0 scenario, variations of 0.75±0.04 °C (2020-2049) to 3.49±0.14 °C (2080-2099) are estimated.

The changes in the % average annual precipitation for the SSP2-4.5 scenario is estimated between -0.98±4.48 % (2020-2039) and -5.81±7.59% (2080-2099). In the SSP3-7.0 scenario they will vary between -1.46±3.60% (2020-2039) and -10.59±12.66% (2080-2099).

Soil moisture (mm) shows that the North, West and Bajío areas have values below 0.1 mm, while 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 by climate change. The changes in NDVI are negative and are related to the reduction in precipitation and increase in temperature. The projected patterns correspond to a severe deficit of soil moisture and water stress in plants, in semi-arid regions, where vegetation is a biodiversity niche. NDVI values are considered as sparse vegetation. The negative values of SPEI12 under the SSP3-7.0 scenario are lower than those of the SSP2-4.5 scenario, with average values of around -1. Conditions considered as moderate semi-permanent meteorological drought over Mexico. The drought map shows that practically the entire country has suffered from moderate droughts (Center and South of the country) to extremely strong (North of the country). Under the SSP2-4.5 and SSP3-7.0 climate change scenarios with increased temperatures and decreased rainfall, the drought outlook in Mexico will be prolonged and exacerbated between now and the end of this century.

Climate change will substantially affect the world's available water resources. For Mexico, the expected effects of climate change will be a significant increase in temperatures (more than 3 °C) and a decrease in precipitation (more than 20%). As a consequence, surface runoff and aquifer recharge will be reduced, and therefore the availability of water, which will add to the water stress due to climate change (low soil moisture, decrease in NDVI and SPEI12 and recurrent droughts) together with that produced by the population and economic growth expected in the 21st century. Another expected effect of climate change will be the decrease in agricultural and livestock productivity, since, as the temperature rises, evapotranspiration also increases and with it the crops are subjected to greater heat stress, drastically impacting their yield.

The application of climate change scenarios provides very valuable information in relation to the vulnerability of forest ecosystems to the increase of CO_2 in the atmosphere. The scenarios highlight the most sensitive vegetation types and geographic areas that could be affected by the changes. Temperate and cloud forests, xerophilous scrub and grasslands will be the most affected forest ecosystems in Mexico. The cloud forest, which, although it occupies a small area in the territory, is highly significant at the biogeographic level and due to its diversity would be one of the most affected.

The range of temperature increases and the proportion of the increase or decrease in rainfall vary for each model, the scenarios proposed by each of them lay the foundations for proposing the type of measures that would be convenient to apply, in order to mitigate the effects of global climate change throughout the country. Based on the results evidenced, it is recommended to design and prioritize actions for adaptation and mitigation to the effects of climate change in the most vulnerable forest regions of Mexico, and with it the proposal of public policies that allow future generations to have the minimum conditions of sustainability in the country.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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