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CLIMATE VULNERABILITY ASSESSMENT FOR MEXICO

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TECHNICAL ADVISORY SERVICES FOR THE PREPARATION OF GCF COUNTRY PROGRAMMES

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Report on Climate Vulnerability Assessment for Mexico

Under the project **Technical Advisory Services for the Preparation of GCF Country Programmes.**

This report was made with the support of the Green Climate Fund (GCF). GCF is the world's largest dedicated climate fund. GCF's mandate is to foster a paradigm shift towards low emission, climate resilient development pathways in developing countries. GCF has a portfolio of over USD 7 billion (USD 23 billion including co-financing) delivering transformative climate action in more than 100 countries. It also has a readiness support programme that builds capacity and helps countries develop long-term plans to fight climate change. GCF is an operating entity of the financial mechanism of the United Nations Framework Convention on Climate Change (UNFCCC) and serves the 2015 Paris Agreement, supporting the goal of keeping average global temperature rise well below 2 degrees Celsius.

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Mexican Federal Ministry of Finance and Public Credit (**Secretaría de Hacienda y Crédito Público, SHCP** by its initials in Spanish), Mexico.
National Institute of Ecology and Climate Change (**Instituto Nacional de Ecología y Cambio Climático, INECC** by its initials in Spanish), Mexico.

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1. INTRODUCTION

1.1. Background to climate impacts vulnerability assessment

This report summarizes activities undertaken as the Climate Vulnerability Assessment (CVA) service component for Mexico, as part of services delivered to the Mexico Nationally Designated Authority, the Ministry of Finance and Public Credit (Secretaría de Hacienda y Crédito Público), under the framework of the GCF Technical Readiness project.

Climate impacts are expected to be widespread and affect societies, sectors, infrastructure and environment in different ways. Climate risk assessment as defined by the IPCC (1) combines the potential exposure to hazards with vulnerability of the exposed (e.g. livelihoods, ecosystems, infrastructure, species, economy) – which has a key bearing on how a climate hazard is experienced. The risk of a heat wave, a hazard with the same temperature and duration in southern Europe is substantially different to one experienced on the Indian sub-continent – both the exposure, as in number of people or infrastructure, and vulnerability, and substantially different. Understanding how changes in climate manifest in changes to water availability, crop yields, or availability of power plants, enables better understanding of the exposure and vulnerability, and ultimately risk, of climate change to important sectors.

In this report for Mexico, we use several indicators from sectoral “impact models” to further understand to what extent the population and land area is exposed. The work has been developed in consultation with the National Institute for Ecology and Climate Change (INECC - Instituto Nacional de Ecología y Cambio Climático). Contextual information included in this report about Mexico derives from a variety of sources, primarily from discussions with INECC and other stakeholders during the Inception and Mid-term mission meetings.

As part of the activities with Mexico, a Macroeconomic Risk Profile (MRP) has also been developed to assess how climate impacts affect key economic sectors of the Mexican economy. Both assessments are structurally similar, in the sense that they both draw on the same five climate models from the ISIMIP project, having 0.5° grid resolution and assessed at 1.5, 2.0 and 3.0°C. Thus, scenario and data design of the studies is quite similar, although there are some important caveats noted in section2.4.

1.2. Structure of this report

This report is structured into 4 subsequent sections:

- Section 2 on Methodology and data preparation introduces the framework of analysis and scenario selection and introduces the preparation of indicator datasets, their scoring and data sources.
- Section 3 on Impact indicators presents results from each of the individual spatial indicators.
- Section 4 assesses the exposure and vulnerability of the population, land and vulnerable population for the impacts.
- Section 5 brings perspective on key sectoral implications.

2. METHODOLOGY AND DATA PREPARATION

2.1. Introduction to the general framework

The climate vulnerability assessment combines tera-bytes of data from a range of climate, hydrological and integrated assessment models to calculate indicators for scenarios of socioeconomic and climate change. Here we introduce those indicators in more detail. Full details of the methodologies, models, and data sources can be found in this paper (2) and supplementary information.

The service component for GCF climate vulnerability assessment builds upon that work, with tailored and detailed approaches for specific countries.

In summary, this work is assessed across the following dimensions:

- **14 indicators** (Table 1), developed using state-of-the-art global models, grouped within 3 sectors (water, energy and land), plus additionally 3 sectoral indicators and the multi-sector indicator. Indicators are mapped to a consistent impact scale (0 to 3) to facilitate comparison.

- **3 climate change scenarios for historical (1971-2000)**, 1.5°, 2.0° and 3.0°C global mean temperature rise above the pre-industrial conditions, applied to the indicator datasets. Data is produced at 0.5° resolution (approximately 50 km at the equator) and stored in netCDF format. This can be handled by standard GIS software such as QGIS and ArcGIS.

- **3 socioeconomic scenarios from the Shared Socioeconomic Pathways** (SSPs 1-3), with novel gridded projections (also 0.5° resolution) of population and income to 2100 for Mexico (3,4).

- **Exposure of the population, and exposure of the vulnerable populations** (i.e. income < $2, 5, & 10 /day, for extreme vulnerability, vulnerable and vulnerable to poverty categories) (5)

2.2. Sectoral indicators

This assessment is centered around a basket of indicators driven by climate change and socioeconomics that represent a number of sectoral challenges (Table 1). These indicators derive from a range of global climate models (GCM), integrated assessment models and sectoral impact models from a large number of research institutions. Models and host institutions are listed in the Annex.

Methodological and data description of the indicators is presented in below, whilst descriptions of what they represent and relevance are presented alongside the results in Section 3.

Table 1. Details about the indicators used in the assessment.

Indicator	Name	Description	Models & data
w1	Water stress index	Water stress index: as a fraction of net human demands (domestic, industrial, irrigation) divided by renewable surface water availability, as known as the withdrawal to availability ratio (6). The index was calculated using ISIMIP Fast Track data from PCRGLOBWB, WaterGAP and H08 hydrological models using monthly discharge data (with societal discharge routing "pressoc"). Water demands were calculated using the SSPs from the IIASA Water Futures and Solutions initiative where more details of the scenario development and model descriptions can be found (7,8).	GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: PCRGLOBWB; WaterGAP; H08
w2	Non-renewable GW abstraction index	Non-renewable groundwater stress index (w2) is calculated as the fraction of total groundwater abstraction that is non-renewable using data (9,10). The transient assessment spanned 1960-2099 to thus compare historical and projected groundwater abstractions.	GCM: HadGEM2-ES RCP6.0 Hydrology: PCRGLOBWB
w3	Drought intensity	Change in drought intensity (w3) is calculated and the proportion between daily water volume deficit (m^3/s) below the 10th percentile daily discharge (Q_{90}) and drought event duration (days), as derived in Wanders and Wada (11).	GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: H.08; LPJmL; PCRGLOBWB; MPI-HM; WBM+
w4	Peak flows risk	Peak flows risk (w4) is derived using a block-maxima approach with Generalized Extreme Value distribution fitting(12) to produce return period values for both historical and future hydrological simulations. With a 20-member ensemble, only locations where there is significant (50%+) ensemble agreement of a doubling or halving of the 20-year return period for river discharge were retained.	GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: H.08; LPJmL; PCRGLOBWB; WBM+
w5	Seasonality	Mean seasonality (w5) is the change in seasonality index, calculated as the coefficient of variation (standard deviation divided by the mean) of mean monthly discharge. Lower values (<1) represent low seasonality (i.e., flows do not vary much through the year).	GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: H.08; LPJmL; PCRGLOBWB; MPI-HM; WBM+
w6	Inter-annual variability	Mean inter-annual variability (w6), is the change in inter-annual variability index, calculated as the coefficient of variation (standard deviation divided by the mean) of mean annual discharge. Lower values represent (<0.5) low inter-annual variability (i.e., annual flows do not vary much between years).	GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: H.08; LPJmL; PCRGLOBWB;

			MPI-HM; WBM+
e1	Access to clean cooking	Access to clean cooking (e1) is projected from the reference energy scenarios for each SSP on a regional basis (IIASA-SSP database). Results for cooking energy access under a no policy scenario developed for the Global Energy Assessment are used to estimate the elasticity of change in access with respect to income (13,14) .The regional elasticity of access to income estimates are then applied to determine regional access under each SSP scenario, considering differences in incomes across these. Assuming that it is the poorest that do not have access to clean cooking, this fraction is used to calculate the income threshold for combination of region, year and SSP and locate the population using the gridded income data (5). Whilst ideally this could include feedbacks with GLOBIOM to understand forest degradation, it is worth noting however, that in several parts of the world, the sources of biomass used for cooking is not forests, but rather crops, animal residue and fallen twigs and branches on common lands and from private field borders etc. In parts of sub-Saharan Africa where charcoal use for cooking is very high, there is indeed a link between charcoal demand and forest degradation and deforestation, but this is not the case in much of Asia or Latin America (15).	MESSAGE for SSPs1-3 Gridded population and income levels aggregated from 0.125 to 0.5°.
e2	Heat event exposure	Change in heat event exposure (e2) is calculated as the sum of days from heat events lasting 3 or more consecutive days above the historical 99th percentile daily mean wet bulb air temperature. Values are then annualised over the 30-year period. Heat event are intended to represent impacts, not only to human health, but also on the energy sector, for which it is know that energy demand can spike, capacity of gas turbines decreases, reliability and efficiency of grid transmission infrastructure reduces (16,17).	GCMs: 5 x ISIMIP GCMs RCP8.5
e3	Cooling demand growth	Cooling demand growth (e3) is based on the absolute change in cooling degree days above a 26°C set-point temperature for the daily mean air temperature.	GCMs: 5 x ISIMIP GCMs RCP8.5
e4	Hydroclimate risk to power production	Hydroclimate risk to power production (e4) aggregates the combined hazard of four hydrological indicators (as used in this study), peak flows risk, drought intensity change, seasonality and inter-annual variability to a continuous risk scale (as used with other indicators). This is multiplied by a capacity score according to the installed capacity in each grid square, using a global dataset of water-dependent thermal and hydro power plant capacity (18–20). The product of these two scores (hazard x	GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: H.08; LPJmL; PCRGLOBWB; MPI-HM; WBM+ Power plants: World Electric

		exposure) gives the hydroclimate risk to power plants.	Power Plant Database, CARMA power plant database; Additional information by Catherine Raptis.
I1	Crop yield change	Climate change impact on crop yield (I1) is estimated by the EPIC crop model under for ISIMIP future climate change scenarios (21) for 18 crops and 4 crop managements systems and overlaid with the distribution of crops and systems as estimated by the GLOBIOM land use model (22) for year 2000 (23) before being aggregated across crops and crop management pixels (using calorie content).	Land model: GLOBIOM + EPIC GCMs: 5 x ISIMIP GCMs RCP8.5 Hydrology: LPJmL
I2	Agricultural water exploitation index	Agricultural water stress index (I2) indicates agriculturally-driven environmental water stress. By identifying locations where the monthly irrigated water demand are in excess of sustainable supply, it measures the fraction of environmental flow requirement (EFR) agricultural demand required to meet the agricultural demands (24–26).	Land model: GLOBIOM GCM: HadGEM2-ES RCP8.5 Hydrology: LPJmL
I3	Habitat degradation	Habitat degradation (I3) is estimated as a % change from the share of land area within a pixel being converted from natural land to agricultural land (cropland and grassland) in the future as simulated by the GLOBIOM model (22) and further downscaled to 0.5° (27).	Land model: GLOBIOM + downscaling GCM: HadGEM2-ES RCP4.5, 6.0
L4	Nitrogen balance/leaching	Nitrate leaching from mineral fertilizer application over cropland (I4) is the flux of nitrate resulting from mineral fertilizer application to cropland and lost to surface water streams as simulated by EPIC (28) for current conditions for 18 crops and crop management systems, and overlaid with GLOBIOM assumptions on R&D-induced future changes in crop yield and crop input use efficiency (29,30) and downscaled GLOBIOM projections of the distribution of crop and crop management systems.	Land models: GLOBIOM + EPIC + downscaling GCM: HadGEM2-ES RCP4.5, 6.0
		1. 5 x ISIMIP GCMs are: GFDL-ESM2M HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M 2. All gridded models at 0.5° resolution unless otherwise stated. 3. In all cases using multiple model ensembles, the model median is used.	

2.3. Socioeconomic pathways, income projections and gridded vulnerability

The three socioeconomic scenarios considered in this assessment derive from the Shared Socioeconomic Pathways (SSPs) which have been developed and used by the international climate change research community. The SSPs are designed to cover a range of socioeconomic pathways primarily defined by challenges to mitigation and adaptation of climate change (31).There are five SSPs, although here we consider the primary axis of SSPs1-3, briefly introduced below from the global narratives:

- SSP1: Sustainability represents a shift to sustainable and inclusive development, with improved international cooperation, reduced regional and national inequalities, investments in health and education that lead to low population growth, increased urbanization, reduced energy demand and subsequently low challenges to both mitigation and adaptation.

- SSP2: Middle of the Road represents recent trends in technological, social and economic development There are both improvements in resource intensity and simultaneously increased environmental degradation. Improvements in education and health mean moderate population growth and stabilization of global population late century, but not fast enough to reduce inequalities, particularly in low-income countries. The world faces moderate challenges to both mitigation and adaptation but with significant differences between countries.

- SSP3: Regional Rivalry represents a trend of increased concerns about nationalism and regional security with worsening international cooperation, less global trade and weaker institutions. Economic and social development is slow, and inequalities worsen, both between regions and within many countries. Population growth remains high in developing countries. With poor and sometimes worsening progress on the sustainable development goals, this pathway represents high challenges to both mitigation and adaptation.

Gridded projections of population and GDP for SSPs 1-3 spanning 2010 to 2050 (3) at 0.125° resolution are used to identify the distribution and numbers of exposed and vulnerable populations. We use recently compiled datasets of global income distributions and inequality (32) to estimate vulnerable populations using an income threshold. These datasets are generated for each scenario using machine-learning regression tree techniques for urban and rural income, which are downscaled using urbanization and migration patterns to give gridded projections of vulnerable population.

This analysis uses definitions from the World Bank for categorizing population as vulnerable. Whilst income level of $1.9 USD/day (2011 purchasing power parity) commonly defines extreme poverty, those living on <$10 USD/day are considered vulnerable to poverty. This category and income level is appropriate because it specifically captures the population fraction that lack "economic stability and resilience to shocks that characterizes middle-class households" (33,34). These shocks can be natural hazards, loss of income, illness or conflict, for example.

2.4. Climate scenarios

Most indicator datasets in this analysis use as inputs the ISIMIP "Fast Track" model database ensemble of five general circulation models (GCMs) from CMIP5 (35): GFDL-ESM2M; HadGEM2-ES; IPSL-CM5A-LR; MIROC-ESM-CHEM; NorESM1-M. The GCMs were consistently downscaled to spatial resolution of 0.5°, bias-corrected (36) to observed data (37), and were selected for coverage of the uncertainty range in temperature and precipitation variables from the CMIP-5 models (38).

Climate hazards are assessed at three levels of global mean surface temperature (GMT) change: 1.5°C, 2.0°C and 3.0°C above the pre-industrial conditions (PiC), compared to a baseline period of 1971-2000, of ~0.6°C above PiC (and acknowledging the importance of the PiC temperature choice (39). These temperatures, possible at multiple timeframes within this century (40), do not represent climate stabilization scenarios, but are used to represent the risks at different levels of warming in a transient climate.

Time-sampling approach (41–43) is used by selecting a 30-year temperature timeslice, centred on the year at which the GCM passes the relevant GMT. GCM model runs are forced by the greenhouse gas and radiative forcing trajectories from the Representative Concentration Pathways (RCP) (44,45), using RCP8.5 in the majority of cases and RCP4.5 and RCP6.0 in a few cases where the SSP-RCP combination is endogenous to the impact model (see SI Table S1 of Byers et al 2018 for exact details).

Table 2. 30-year periods selected for each global mean temperature level above pre-industrial conditions for the different GCMs. Below is shown only for RCP8.5.

RCP8.5 30yr periods	**Historical baseline (~0.6°C)**	**1.5°C**	**2.0°C**	**3.0°C**
GFDL-ESM2M	1971-2000	2019-2048	2036-2065	2066-2095
HadGEM2-ES	1971-2000	2002-2031	2014-2043	2035-2064
IPSL-CM5A-LR	1971-2000	2007-2036	2019-2048	2039-2068
MIROC-ESM-CHEM	1971-2000	2004-2033	2016-2045	2035-2064

NorESM1-M	1971-2000	2014-2043	2030-2059	2056-2085

With respect to the Macroeconomic Risk Profile, the most notable difference is the generation of model data - the MRP uses the latest CMIP6 generation whilst the CVA has had to use the previous generation from CMIP5. Although there are differences, notably that the climate sensitivity and warming in CMIP6 is higher than in CMIP5, the differences are likely comparable if not significantly smaller than uncertainties that arise from other aspects of the assessments, such as socioeconomic projections and uncertainties within the impact models.

2.5. Indicator scoring methodology

The approach (Byers et al, 2018) (2) maps the sectoral impact indicators onto a continuous risk-indicator scale, ranging between no negative impact to high negative impacts and scored between 0 and 3. Intervals on the scale are specified by the sectoral modelling teams at [0,1,2,3] to represent no, low, moderate and high levels of impact. The levels of impact were judged through interrogation of the original data in combination with various experts' judgements with knowledge of the impact models. The sensitivity of the score ranges applied to impacts was extensively tested in previous work and introduced below (section 2.5). The continuum between 0 and 3 can be linear or any other line (SI Figures S4-5). Every grid square in each spatial indicator dataset is subsequently scored using the continuous scale.

Indicator scoring schematic example

i. In the top right panel, the original dataset, in this case w3 Drought Intensity (% change) is shown, with varying degrees of drought intensity change expected across the world.

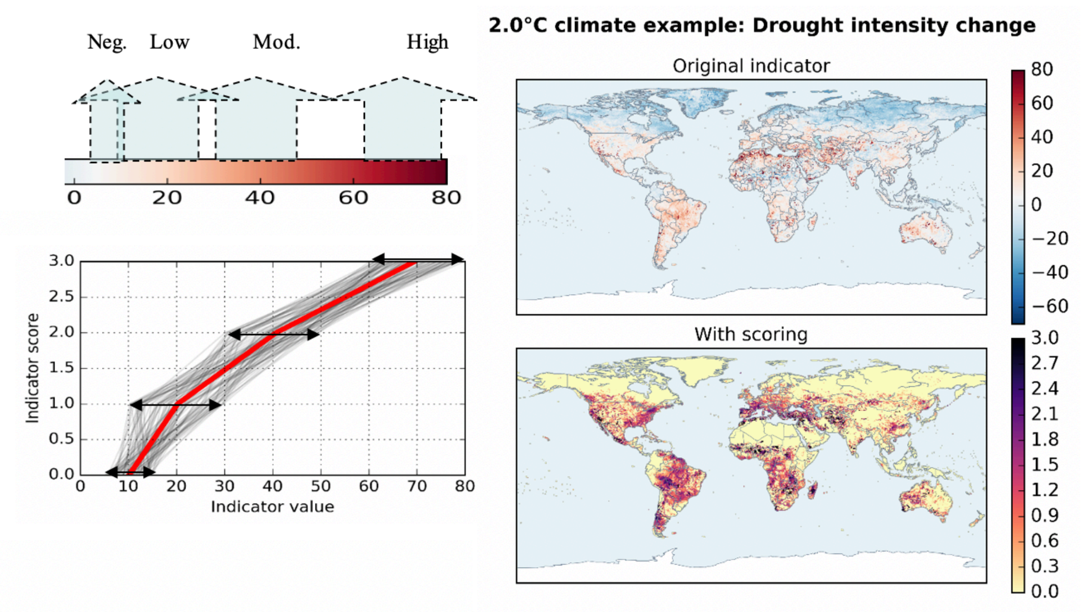
ii. In the top left panel, the changes (increasing intensity) are shown with the dotted arrows depicting the ranges selected by the modelling teams for each intermediate risk category on the scale.

iii. In the bottom left panel, the mapping from original indicator value (x-axis) is made to indicator score (y-axis). For example, and 30% increase in drought intensity gets a score of 1.5.

The grey lines show the randomly and uniformly sampled points, 100 for each of the 4 ranges, that sample the low-high range of the expert judgement. For example, high impact in drought intensity change in Figure S 4 are considered between 60-80% change. The red line shows the median points of the range.

iv. In the bottom right, every pixel of the indicator is converted to a score between 0 and 3, using the score function (either the median case or one of the random samples in the case of running the uncertainty analysis).

Figure 1. Schematic showing the conversion of an indicator map (top right) into an indicator score map (bottom right) using the values from Table A 2 (Annex).



Note: Described in more detail (i to iv) above.

3. IMPACT INDICATORS

This section analyses the results of each indicator individually under the relevant socioeconomic and climate scenarios. In the majority of cases, we show the changes across the climate scenario range, 1.5°C to 3°C. In a few cases for Energy and Land the indicators are presented across the Socioeconomic dimension, SSP1 to SSP3, as these are more substantial.

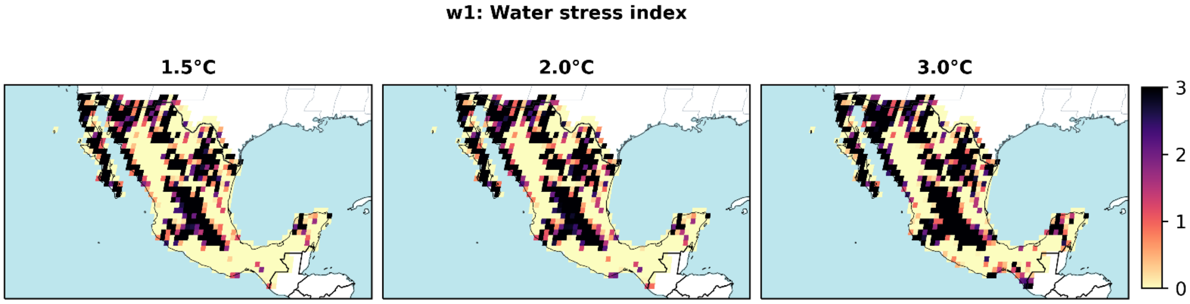
3.1. Exposure Water indicators

Water indicators described below consider both biophysical representation of the hydrological cycle and key societal interventions, including land use, demands and major water infrastructure. The indicators are calculated from up to five "global hydrological models" (GHMs) that are run at daily timestep at a gridded resolution of 0.5° (approximately 50km at the equator). Each model was simulated with five "global climate models" (GCMs), consistently downscaled and bias-corrected to 0.5° grid (36), chosen from the CMIP5 ensemble for covering the range of ensemble uncertainty in temperature and precipitation (38). Thus, the indicators derive from a 25 run ensemble designed to cover a wide range of hydro-climate uncertainty, which was assessed in more detail (2).

3.1.1. Maps and results of the water indicators

Water stress index compares water demands to available water supply. High water stress means that a high proportion of the available water is being used for human activities. Water stress can change due to both changes in societal demands and changes in the volume and timing of water. Water stress can constrain agricultural, industrial and energy sector productivity and affect quality of life in households. Water stress also impacts the environment, altering ecosystems and reducing water quality.

Figure 2. Indicator score map for Water stress index by climate scenario.



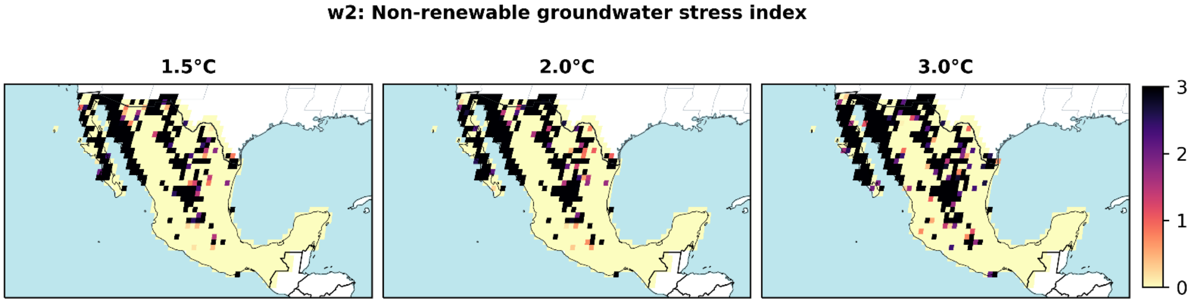
- In Mexico, large parts of the country are already under severe water stress in almost all inhabited and cultivated areas. Expected reductions in surface water availability due to climate change combined with increased societal activities means an intensification of water stress in all scenarios is projected.

- Water stress in Mexico appears to be characterized by an intensification of stress in already-affected areas, as opposed to a large spatial increase in affected areas.

- Most impacted regions are expected to be northern states of Chihuahua Sonora and the Baja California, the central states in the Bajío and Central Mexico, and on the Yucatán Peninsula and Oaxaca.

Non-renewable groundwater abstraction index compares water demands for groundwater to available, non-renewable groundwater supply. Groundwater is typically used as an alternative source when surface water sources are lacking in volume, quality or means for distribution. For example, groundwater is often used by farmers for irrigation there is a lack of distribution canals from surface water sources. Unsustainable use of groundwater can lead to water quality issues and have downstream impacts on quality and volume through reduced baseflow in rivers.

Figure 3. Indicator score map for Non-renewable groundwater stress index by climate scenario.



- Groundwater use in Mexico is prevalent in cultivated areas, predominantly in the central-northern regions and around the Baja California.

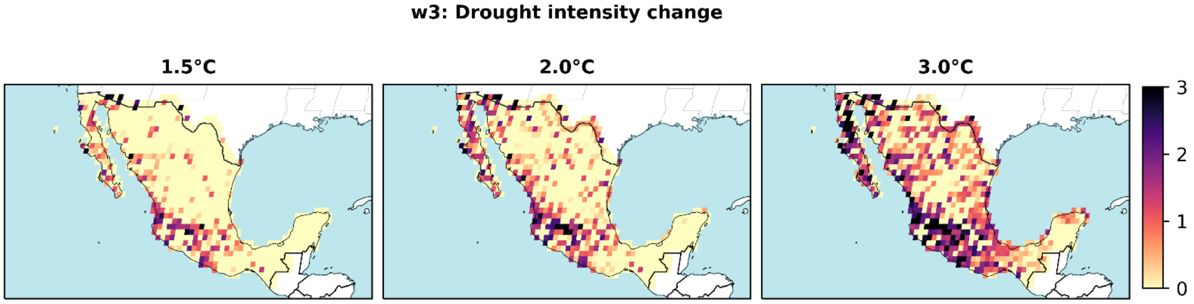
- Estimates of current and future groundwater use are expected to significantly exceed the renewable supplies, and at higher levels of climate change, the areas under stress may expand.

  Non-renewable groundwater use is projected to increase under climate change as surface water supplies are projected to become even more limited, with subsequent impacts on baseflow.

- States that may be most at risk include: Baja California, Baja California Sur, Sonora, Chihuahua, Coahuila and the central states comprising the Bajío and Central Mexico.

Drought intensity indicates locations where the intensity of hydrometeorological droughts in discharge is increasing – as a function of both duration and the water deficit. Increases in drought intensity are primarily driven reduced precipitation and subsequent runoff and increased evapo(transpi)ration. Increases in this index does not necessarily mean droughts are occur more frequently (although drought conditions may occur frequently), merely that they are more severe when they occur.

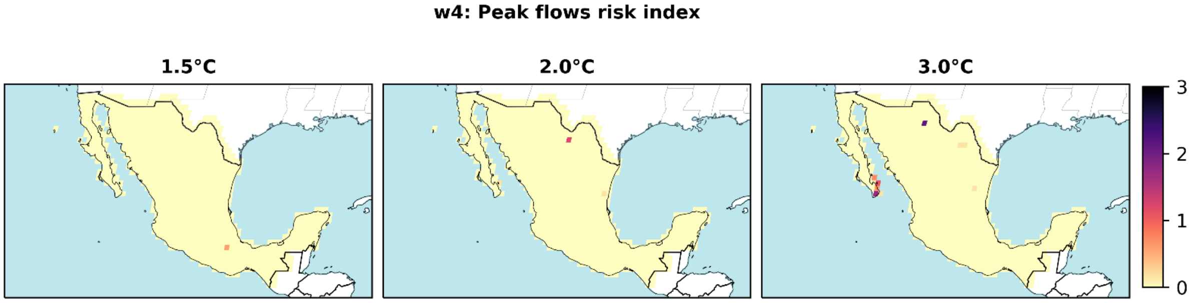
Figure 4. Indicator score map for Drought intensity by climate scenario.



- Drought intensity in Mexico is expected to increase under climate change most severely in the Pacific coast states (Jalisco, Colima, Michoacán, Guerrero and Oaxaca), also including Baja California. In the 3°C scenario, large parts of the country can expect to see growing intensity of drought.

Peak flows risk indicates locations where the risk of extreme high river flows is expected to increase. This indicator primarily proxies fluvial flood risk through increased peak discharge, although it does not represent flood control measures neither inundation extents. Peak flows and flooding, often brought on by a number of conditions such as wet antecedent conditions, prolonged and/or extreme precipitation, can bring substantial danger to human life and costly damage to the environment, property, agriculture and infrastructure.

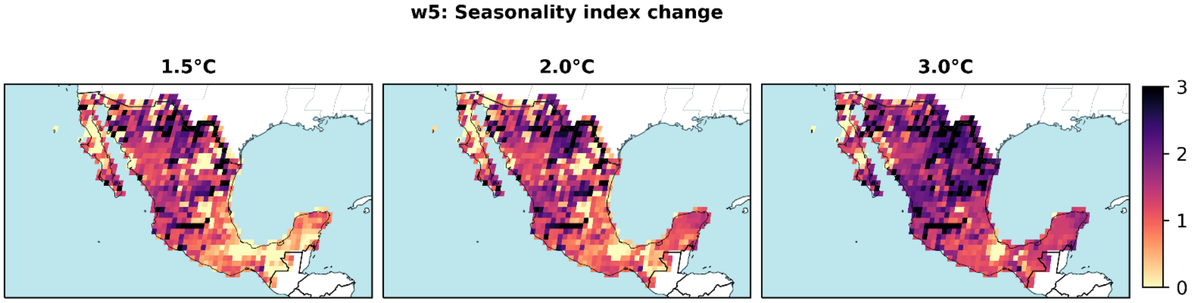
Figure 5. Indicator score map for Peak flows risk index by climate scenario.



- Peak flows risk indicator shows almost negligible increase in impacts across the models used and is not further assessed here. This does not conclude that peak flows and flooding is not a risk in Mexico – merely that the models used in this assessment were inconclusive in this regard as some model projected increases whilst others projected decreases.

Seasonality index change indicates locations where the differences between wet and dry seasons are expected to increase i.e., the differences between water availability in the dry and wet seasons is increasing, and likely are less predictable. This can impact ecosystems and economic sectors, such as agriculture and hydropower production whose activities are highly dependent on the seasonal timing of water availability.

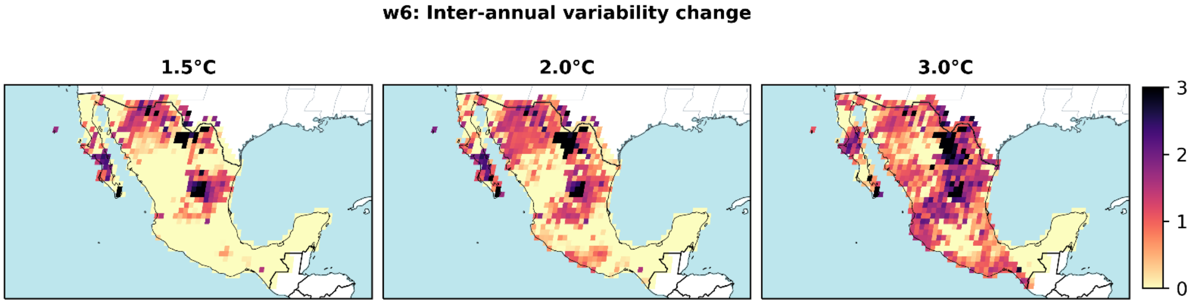
Figure 6. Indicator score map for Seasonality index by climate scenario.



- Seasonality index is expected to increase across all of Mexico, with even less discharge in the winter months (dry season) compared to the summer. The differences between the climate scenarios however are minor, but some regions bordering the main rivers may see the greatest changes, in particular surrounding the Rio Lerma-Santiago and Rio Balsas in the southwest, and the Rio Bravo del Norte and Rio Conchos in the Northeast and north.

Inter-annual variability index change indicates locations where the differences between wet and dry years are expected to increase i.e., annual water availability is becoming more unpredictable. This means that the difference between dry and wet years is increasing, making long-term planning that requires reliable water availability increasingly difficult. Key sectors impacted include agriculture, electricity supply in particular hydropower, industry and municipal water supply.

Figure 7. Indicator score map for Inter-annual variability index by climate scenario.



- There is a strong signal of growing inter-annual variability in Mexico under the climate change scenarios, with considerably larger area affected with moderate changes, whilst a few areas may experience growing intensity. States projected to be most intensely impacted include Nuevo Leon, San Luis Potosí, and Baja California Sur, with moderate impacts in Chihuahua.

- Impacts under a 3°C scenario may be widespread, with additionally southern Pacific states impacted, as well as areas in the Bajío and Central Mexico.

3.1.2. Summary of findings

With already high levels of water scarcity, water-dependent sectors and the environment in Mexico are projected to be substantially impacted by climate change and changes in the hydrological cycle. Most critical indicators form this assessment include water stress index, drought intensity and inter-annual variability – all of which indicate possibly substantial changes across large parts of Mexico and a growing intensity at higher levels of global warming.

Projections indicate that the most impacted regions include: Baja California Sur, Sonora and Chihuahua in the north; Jalisco, Colima, Michoacán, Guerrero and Oaxaca along the southwest Pacific coast; and the Bajío.

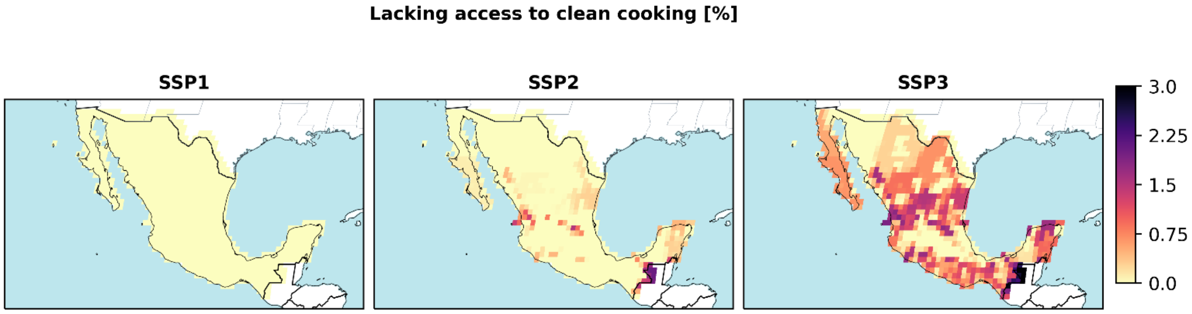
3.2. Energy indicators

Indicators for the Energy sector are chosen to combine a range of important dimensions, including energy access and health, pressures of rising demand and climate impacts on security of supply. They combine downscaled projections from the Integrated Assessment Model, MESSAGE, for the clean cooking access indicator, whilst datasets from GCMs and GHMs are used for the other three indicators. Uncertainty in these latter three is covered using 5 GCMs for heatwave stress events and cooling degree days, whilst the hydroclimate risk to power plants also uses 5 GHMs.

3.2.1. Maps and Results of the energy indicators

Access to clean cooking fuel projections indicate where low-income populations lack access to clean cooking fuels like electricity and gas, and thus rely on solid fuels like biomass, coal or animal dung. Lacking clean cooking access has severe impacts on health in the household, predominantly impacting women and children with respiratory illnesses (13,46).

Figure 8. Indicator score map for clean cooking access by socioeconomic scenario.



- Clean cooking access indicator for Mexico does show noticeable differences across the three socioeconomic scenarios, despite rapid economic growth. Currently, clean cooking access in Mexico approaches 90% (World Bank, SE4All, WHO[1]), yet in poorer regions outside Central Mexico, rural communities are still dependent on traditional fuels, primarily firewood. Government programs to tackle the problem have made substantial progress in recent years, yet struggle to access the most marginalized rural communities, some of which are indigenous and/or lack access to transport infrastructure.

- The socioeconomic scenarios modelled by this indicator are based on the Shared Socioeconomic Pathways and combines:
    - projections of clean cooking access from the MESSAGE energy model in line with global pathways; with
    - projections of GDP, income and income inequality at the sub-national level for Mexico, which are downscaled to gridded maps of low-income rural population.

- Particularly relevant to this indicator are that the SSPs are characterized by different progress on socioeconomic dimensions include, health, education, gender equality and urbanization.

- The SSP3 scenario, which includes generally poor socioeconomic outcomes, projecting higher rural population and high-income inequality, indicates that clean cooking access could remain a problem in Mexico for the poorest communities without additionally targeted interventions.

- Implicated states could include Sinaloa and Nayarit across to Tamaulipas, the southwest pacific coastal states from Jalisco to Oaxaca, the Yucatán peninsula, and by far most severely the southern state of Chiapas.

Heat stress event exposure indicates where there are increases in the number of 3 consecutive days (a heat stress event), using the wet bulb temperature and compared to the historical 99th percentile daily mean wet bulb temperature. Wet bulb temperature considers both the (dry bulb) air temperature and humidity. Heat events pose risks not only to human health, but also on the energy sector, labour productivity, crop yields and industrial processes (47). For example, warmer temperatures can cause energy demand to spike, while the capacity of gas turbines can decrease, and the reliability and efficiency of grid transmission infrastructure may also be reduced (16). Only areas with population density above 10 persons /km2 are considered to highlight the populated areas most at risk.

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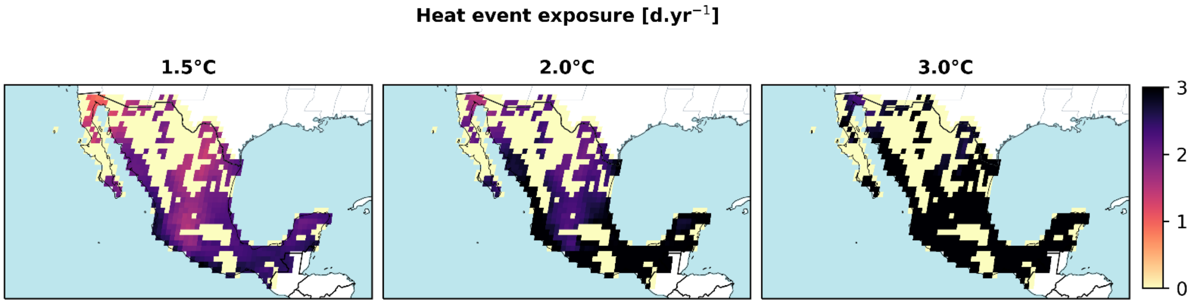
[1] https://data.worldbank.org/indicator/EG.CFT.ACCS.ZS?locations=MX

Figure 9. Indicator score map for Heat stress event exposure by climate scenario.

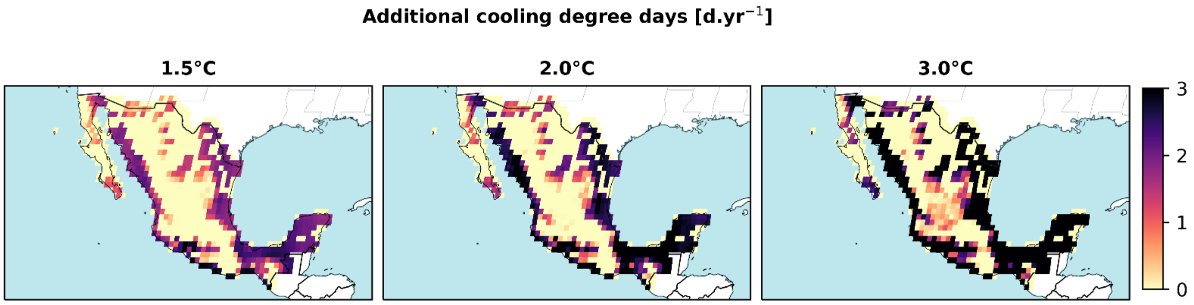


The projections indicate a robust increase in heat stress event exposure in a warming climate, with the annual average number of heat stress days (occurring in 3-day events) expected to increase from 4 to ~25 per year in a 1.5°C scenario, to well over 50 days per year in a 3°C scenario.

- This change in exposure is at the high end globally, driven not only by rising air temperatures but also higher humidity, particularly in the southern regions of Mexico.

Cooling demand growth indicates locations where rising air temperatures are expected to increase the need for space cooling. Space cooling demands increase with warmer temperatures as well as growing incomes. It can provide necessary comfort, particularly if available to vulnerable people, but results in energy and peak demand growth (48). Here, only the changes in temperature above 26°C are calculated, which was chosen as a conservative level from which to estimate the change in space cooling requirements to mitigate increasing numbers of "hot days".

Figure 10. Indicator score map for Cooling degree days by climate scenario.



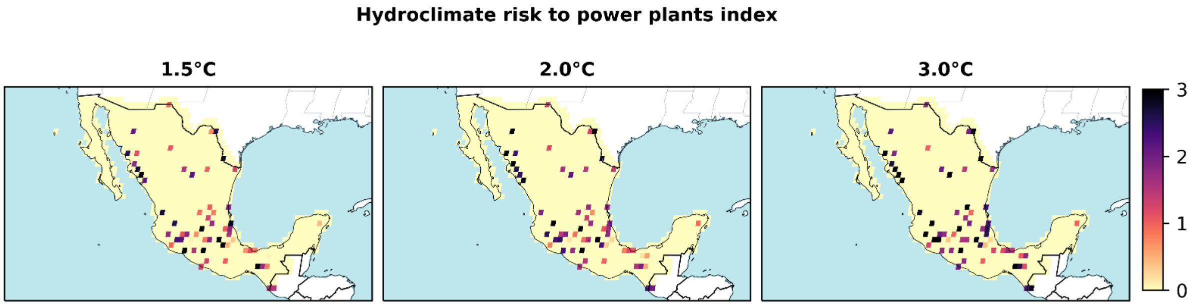
- Space cooling demand growth due to rising temperatures is robustly projected across most of the lower altitude and primarily coastal regions of Mexico. Cooling demand growth in most areas would be moderate, with approximately 200 additional cooling degree days (CDD, °C) per year above 26°C at 1.5°C, and well over 400 additional CDD per year in a 3°C climate.

- Areas in the Bajío and Central Mexico that currently only experience temperatures above 26°C relatively infrequently, may experience more warmer days in summer that may drive demand for air conditioning, particularly if incomes also rise as is expected.

- Thus, it is important to consider three driving factors: growth driven by rising incomes as AC becomes more affordable; growth driven by rising temperatures resulting in more usage of AC units; and growth driven in locations that previously did not require cooling but will likely require it under climate change.

Hydroclimate risk to power production indicates locations where changing conditions in the water cycle will complicate the operation of water-dependent power plants i.e., hydro power and water-cooled thermal plants. This combined indicator considers multiple water cycle indicators, including water stress, drought intensity and peak flows, to give a high-level indication of the hydroclimate risks to power plants.

Figure 11. Indicator score map for Hydroclimate risk to power plants index by climate scenario.



- This indicator shows several locations within Mexico with expected moderate to high risk, with a strengthening signal towards 3°C. This primarily includes powerplants in states such as Sinaloa, Jalisco and Michoacán de Ocampo, Veracruz-Llave and Chiapas, and several locations in Central Mexico. This is supported by the signals from other indicators relating to both hydrology and rising temperatures. Most of the generation units are currently in the southern regions with hydro located along the west and central, with gas in the central and east. Thus, widespread drought affecting hydropower combined with heatwaves impacting gas capacity could simultaneously threaten large proportions of Mexico's supply.

3.2.2. Summary of findings

Warming temperatures and an increasingly variable hydrological cycle are expected to bring challenges to the energy sector in Mexico. Hotter summers and higher humidity would substantially increase exposure to more frequent and hotter heat stress events across large parts of the country, particularly central and southern regions. Generally warmer summers would increase space cooling energy demands predominantly in lowland areas along the coast. The extent of locations experiencing hot days is expected to increase, importantly in populated Central Mexico and Bajío regions, which may drive the purchase of AC units in locations where it was previously not needed. Thus, subsequent impacts on electricity demand are expected to be substantial and this is corroborated by other sources, further discussed in section 5.1.2.

Hydroclimate risk to power plants is also expected increase in the climate scenarios, supported by the signals from other indicators relating to both the timing and availability of water supply and rising temperatures that may have subsequent impacts on wet-cooled thermal plants and hydropower. Dry winters with below-average precipitation may be used to anticipate potential water shortages later in summer.

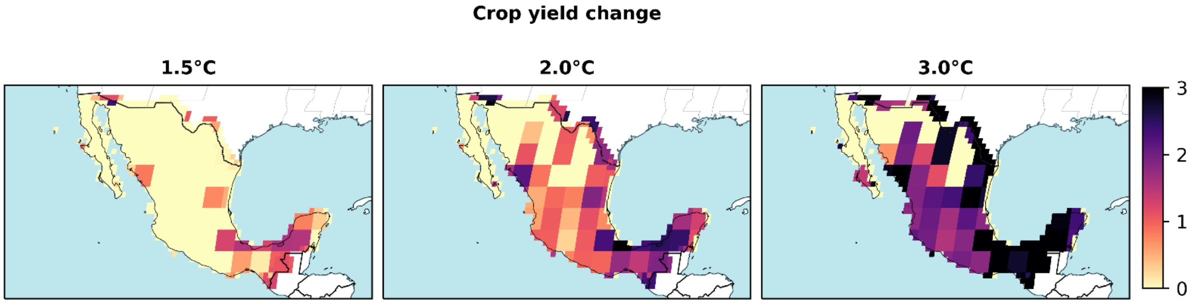
3.3. Land indicators

The Land indicators cover a range of land, agricultural and environment indicators relating to security of food supply, interactions with the hydrological cycle and environmental impact. The indicators derive from the Integrated Assessment Model, GLOBIOM (22), which is an agro-economic systems optimization model that incorporates crop production (EPIC model) and hydroclimate impacts from GCMs and the GHM LPJmL.

3.3.1. Maps and Results of the land indicators

Crop yield change indicator indicates where a changing climate will negatively impact crop yields, primarily through high temperatures and reduced water availability. In some cases, crop yields may also increase. More extreme events can lead to partial or complete crop failure which may become more likely with climate change (49). This indicator shows the long-term trend in yield (by calorie content) for a basket of 18 crops.

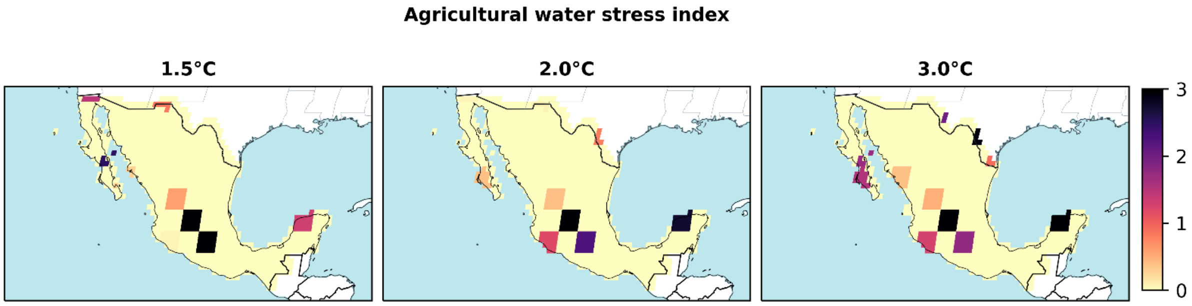
Figure 12. Indicator score map for Crop yield change by climate scenario.



- Crop yield change indicator projects robust reductions in crop yield due to changing climate across the majority of Mexico from warming temperatures and expected changes in the hydrological cycle (Figure A 3. Land sector indicator maps). Crop yields are expected to reduce by -5% in a 1.5°C scenario, reducing to as much as -10% at 2.0°C. At 3.0°C reductions could generally be in the order of -15%, with a few locations exceeding -20%.
- In general, the southern regions towards Yucatán peninsula are projected to be more impacted than the north, the most severe locations are Sinaloa, southern Veracruz Livre and Tabasco. Areas in the north along the Rio Bravo del Norte are also at moderately high risk.

Agricultural water stress index indicates locations of environmental surface water stress driven by agricultural activities, primarily irrigation. This occurs when agricultural demands are in excess of water available when environmental flow requirements are considered. Thus, either agricultural production is constrained, or it is taking water from the environmental flows allocation. With climate change this can be expected to increase, driven both my reduced physical water availability and increased demands from irrigation in warmer and drier conditions.

Figure 13. Indicator score map for Agricultural water stress index by climate scenario.

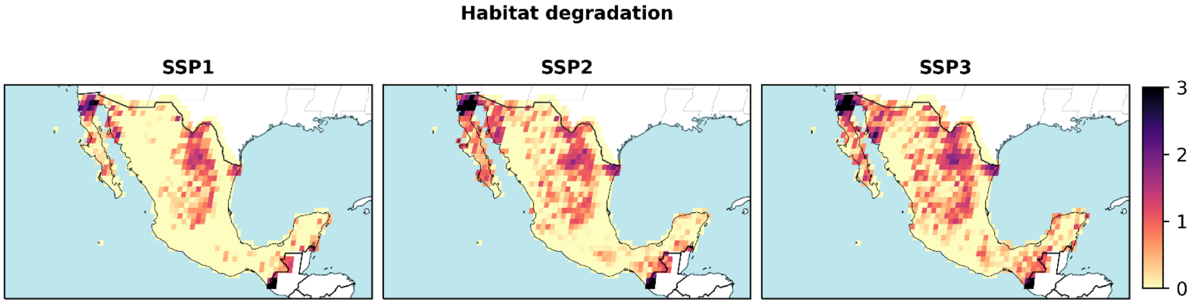


- Expected impacts in Mexico are expected to be relatively minor and limited to only a few locations of Jalisco, Guanajuato, Baja California Sur, along the Rio Bravo del Norte, Sinaloa and Yucatán. Except for Yucatán, these locations of agricultural water stress all coincide with locations where irrigation from surface water supplies currently occurs.
- Considerable water stress can also be expected in northern drylands regions which predominantly rely on groundwater sources.

Habitat degradation occurs where human activities put pressure on natural ecosystems, primarily driven by land-use changes in rural areas at the frontiers of agricultural land and natural habitats. This indicator is driven primarily by socioeconomic development, and more specifically the land-use management and agricultural practices that are used.

Note that this indicator does not consider a value of natural habitats, thus conversion of drylands and rainforest into agricultural land are considered equally.

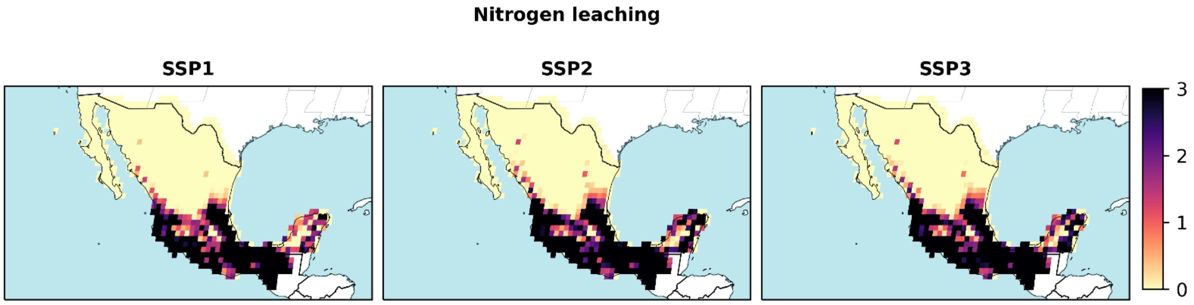
Figure 14. Indicator score map for Habitat degradation by socioeconomic scenario.



- Habitat degradation in Mexico is projected to be increasingly severe in all scenarios, although particularly so in SSP3 socioeconomic scenario, which uses more extensive agricultural practices, includes more livestock farming and requires higher fertilizer inputs. Thus, pressure on ecosystems and land use change into agriculturally productive land would be higher. Pressures are expected to be most severe in the northwest around Baja California and Sonora, in Coahuila stretching down to Zacatecas and San Luis Potosí, and along the southern border with Guatemala.

Nitrate leaching from mineral fertilizer applied to cropland (I4) is the flux of nitrate that is lost to water sources. It has direct impacts on water quality and can contribute to eutrophication (algal blooms) in water bodies and the toxicity of water supply.

Figure 15. Indicator score map for Nitrogen leaching by climate scenario.



- Nitrate leaching is projected to be particularly severe in the southern half of Mexico, although there are little differences between the scenarios.

3.3.2. Summary of findings

Warming temperatures potentially brings some challenges to the Mexican agriculture sector, with a generally strong signal of crop yield reductions driven by drier conditions. From the water indicators, there are strong signals that indicate an increasingly variable climate (drought intensity, seasonality and inter-annual variability) - this may result in more severe drought events and dry years than have been previously experienced. Habitat degradation could be driven by expansion of agriculture further into the drylands of the north.

Simultaneously, increased production needs to be carefully managed if environmental and ecosystem quality and services are to be maintained. Nitrate leaching is projected to increase in all scenarios in the southern half of Mexico, so localised approaches to manage pollutants could be increasingly necessary.

4. EXPOSURE AND VULNERABILITY

4.1. Population and vulnerability scenarios

Socioeconomic scenarios can be used to understand both how exposure and vulnerability to climate impacts changes under different macro scenarios.

The effects of various socioeconomic policies can be expected to have substantial differences in the overall population projection for Mexico, with a range of 41 million between the SSP1, SSP2 and SSP3 scenarios by 2050, projecting between 137, 152 and 177 million people, respectively (Figure 16).

In 2010, approximately 70 million (62%) of Mexico's population of 114 million had daily income of <20 US$2010 per day. 43 million (37%) had daily income less than $10 and 4.8 million (4%) under the extreme poverty line of $2/day[2].

Figure 16. Population projections for Mexico under the three SSP scenarios.

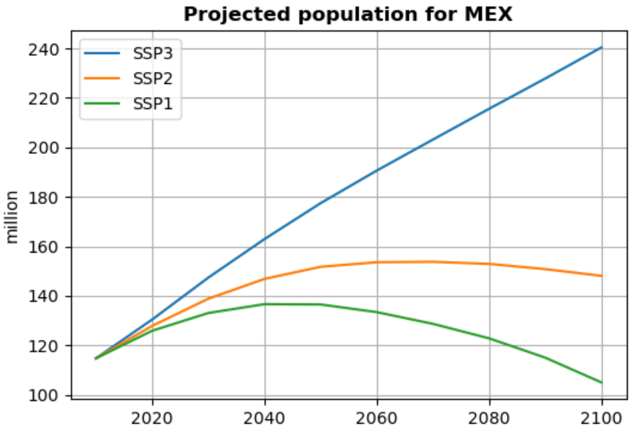
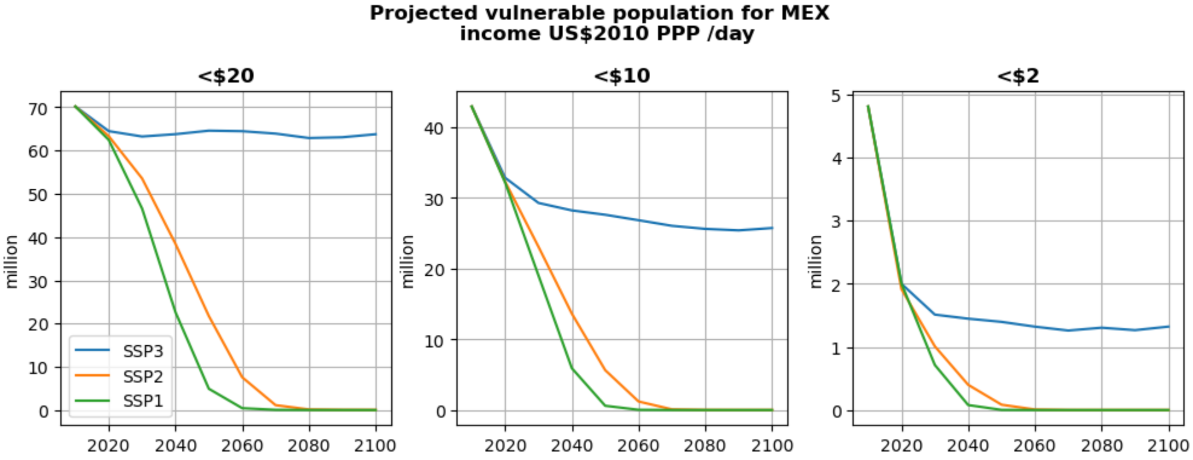


Figure 17. National projections of income thresholds for Mexico by SSP scenario.



The differences between SSP1 to SSP3 in assumptions regarding economic growth, income distribution and inequality are evident (Figure 17) – with much higher numbers of people below the income thresholds in SSP3, in the order of 10x more than SSP1 by 2050. SSPs 1 & 2 see rapid near-term reductions in inequality with eradication of extreme poverty by the 2060s, as well as substantial

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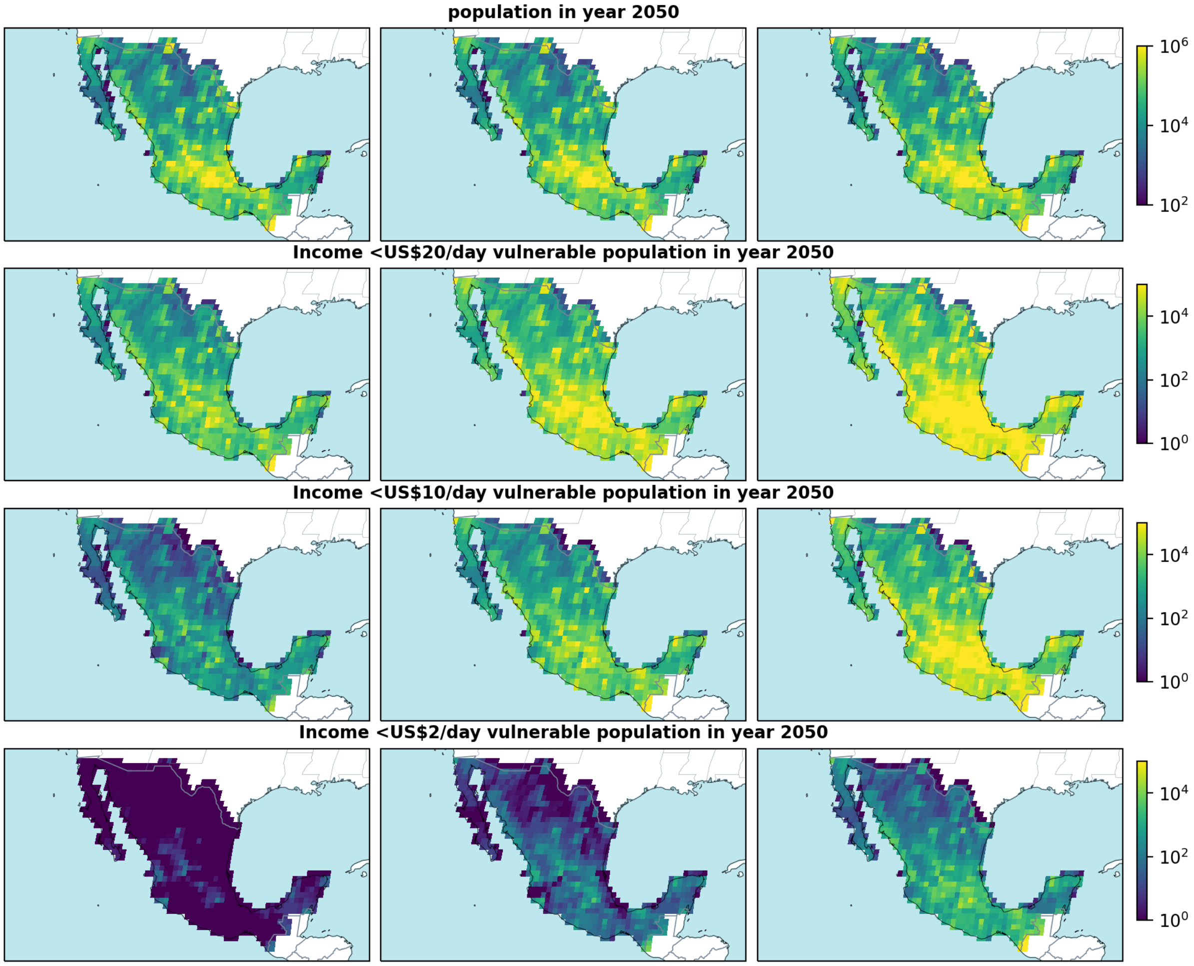
[2] World Bank Group, 2020, PovcalNet. http://iresearch.worldbank.org/PovcalNet/povOnDemand.aspx

reductions in equality that raise most of the population above the 10 and 20$ thresholds by the 2050s.

Evaluated here in 2050, the maps indicate the density of population in each grid square, and the density of population with income below three thresholds of 2, 10 and 20 $ per day (US$2010, PPP).

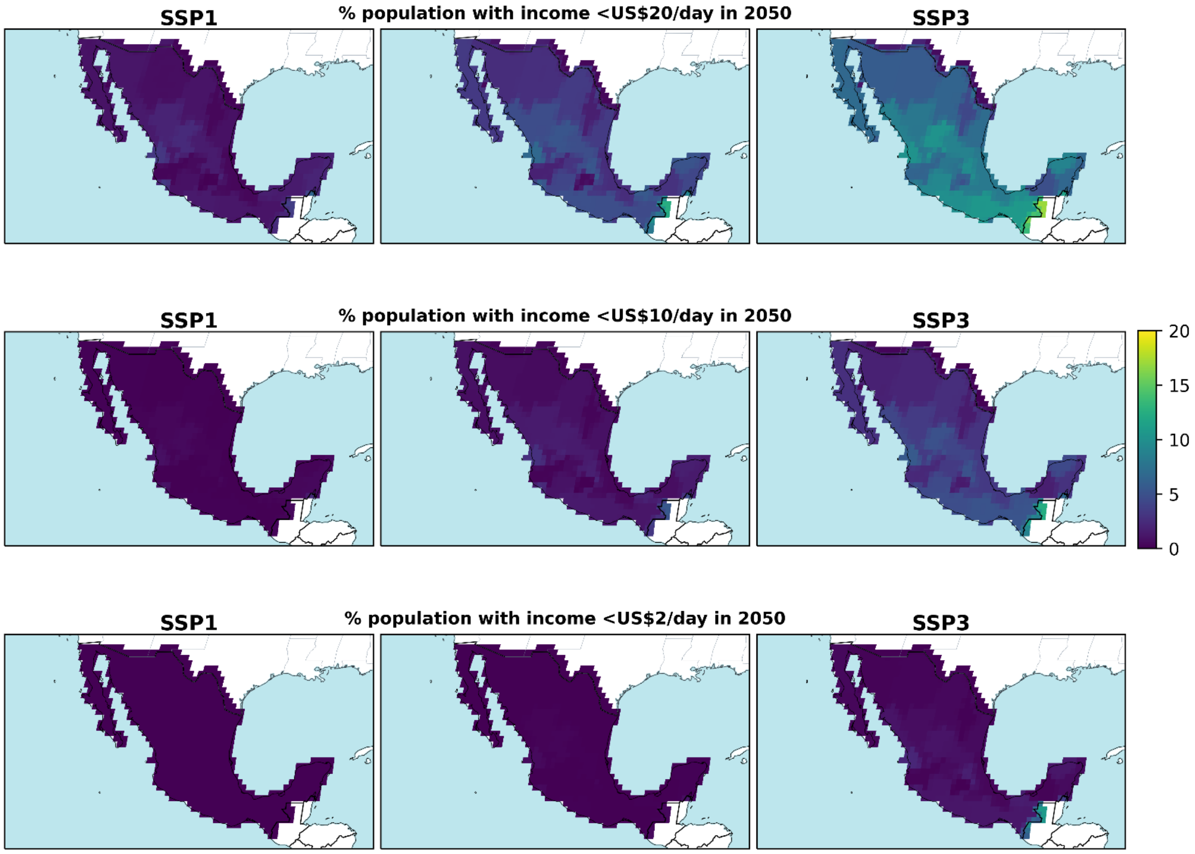
Figure 18. Gridded population density projections for 2050 compared across the three socioeconomic scenarios for the full population and at the three income levels (<2, <10 & <20 US$2010 PPP /day).



Sources: (3,5).

Considering the proportion of population under vulnerable income thresholds indicates areas where relatively high numbers of vulnerable people are located. The differences between SSP1 and SSP3 are clear, with considerably higher proportions of low-income population in SSP3 than in SSP1. They are primarily concentrated in the central and southern regions, noting however also that these regions are also more populated.

Figure 19. Percentage of population below income thresholds for the three SSP scenarios.



. Sources: (3,5).

4.2. Population and land area exposure

4.2.1. Exposure at the national level

Exposure to the indicators is calculated based on the national population and land area (Figure 20). High levels of exposure can be expected in many the indicators for both population and proportion of land area.

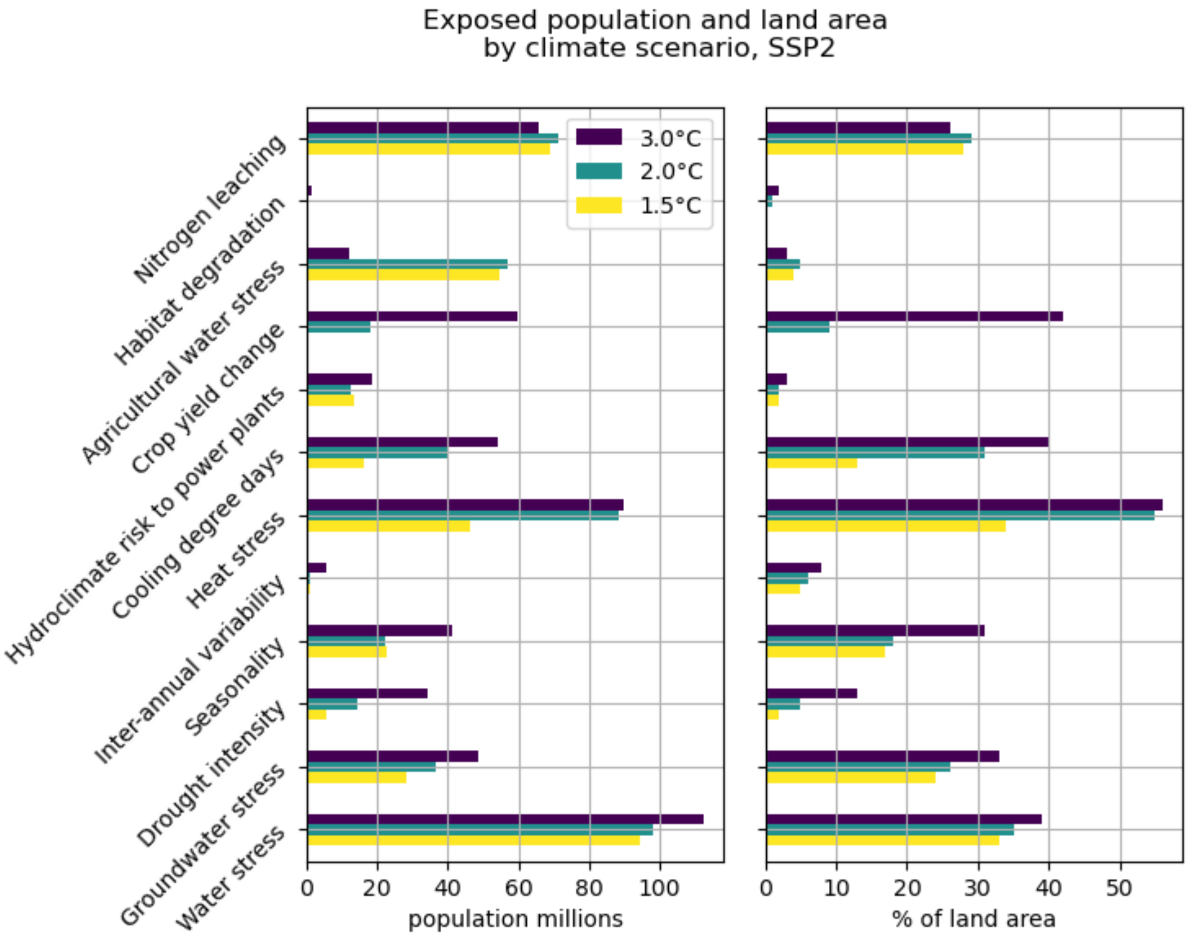
In interpreting the results, it is important to consider:

- In cases where absolute numbers are large and differences between scenarios are small, this indicates close to maximum exposure and that the baseline 1.5°C conditions already represent substantial exposure. This is the case, for example, with water stress index and nitrate leaching indicators.
- In cases where there are large differences between scenarios, this indicates substantial differences between the scenarios, and thus that mitigation and adaptation actions can have meaningful differences in

outcomes. This is the case, for example, with heat stress and cooling degree days indicators.

Exposure at the national level covers most indicators with high levels of people and land area impacted, particularly for water stress, heat stress and nitrate leaching.

Figure 20. Population and land area exposure at the national level to the key indicators in 2050.



4.2.2. Exposure by climate zone and mesoregion

Exposure has been calculated by different climate zones, mesoregions and federal states. These are defined using the shapefiles provided by INECC and are shown below[3].

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[3] The shapefiles provided by INECC used here include Climate Zones, Mesoregions and Federal States.

Figure 21. Spatial disaggregation by climate zone, mesoregion and Federal state.

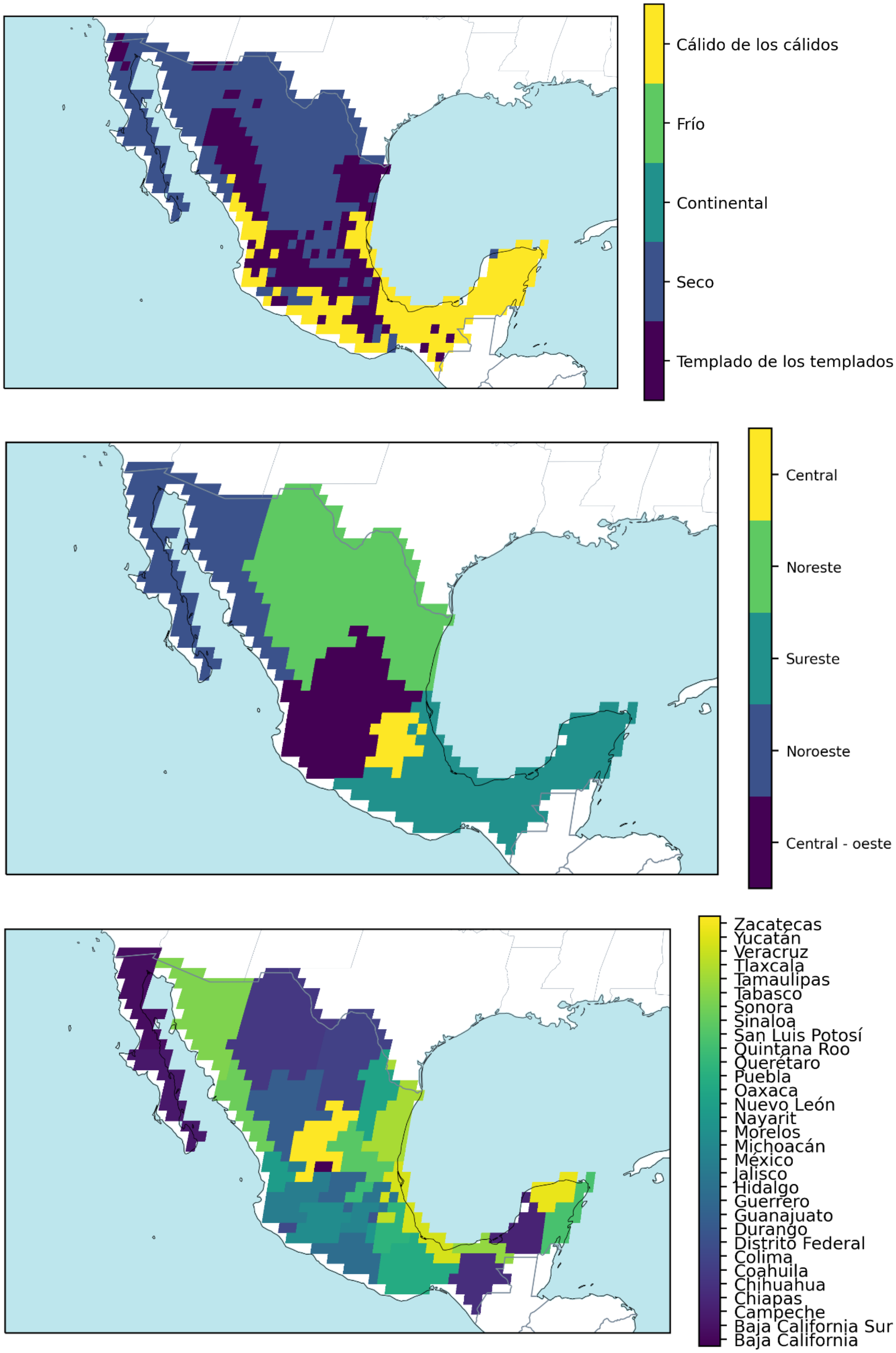
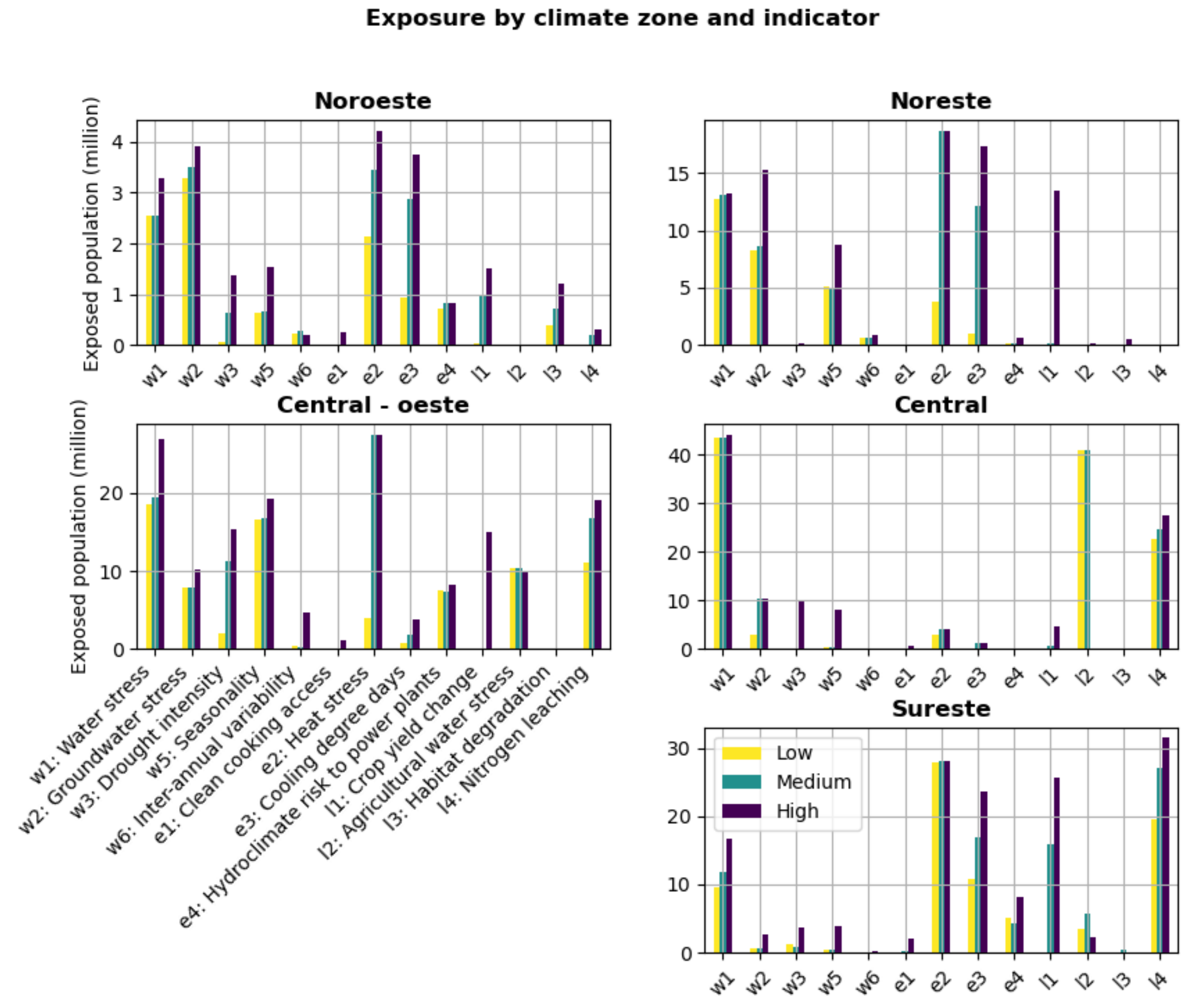


Figure 22. Population exposure to indicators by mesoregion.



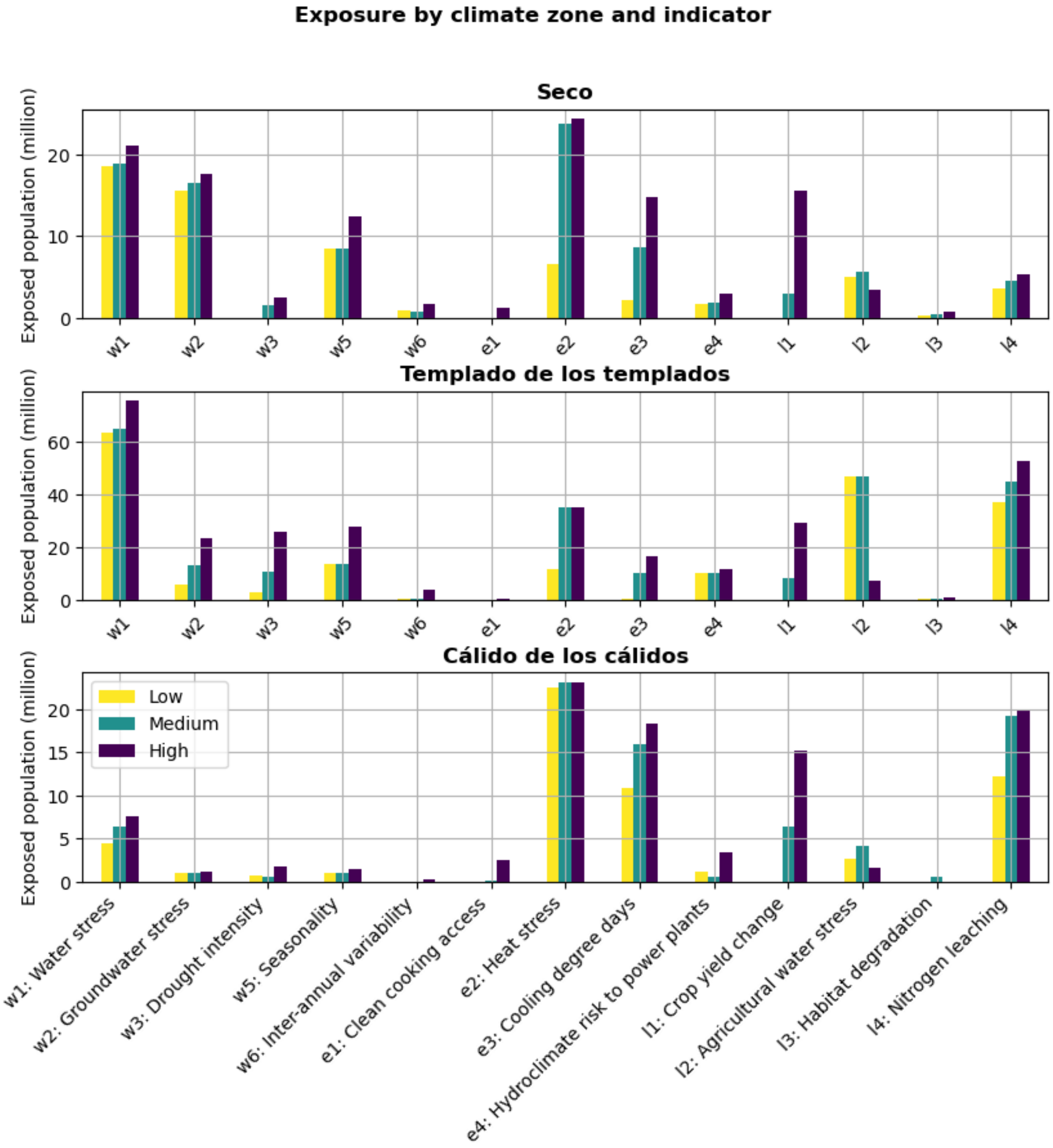
For all indicators, Low/Medium/High corresponds to the SSP2 scenario
at 1.5, 2.0 and 3.0°C;
except indicators e1, l3 & l4 where SSPs1-3 at 2.0°C are shown.

The key findings relating to population exposure by mesoregion are as follows:

- Western regions (Noroeste and Central-Oeste) are expected to be affected by large numbers of indicators, and the small changes between the Low-High scenarios indicate that the areas are already, and at 1.5°C, facing high levels of exposure.
- Central region appears to be least impacted by large numbers of indicators, yet due to the high population of the region, the numbers are substantial, with over 40 million in moderate-high levels of water stress.
- Noreste region is more impacted by water-land indicators, due to projected warming and drying conditions, and lower levels of agricultural activity in the drylands. Significant changes from 2 to 3°C are evident in the results.

- Sureste region faces high exposure to energy and land indicators, due to projected warming conditions and more agricultural activities. Significant changes from 2 to 3°C are evident in the results.

Figure 23. Population exposure to indicators by climate zone.



For all indicators, Low/Medium/High corresponds to the SSP2 scenario
at 1.5, 2.0 and 3.0°C;
except indicators e1, l3 & l4 where SSPs1-3 at 2.0°C are shown.

The map of 5 climate zones for Mexico was used to determine exposure, although only three zones feature in the Mexican territory:

- Templado de los templados: Temperate
- Seco: Dry/arid
- Continental: Continental (not present)

- Frío: Cold (not present)
- Cálido de los cálidos: Hot

The key findings relating to population exposure by climate zone are as follows:

- Regions with Dry and Temperate climates may face moderate-high impacts across a range of indicators with possibly tens of millions of people exposed to multiple indicators in all the sectors.
- Regions with Hot climates predominantly would face impacts in energy and land sectors, in particular heat stress, cooling demand growth, crop yield reductions and nitrate leaching.

Results are also produced by Federal State, as in Figure 22 – but due to the high level of detail are not presented or discussed in detail. These are provided as separate data files.

4.3. Vulnerable population exposure

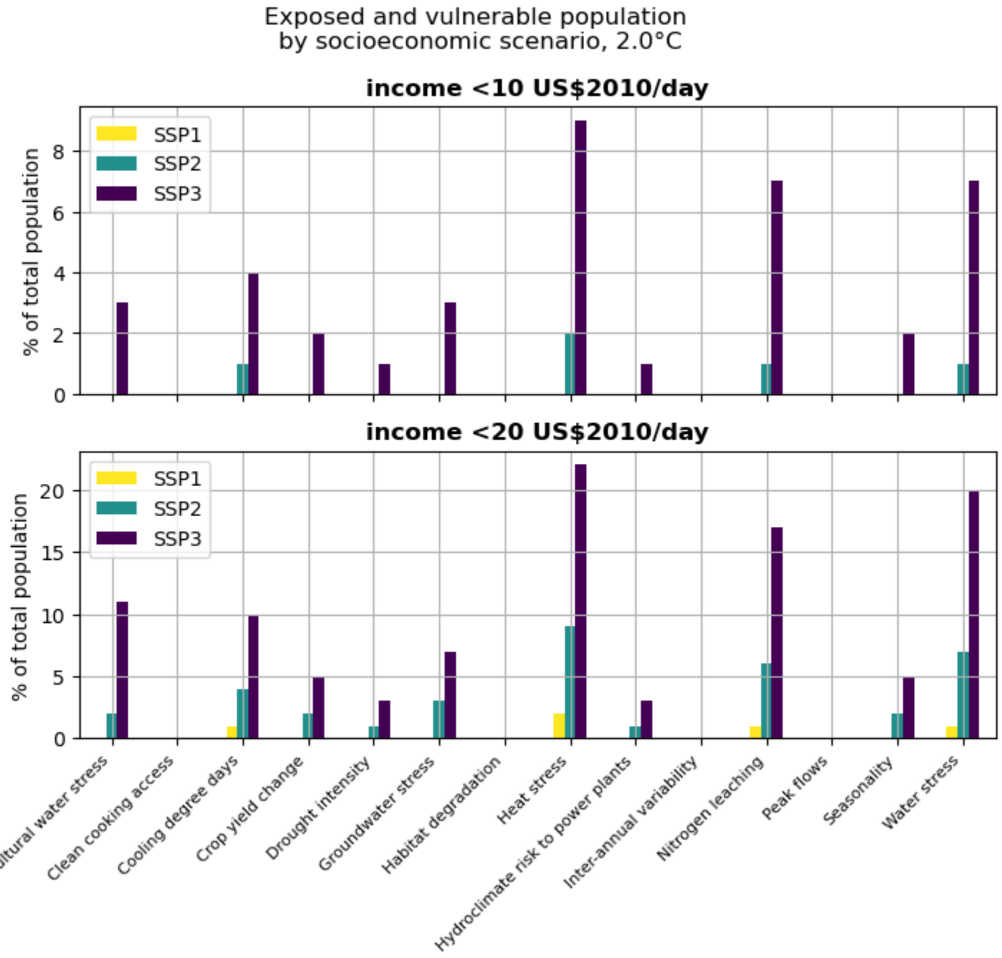
4.3.1. Exposure at the national level

This section assesses the exposure of the most vulnerable Mexican population to the impacts under the scenarios of climatic and socioeconomic change. Socioeconomic development can be an important mechanism for reducing vulnerability and increasing adaptation. Here we specifically assess exposure to the <$10 and <$20 low-income populations (Figure 17) under different socioeconomic scenarios at 2.0°C (Figure 24).

- Key risks in areas with higher numbers of vulnerable people include heat stress, nitrate leaching, and both water stress and agricultural water stress. Impacts for these indicators would be fairly widespread across the whole country.
- In the SSP1-Sustainability socioeconomic scenario with substantially reduced inequalities, the population below the $10 and $20 is greatly reduced, hence exposure would also be minimal, affecting 1-2% of the population. Even for SSP2 (Middle of the Road) at <$10 exposure is limited to a few of the more widespread indicators, cooling degree days, heat stress, nitrate leaching and water stress, to between 2-4% of the population.

The differences to the SSP3 (Regional rivalry) socioeconomic scenarios are substantial – with both more people impacted and, in more indicators, particularly at <$20. This is because the differences between the socioeconomic scenarios are greatest for the lowest income groups, highlighting the reduced inequalities of SSP1 and increased inequalities of SSP3 (compared to today).

Figure 24. Vulnerable exposed to at least moderate risks under the three socioeconomic scenarios. (SSP1-Sustainability; SSP2-Middle of the Road; SSP3-Regional rivalry) for two low-income levels, <2, 10 and 20 US$2010/day in 2050.



4.3.2.Exposure by climate zone and mesoregion

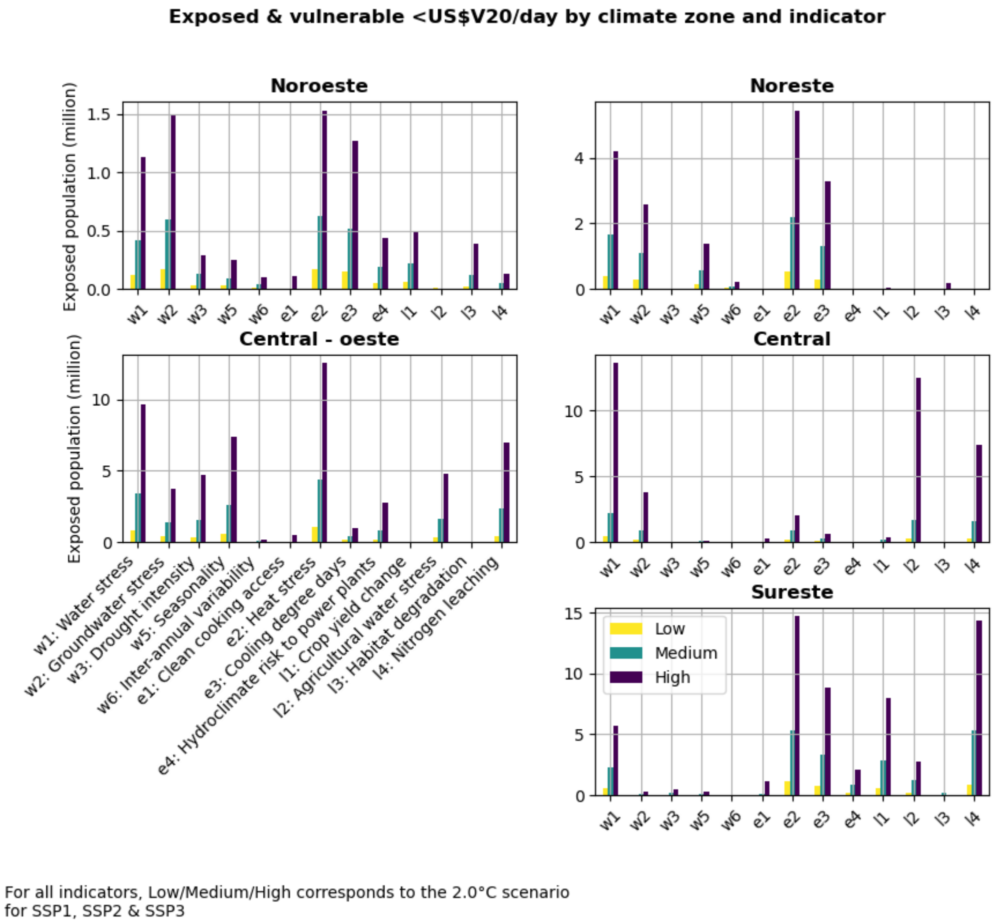
Disaggregated by mesoregion, exposure of the most vulnerable population varies considerably. It is observed that:

- Noroeste and Central-Oeste regions have generally high exposure across most indicators. They also have comparatively higher proportions of vulnerable people in the SSP1 Sustainability scenario, suggesting that inequality reduction here may not be as fast as other regions.
- Noreste region is exposed primarily in the water and energy indicators and not in the land indicators, due to a combination of low impact in the indicators and relatively low vulnerable population.
- Central region is impacted with the fewest indicators yet has high numbers of vulnerable people exposed due to the high population density. Overall, however, we also see comparatively higher income levels, with

negligible population at the $2 levels. Key indicators are water stress, groundwater stress, agricultural water stress and nitrate leaching – all of which are substantially driven by societal activities in the region.

- Sureste region has the highest population exposed, mainly across the energy and land indicators, and additionally water stress.

Figure 25. Exposed and vulnerable population with income <$20 /day for the five mesoregions.



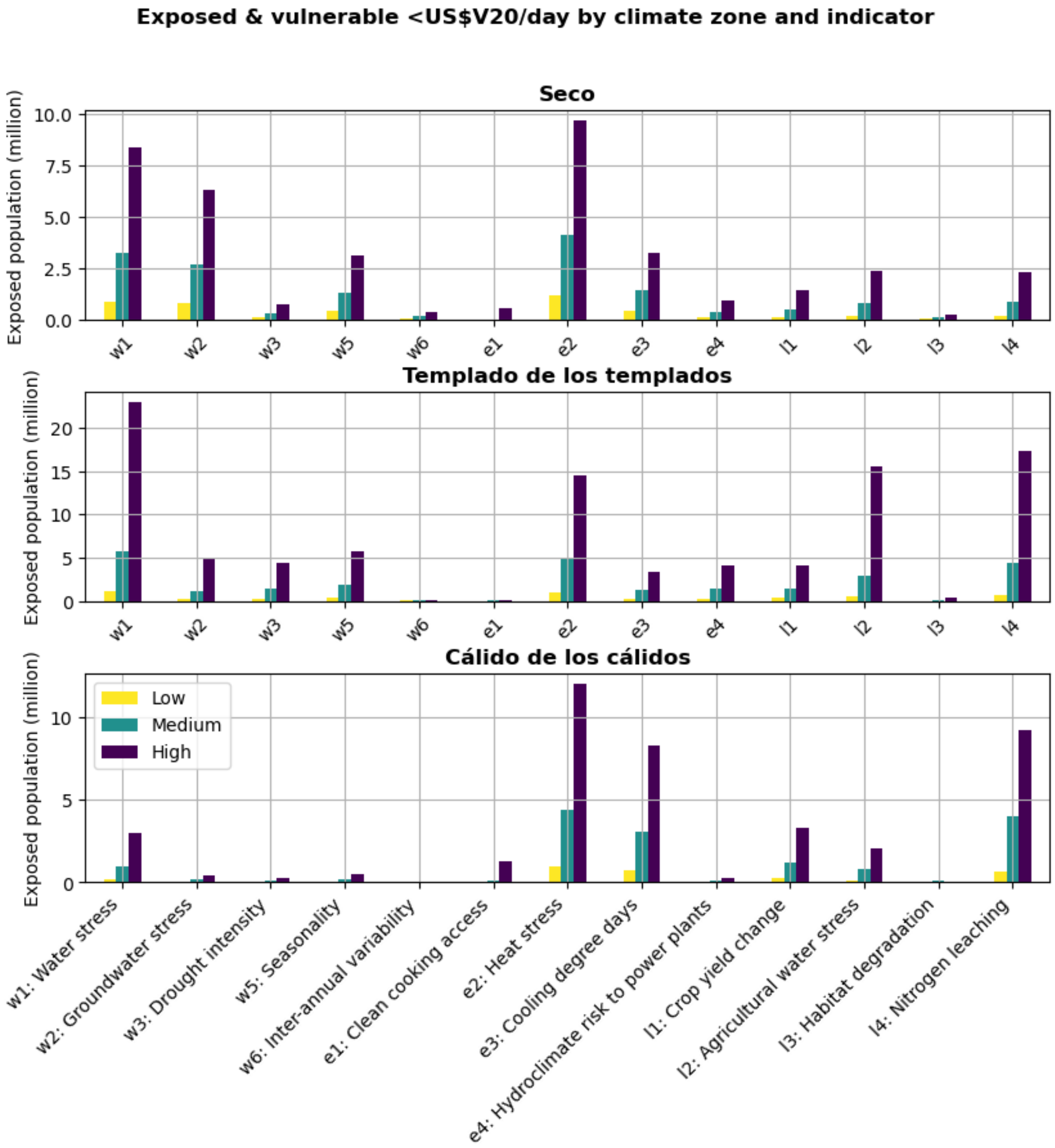
For all indicators, Low/Medium/High corresponds to the 2.0°C scenario for SSP1, SSP2 & SSP3

Note: The differences between "High" and "Low" are for the SSP3 and SSP1 scenarios, respectively.

By climate zone, somewhat similar trends are observed:

- Seco and Templado areas have generally moderate exposure across most indicators.
- The Cálido areas are predominantly exposed to energy and land indicators, to a lesser extent water.

Figure 26. Exposed and vulnerable population with income <$20 /day for the three climate zones.



For all indicators, Low/Medium/High corresponds to the 2.0°C scenario
for SSP1, SSP2 & SSP3

Note: The differences between "High" and "Low" are for the SSP3 and SSP1 scenarios, respectively.

5. PERSPECTIVE ON KEY SECTORAL RISKS FOR MEXICO

This section discusses the findings of the analysis from the perspective of key economic sectors in Mexico, highlighting which indicators are considered to be most important and potential adaptation options.

5.1.1. Water sector

Key indicators

- Water stress index
- Non-renewable groundwater stress index
- Drought intensity
- Seasonality
- Inter-annual variability
- Habitat degradation
- Nitrogen leaching

The scarcity and variability of water availability in Mexico presents substantial challenges to all water dependent sectors. Most critical for the water supply sector in this case include:

- High levels of water scarcity, throughout most of the northern and central regions as well as urban areas
- Increasing intensity of droughts
- Increasing variability, particularly seasonal but also inter-annual – making shortages of water more acute and less easy to predict. In short, the reliability of water supply is reduced.

Competition for water may also result with other sectors, particularly in agricultural and urban areas. Water scarcity is and will be increasingly acute in populated areas and will drive exploitation of non-renewable groundwater resources, which is already occurring and evident from significant increase in the 3.0°C scenarios.

In these areas, habitat degradation and pollution (e.g., nitrogen leaching from fertilizer runoff) threatens the quality of water, both with impacts for:

- ecosystems services will be challenged – poor water quality impacts on ecosystems and poor ecosystems have detrimental impacts on water quality.
- lower water availability means that wastewater effluent is not sufficiently diluted and/or more energy must be used to treat water and wastewater.

5.1.2. Energy

Key indicators

- Cooling degree days
- Hydroclimate risks to power plants
- Water stress index
- Drought intensity
- Seasonality
- Inter-annual variability

Energy sector challenges for Mexico relate primarily to potential growth in electricity demand for cooling during warm temperatures, and the potential climate impacts on supply. Rising affluence and warmer summers can be expected to substantially drive the demand for cooling, particularly in the southern portion of the country – and this growth in demand may increase the level of peak demand supplied on warm days. More than half of the electricity supply mix currently comes from gas, and gas turbines are subject to “de-rating” (reduction of output power) during very warm temperatures.

Hydro power plants are mainly located along the west, central and southern regions of Mexico, while fossil-fuelled gas and oil plants are in the central, and eastern regions. These powerplants are potentially impacted by growing drought intensity and seasonal and inter-annual variability of water supply.

Adaptation of the sector will require efforts to improve long-term planning and forecasting – to anticipate growth in demand and develop necessary capacity; over-arching strategy to reduce electricity sector dependence on water; and to evaluate meteorological and climate related risks on a periodic basis. Infrastructural options may include assessment of alternative cooling water supply options and dry cooling technologies, updated reservoir management regimes and increased water storage.

Adaptation of the energy sector will require measures on both the supply and demand side. Supply side of electricity generation can increase resilience through a further diversified supply mix and use of generation technologies less dependent on water, which includes wind and solar, both of which have high potential in the region. Growing summertime demands and increased electrification of services (such as heat and transport) can be facilitated with increased national intra-regional transmission capacity to improve load-balancing and resilience. This may bring challenges for meting peak electricity demand on hot days if there is not sufficient growth in capacity.

5.1.3.Agriculture

Agricultural sector in Mexico will face primarily environmental and water-related challenges.

Most critical and related to water, for the agriculture sector in this case include:

- High levels of water scarcity and a growing dependence on irrigation which supports high value agriculture
- Increasing intensity of droughts, which means either or both increased duration and increased water deficit during droughts.
- Increasing variability, both seasonal and inter-annual – making shortages of water more acute, less easy to predict and increasing the risk of crop failure.

Key indicators

- Water stress index
- Non-renewable groundwater stress index
- Drought intensity
- Seasonality
- Inter-annual variability
- Crop yield change
- Agricultural water stress
- Habitat degradation
- Nitrogen leaching

Water scarcity is and is expected to be increasingly acute in populated areas and will likely lead to exploitation of non-renewable groundwater resources, which is already occurring. Production of some typical crops in Mexico which are typically irrigated, including maize, rice and fruits, is expected to be impacted negatively, particularly in warmer climate scenarios.

In agricultural productive areas, habitat degradation and pollution (e.g., nitrogen leaching from fertilizer runoff) threatens the quality of water, both with impacts for:

- ecosystems services will be challenged – poor water quality impacts on ecosystems and poor ecosystems have detrimental impacts on water and soil quality.
- lower water availability means that wastewater effluent is not sufficiently diluted, possibly polluting water sources used for irrigation.

Adaptation measures could include:

- Ensuring crop diversity from the national to the producer level to mitigate the risk of more severe droughts. Testing and deployment of more drought-resistant varieties and storage infrastructure to mitigate drought years and crop-failure.
- Pro-active land-use management policy to reduce natural ecosystem loss in more intensively cultivated areas.
- Pro-active improvement of soil and water quality management practices (including crop rotation practices and in-situ monitoring) to reduce Nitrate leaching.

5.1.4. Environment

With a diverse range of climates and landscapes, tracking climate changes and impacts on the environment and ecology of Mexico will be challenging task. Trends in the climate will likely differ by location, as would the ecological responses, making generalizations difficult. For example, whilst most of Mexico is expected under climate change to experience fewer “wet days”, the Central region is expected to have more (50).

Key indicators

- Water stress index
- Drought intensity
- Seasonality
- Inter-annual variability
- Agricultural water stress
- Habitat degradation
- Nitrogen leaching

Environmental policy, regulation and management will need to proactively consider a rapidly changing climate, for example when considering land use change, maintaining biodiversity, environmental flow requirements in water sources and other ecosystem changes. In particular these policies must consider the very different characteristics of climatically and ecologically different regions. For example, a key risk to water and soil quality is that of Nitrate leaching – which although primarily driven by agricultural practices, is also dependent on environmental conditions. Reductions in water availability and a warmer climate with warmer water temperatures may likely make Nitrate water pollution more difficult to manage – less water means less potential for dilution and warmer temperatures increase the growth of Nitrate-driven algal blooms. The expected pressures on natural habitats also have a trade-off with the intensification of agriculture. More intense agriculture and higher productivity mean less pressure to convert natural habitats into farmland – but brings the risk of soil degradation, pollutants and interactions with water quality that need to be managed.

5.1.5. Infrastructure

Key indicators

- Drought intensity
- Seasonality
- Cooling degree days
- Heat stress events
- Hydroclimate risk to power plants

With steady economic growth averaging 2.5% p.a over the past decade, investments in infrastructure (energy, telecommunications, transport and water) in Mexico have increased now ranging approximately US$12-15 billion per year, at approximately 1-1.5% of GDP (51). Projected investment "needs" are approximately double, between 2.5-3% of GDP per year, noting that this gap is predominantly driven by a substantial increase in road transport investments. OECD has stressed the importance of national policy ensuring that infrastructure investments are in line with national policies for emissions reduction and meeting the Sustainable Development Goals (52). Thus, infrastructure policy that is low carbon and resilient to climate impacts should be considered.

Road and rail transport are both particularly vulnerable to some of the impacts featured in this assessment. Extreme heat events cause damage to road and railways, including bridges, accelerating their wear and tear and causing disruption in cases where potential failure requires closure of the asset for prolonged periods – such as when rail lines buckle, or bridges hit the limits of their expansion joints. Drought results in drying up of the soil, resulting in subsidence of embankments and foundations under heavy infrastructure, whilst extreme rainfall and wet conditions increase the propensity of landslides. It is thus suggested that design and financing of infrastructure should consider worst case scenarios of climate impacts and additional lifetime operational, maintenance and repair costs that may occur at high levels of global warming. Interdependencies between infrastructure assets is also worth of further consideration, as is consideration of locations that are subject to multiple climate risks, such as identified in this assessment.

6. CONCLUSIONS

Depending on both the success of global emissions mitigation and emissions-temperature responses in the global climate, the differences experienced by Mexico under 1.5°C or 3.0°C global mean temperature are noticeable. The primary uncertainties explored here cover what is considered ‘scenario uncertainty’ – relating to different outcomes of climate change and socioeconomic development. Particularly with respect to climate, it is possible that multiple scenarios are realized, i.e., firstly experiencing impacts at 1.5°C and subsequently impacts at higher warming later in the century.

Further uncertainties derive from the global climate models and the impact models, which for the majority of cases the median of a model ensemble has been used. Uncertainty between the models can be considerable, although generally equivalent to the differences in socioeconomic scenarios. In previous similar work (2), a more detailed exploration of the uncertainties found that when considering land area exposure the model uncertainties dominate. However, specifically when considering population exposure, and especially the low-income vulnerable population, then uncertainty between the socioeconomic scenarios dominates. This leads to a conclusion of two distinct points:

- understanding the different levels of impacts is generally important when considering the economy and population in general, and mitigation to lower levels of warming brings widespread benefits shared by all.
- However, for vulnerable populations, especially those living in areas with higher exposure to climate impacts, targeted vulnerability reduction is particularly beneficial, i.e., more beneficial than the differences they experience between 1.5 and 3°, for reducing the climate risk burden and avoiding a climate-poverty trap.

Even under the most optimistic scenarios, global mean temperature warming of 1.5°C can be expected to occur in coming decades with a high likelihood. Thus, even the lowest the impacts presented in this assessment are de facto highly likely, notwithstanding inherent uncertainties of the impacts models used.

- At 1.5°C, compared to the historical pre-industrial baseline, increased surface- and ground-water stress, and seasonality of water availability, and heat stress events are all expected, at moderate-high levels of impact. Additionally, more seasonality and cooling degree days are also expected at a moderate impact level. Even in the best-case socioeconomic scenario (SSP1-Sustainability), high pressures resulting from habitat degradation and Nitrogen leaching are expected for the land sector across the country.

- At higher levels of 2.0 and 3.0°C, the above-mentioned indicators are intensified to generally high levels of impact, also affecting larger land areas and more population. Additionally, higher drought intensity and inter-annual variability, and reductions in crop yield become more widespread and prominent.

- Three indicators are prominent in this assessment relating to high levels of risk, considered in terms of at least moderate severity of impact combined with exposure to population/land.

- There are substantial differences in the scenarios for crop yield reductions, both in terms of population and land area impacts, with 3.0°C scenario substantially worse than at 1.5 and 2.0°C. Thus, considerable attention should be paid to preparation and adaptation in the agriculture sector, especially given the importance of the sector to the economy, the high number of dependent and vulnerable livelihoods, and the growing production of high-value crops for export that may be more water-intensive and vulnerable to climate impacts.

- The two temperature-related energy risks of heat stress and cooling degree days, which even at 1.5°C are expected to impact a large of the population, and substantially more so at 3.0°C. These two indicators are also particularly difficult for vulnerable populations who lack income for adaptive measures to improve thermal comfort.

- Water-related risks concerning surface, ground and agricultural water stress. Exposure to these indicators is driven both my biophysical changes in supply and also socioeconomic pressures, and could impact large proportions of society, economy and the environment in different ways. Highly populated areas would require increased investments and good governance to manage demand, maintenance and security of supply. Rural agricultural areas may require more decentralized approaches to manage resources and demands from the agricultural sector, considering the vulnerable nature of rural livelihoods and expected growth of high-value irrigated crops.

The socioeconomic development of Mexico may also result in a wide range of outcomes, captured by the SSP scenarios.

- In the best-case and central socioeconomic scenarios (SSP1-Sustainability; SSP2-Middle of the Road), lower population growth and reduced inequalities could substantially reduce the level of climate risk faced by Mexico by reducing vulnerabilities of the population and through improved coping capacity, safety nets and adaptation. These scenarios envisage a population a little higher or lower than today by 2100 with near-eradication of extreme poverty by the 2050s, and 96% of the population with income >10 US$2010 per day – a level characterized by World Bank as being “vulnerable to poverty”.

- Achieving these positive socioeconomic developments for Mexico would likely require achievement of multiple Sustainable Development Goals and sustained progress through the 2050s, particularly relating to Goals #1-7, for poverty eradication (#1), zero hunger (#2), health and well-being (#3), education (#4), gender equality (#5), water and sanitation (#6) and clean energy (#7). Progress on these targets have synergistic societal benefits and substantially reduce vulnerability, thus helping people escape the climate-poverty trap.
- In the pessimistic socioeconomic scenario (SSP3-Regional rivalry), higher levels of population are expected to result in considerably higher exposure to climate impacts, and higher inequalities and thus vulnerability; combining to elevate the overall climate risk. This scenario envisages in the 2050s a population approximately 40% higher than today (~177 million) and high inequalities, with only moderate reductions in the number of people living in the categories of extreme poverty (<$2/day) and vulnerable to poverty (<$10/day).
- Outcomes of this SSP3 scenario could be expected to occur if there is no progress on the SDGs and would result in and growing proportion of the population existing in a climate-poverty trap. Such a situation would occur when vulnerable people are exposed to multiple challenges, such as recurrent climate impacts or economic instability, that prevent them from improving their livelihoods and reducing their vulnerability.

In light of this assessment and the socioeconomic uncertainties, vulnerability reduction through sustainable development is evidently an important and effective strategy for reducing the overall climate risk burden faced by Mexico.
Prioritisation of measures to reduce vulnerability and enhance coping and adaptation should where possible be primarily targeted at areas with high levels of vulnerable population and/or expectation of high climate impacts.

- Based on the results areas expected to face multiple, moderate-high exposure to climate impacts, the regions impacted vary.
- Northern and Central-Oeste regions are expected to be predominantly exposed to water and energy-related indicators, in particular water stress, hydroclimate variability and rising temperatures.
- The southern region (Sureste) is more exposed by multiple energy and land indicators.
- Proportionally higher levels of vulnerability are expected in rural areas of the Bajío and Sureste regions, where impacts relating to water stress, heat stress, cooling degree days, crop yield reductions and Nitrogen leaching are expected. This will require complementary but possibly different approaches to reducing vulnerabilities and increasing adaptive capacity.

Data supporting the assessment and covering the full ranges of scenario uncertainties is provided to INECC in tabular and spatial formats to support further assessment on climate impacts and vulnerability. With a range of indicators, the assessment should help to identify challenges for a number of sectors, and could be extended and interpreted to more sectors than considered in this report. Exact numbers relating to exposure and impacts at the grid squares should be used with caution and ideally together with other detailed assessments, such as the accompanying Macroeconomic Risk Profile, which has used a similar conceptual and data framework. However, a rage of overarching climate and socioeconomic trends are captured here, with the aim of highlighting the potential scale and range of outcomes that may arise in relation to both climate impacts and vulnerability.

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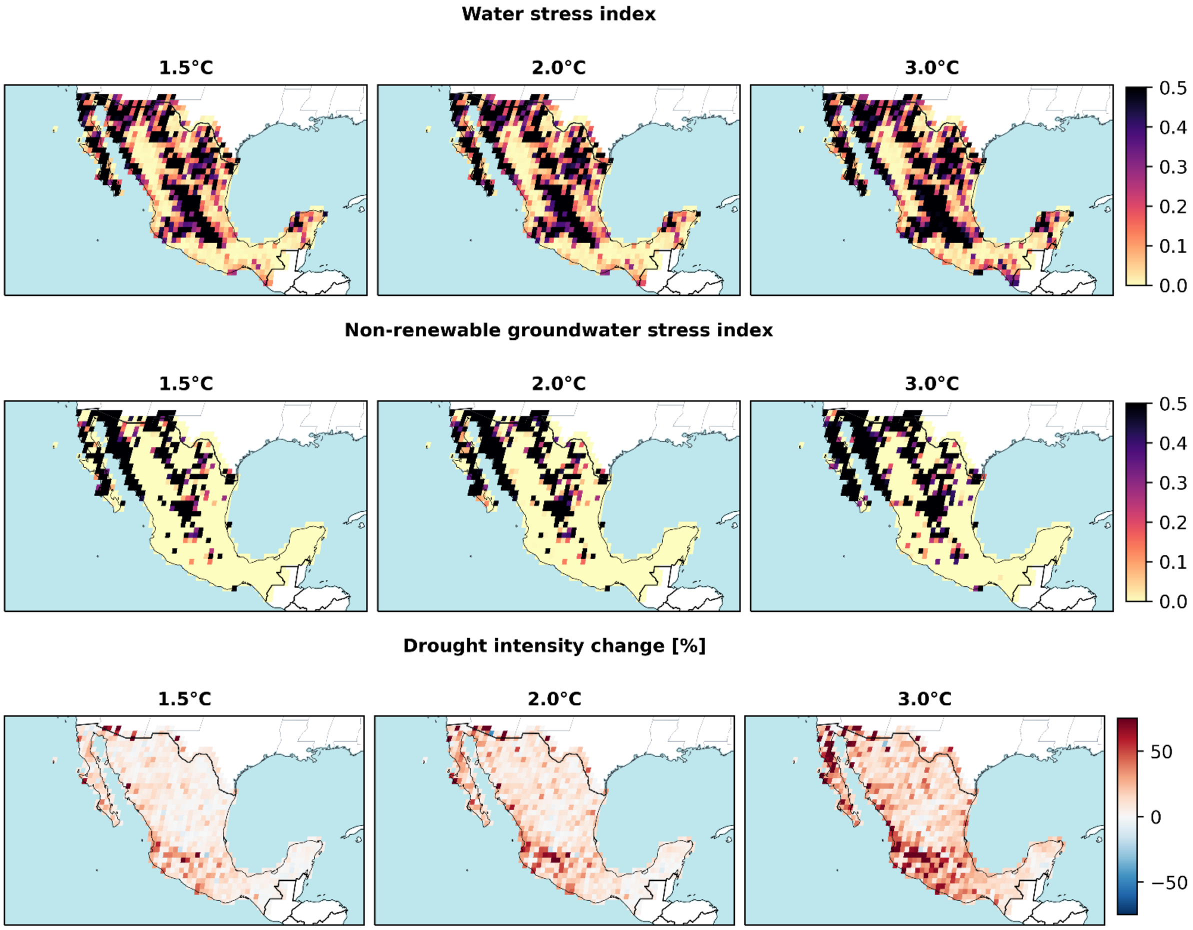
8. ANNEX

8.1. Additional figures

8.1.1. Additional indicator maps

Figure A 1. Water sector indicator maps.



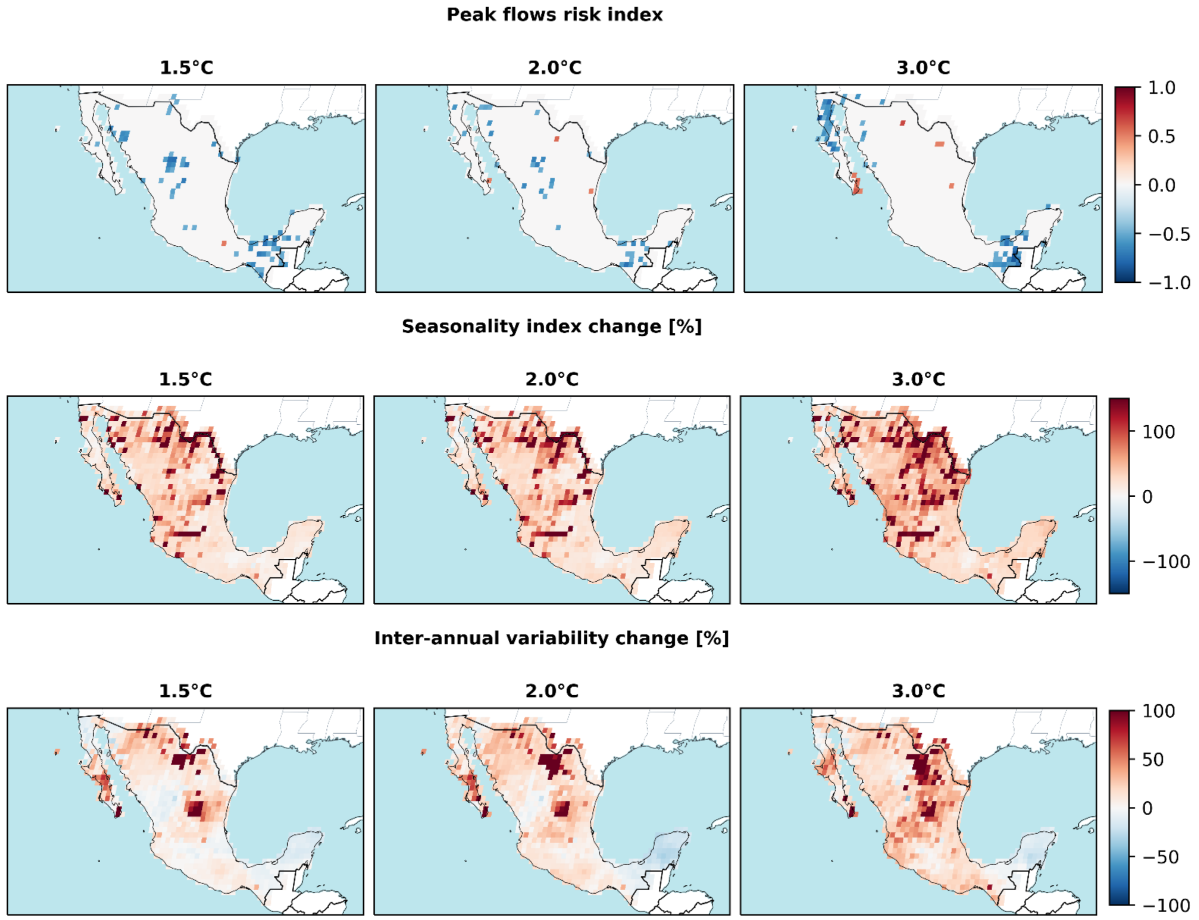
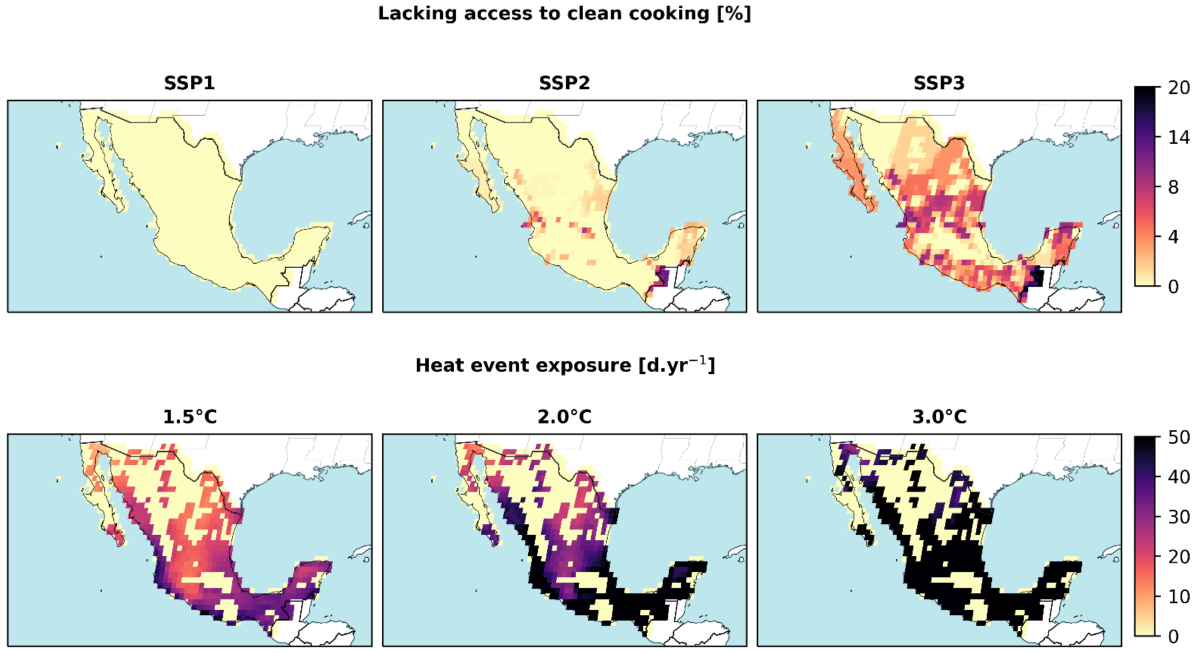
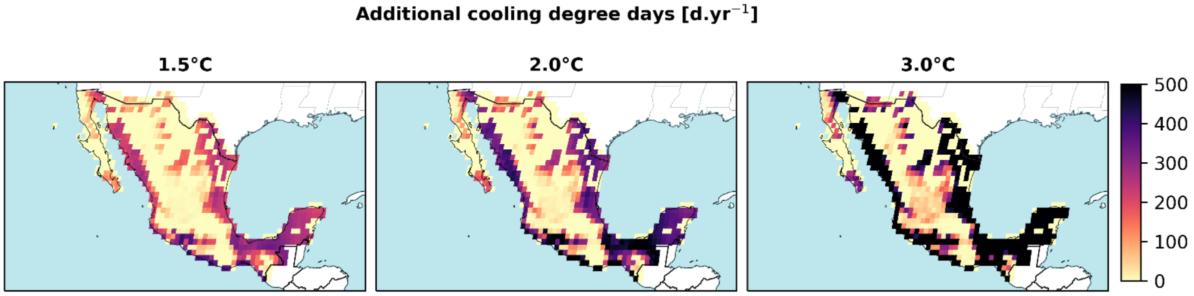


Figure A 2. Energy sector indicator maps.





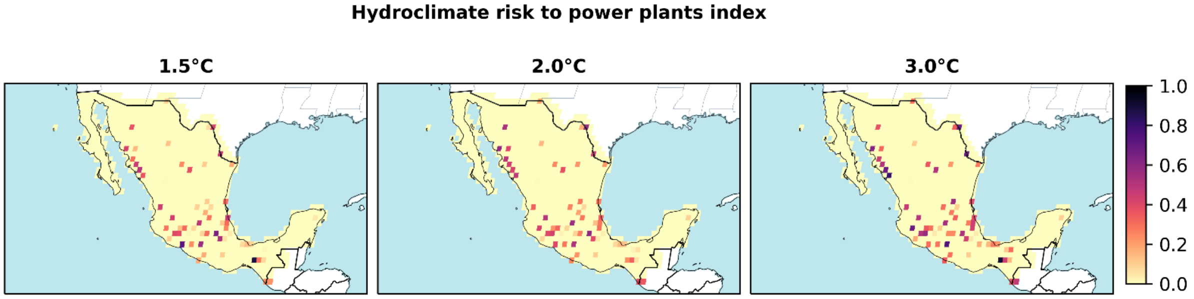
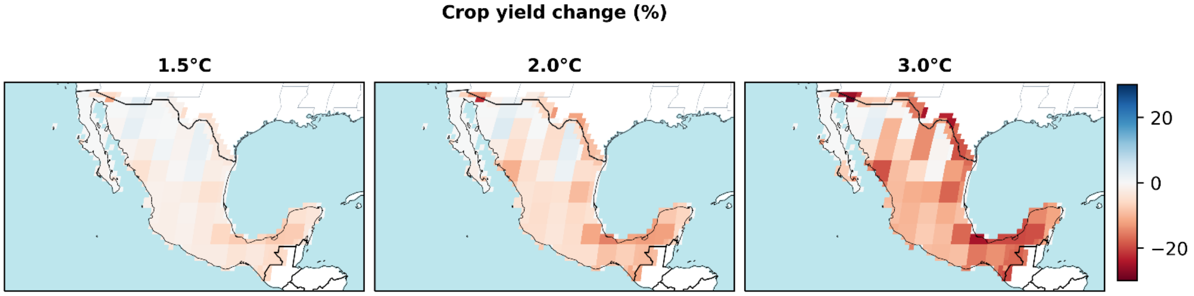
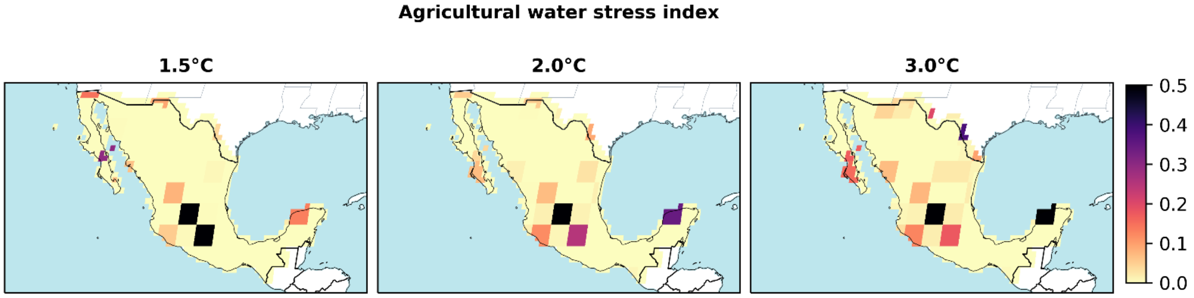
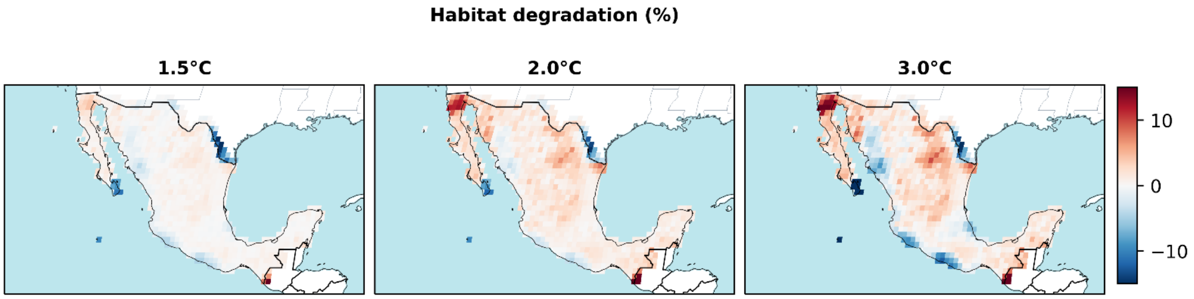


Figure A 3. Land sector indicator maps.





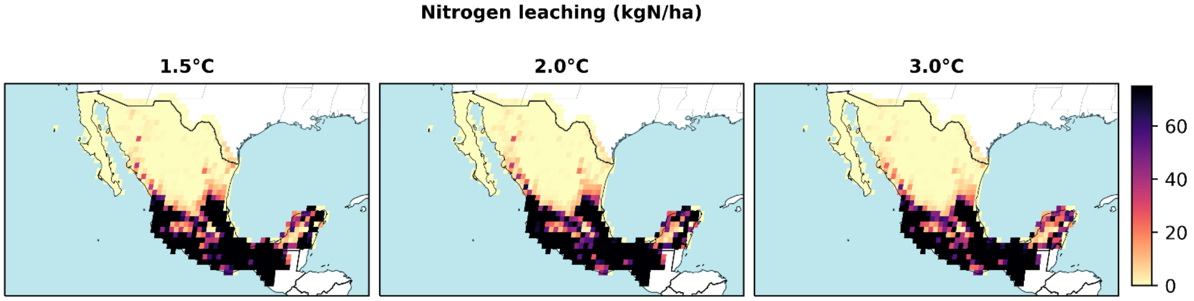


Habitat degradation (%)

1.5°C

2.0°C

3.0°C



Nitrogen leaching (kgN/ha)

1.5°C

2.0°C

3.0°C

8.2. Model and data source information

Table A 1. Model references and further information

Model name	Type	Lead Institution*	References
GFDL-ESM2M	General Circulation Model	National Oceanic and Atmospheric Administration, US	(53)
HadGEM2-ES	General Circulation Model	Hadley Centre, Met Office, UK	(54)
IPSL-CM5A-LR	General Circulation Model	Institut Pierre Simon Laplace, France	(55)
MIROC-ESM-CHEM	General Circulation Model	Japan Agency for Marine-Earth Science and Technology, Japan	(56)
NorESM1-M	General Circulation Model	UNI Bjerknes Centre for Climate Research, Norway	(57)
H.08	Gridded global hydrological model	National Institute for Environmental Studies, Japan	(58)
LPJmL	Dynamic Global Vegetation model	Potsdam Institute for Climate Impact Research, Germany	(59)
PCRGLOBWB	Gridded global hydrological model	University of Utrecht, Netherlands	(60,61)
MPI-HM	Gridded global hydrological model	Max Planck Institute for Meteorology, Germany	(62)
WBM+	Gridded global hydrological model	City University of New York, US	(63)
EPIC	Land management impacts model	International Institute for Applied Systems Analysis, Austria	(28)
GLOBIOM	Agro-economic crop and land-use model	International Institute for Applied Systems Analysis, Austria	(22,64)

MESSAGE	Integrated Assessment energy-economic model	International Institute for Applied Systems Analysis, Austria	(64–66)
Salamanca	Gridded income and inequality model	International Institute for Applied Systems Analysis, Austria	(5)
* From which the relevant model runs are derived, not necessarily original host/ creator of the model.			

8.3. Indicator score ranges

Each sectoral modelling team from the IIASA Water, Energy and Ecosystems Services & Management research programs reviewed and justified the score ranges for each indicator.

Table A 2. Table of indicators showing the weights, type of scale and low, central and high ranges selected for the analysis. Where scale is "index", the data is constrained between 0-1. Where scale is "relative", the data is expressed as a percentage change (%).

Indicator	**Name**	**Scale**	**3**	**2**	**1**	**0**
w1	Water stress index	Index	0.4	0.3	0.2	0.1
w2	Non-renewable GW abstraction index	Index	0.4	0.3	0.2	0.1
w3	Drought intensity change	Relative	70	40	20	10
w4	Peak flows risk index	Index	0.75	0.65	0.55	0.49
w5	Seasonality index change	Relative	150	50	20	10
w6	Inter-annual variability index change	Relative	100	50	20	10
e1	Lack of access to clean cooking	Index	0.2	0.1	0.05	0.02
e2	Heat event exposure	Absolute	50	20	8	4
e3	Cooling demand growth	Absolute	400	250	100	20
e4	Hydroclimate risk to power index	Index	0.5	0.35	0.1	0.01
l1	Crop yield change	Relative	-15	-10	-5	-3
l2	Agricultural water stress index	Index	0.4	0.2	0.1	0.05
l3	Habitat degradation	Relative	10	8	3	1
l4	Nitrogen leaching	Absolute	75	50	20	5

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