Essay

Why is Mexico highly vulnerable to climate change?

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Abstract

This manuscript provides an overview of the vulnerability of Mexico, as a geographic region, to the impacts of climate change. It is in the dynamism of the primary sector where global climate changes have the greatest influence. To rescale global observations at a local, regional and national scale, INIFAP as a public research center, provides technological solutions available to users, decision makers, researchers, academics and consultants. Since its creation, the institute maintains lines of research to study the impacts of climate change on agriculture, livestock and forestry. This is carried out through the organization of national and international technical-scientific exchange meetings and the execution of research and service projects. Through the integration and analysis of databases, the implementation of machine learning techniques in computing architectures, time series of satellite images and data on exchange processes between the ground cover and the atmosphere, the National Laboratory Modeling and Remote Sensors offers the user products and services based on ICTs. Numerical rain and drought forecasts make up the institutional offer to provide useful information to mitigate the effects of climate change in the primary sector. Through these products and services, a paradigm shift is promoted for the study of the impacts of climate change in Mexico.

Keywords: climate change, climate variability, Mexico, primary sector.

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Mexico is the fourteenth largest country in the world, eleventh in number of inhabitants and seventh in oil production. Due to its geography, coastal areas would be the most affected by increases in air temperature, extreme events such as drought and cyclones, landslides, and decreases in the precipitation volume. These impacts create new risks to the population and instability to ecosystems (Oswald-Spring and Brauch, 2009b). The variables associated with climate expression are indicators that 'measure' the impact of climate change. Forecasting its trend and intensity in the short, medium and long term show its seasonality and close relationship with the availability of the water resource. The National Institute of Forestry, Agricultural and Livestock Research (INIFAP) has maintained research lines to study in parallel manner the evolution of climate change impact indicators and their impact on agricultural, livestock and forestry production systems. Through specific technology packages by crop and geographic region and the development of web services, it has maintained interest among the scientific community in studying global climate change and the methods of re-scaling global solutions at local, regional and national levels.

In this task of exploring and analyzing the effects of climate change, the concept of large numbers takes on relevance. The exponential growth of large databases, that track the dynamics of the planet's biogeochemical cycles, demands to have trained human resources, high computing and data storage capacity. In the execution of computing processes on the cloud, the selection of large databases analysis tools, intelligent analysis platforms and technological solutions play a relevant role (Oury and Sing, 2018; Almgren *et al*., 2019). It is intended, on the one hand, to understand the evolutionary dynamism of the planet's biogeochemical cycles, such as the water cycle, the carbon cycle and rotation and translation movements, and on the other hand, to derive solutions in which to support specific programs of mitigation practices for climate change effects.

Among the main impacts, variations in agricultural production -which is not alternating in production- are strongly associated with a geographical component. Changes in the geography of production, a decrease in water resource, a decrease in crop yield and an increase in frequency and intensity of extreme meteorological events associated with air temperature and rain, resulting in ecosystem disturbances (Fellmann, 2012).

After nearly half a century of development and technical design, 3D observation systems of regent systems on Earth have been put into operation. They record the electromagnetic spectrum in the visible, infrared and microwave light regions. Prior to these systems, data recording was done at the local level and rarely at the regional level. Networked interconnected sensors were used. INIFAP currently manages a key database of 340 automatic meteorological stations that record every 15 min data packages of six variables: air temperature (°C), relative humidity (%), accumulated rainfall (mm), solar radiation (W $m^{-2)}$, wind direction and speed (m s^{-1}).

However, the spatial representativeness of the monitoring point is restricted only to the recorded variables, without noticing other geophysical and biotic phenomena due to insufficient densification of devices in the field and poor vertical resolution of data (Hua-Dong *et al*., 2015). Along with the design of observation systems, data analysis techniques have been converted to data architectures with high management and storage capacity.

In the complexity of studying climate change, large databases are the necessary resource to track seasonal changes (Manogaran *et al*., 2018), understand the paradigm of change (Faghmous *et al*., 2014), identify risks (Ford *et al*., 2016) and explore soft data sources. Array of data in multitemporal, multi-origin, multivariate, and multiscale time series makes it necessary to design compute architectures and use large database management tools.

Techniques of machine learning (ML) are distinguished by their predictive and large database management capabilities. Through their computing vision, they can manage domains such as electricity distribution systems, drinking water management in cities (Hao, 2019), agricultural, livestock and forestry production units and simulate the climate in the short, medium and long term. The domain depends on the re-scaling solution. Typically, an increase in spatial resolution reduces coverage on the ground.

Frontline classifiers are used in data insufficiency, low computing power and reduced offer of search algorithms. They are low-complexity, parsimonious analysis methods such as random forests, support vector machines and neural networks.

This manuscript addresses the use of data analysis techniques to produce numerical indicators of Mexico's vulnerability to climate change. It is emphasized how through the analysis of large databases and machine learning techniques, predicted indicators are obtained at the local, regional and national levels, that contribute to the design of strategic climate change mitigation programs. It also outlines INIFAP's contribution as a public research center (PRC) in the study of climate change. It should be noted that the review does not address the diversity of concepts and interpretations of vulnerability, or the scope of the analysis methods used.

Description and scope of the problem

Climate change in Mexico has social and economic components that are evident at the local, regional and national levels. The affectations are palpable due to the rate of change in land use, air quality, water shortage and deficient provision of essential services to the population. Mexico's geographic space represents a mega diversity (Groombridge and Jenkin, 2002), with a territorial extension of 1 959 million km^2 on the continental shelf, where two thirds are considered arid or semi-arid (50-100 mm of annual accumulated rainfall) and a third humid (annual accumulated rainfall >2 000 mm).

Climate variability is high and climate expression is strongly influenced by factors associated with topography and sea surface temperature. Warm and dry conditions prevail in the Northwestern region in the Sonoran Desert, where the annual precipitation is only 100 mm, to the humid-tropical climates of Chiapas and the coastal region of the Gulf of Mexico where the accumulated annual rainfall is greater than 2 000 mm (Lieverman, 1999).

Climate expression originates from latitudinal belts of atmospheric circulation. The winds of the west bring precipitation to north of Mexico in winter. When the winds deliver rains in summer in the central and southern regions of the country, it is due to stable and dry conditions which extend to the inter tropical convergence zone (ITCZ).

Other key influences on precipitation are autumn hurricanes in the Caribbean and Pacific coasts, summer monsoons in the north and the high summer pressure that disrupts humid air flow and creates a period of dry conditions known as the canícula. Mexico’s mountainous and variant topography dominates many other climate influences that generate cooler temperatures and higher precipitations in the highlands and in the central Plateau, and light rains behind the coastal mountains (Metcalfe, 1987).

Geographic space can be represented by seven major concepts: place, space, environment, interconnectivity, sustainability, scale and change (Groombridge and Jenkin, 2002). The concept of place is adjusted according to the relevance of the ecosystem by its intrinsic characteristics. Space is the how and why of the asycodo of the elements of the ecosystem according to the needs of the population. The concept of environment is related according to its influence on habitat, life forms and their interrelationships. Interconnectivity is the interrelationship between living and non-living things, the central idea is that an event that occurs in one place can cause a change in another place and that no geographical element can be studied separately.

In practice, sustainability is an interconnectivity of elements such as: environmental health, social equality, rational exploitation of natural capital and the strengthening of production chains. Scale is how geographic events and origin characteristics can be explained at different levels, it can be local (water distribution in the soil), regional (heat wave), national (cold fronts, polar wave, hurricane trajectory, etc.). The concept of change analyses how the ecosystems and life forms that constitute natural capital have changed over a period.

In Mexico, the number of environmental services associated with production systems is a hallmark due to their obvious geographical variation. To name a few, air quality, water harvesting, water quality, sustainable land use, biodiversity, conservation of food chains and strengthening of food production chains.

Agricultural practices in production systems are geographically dependent. They are classified according to the production approach in business and social. Business practices are implemented with a sense of market, where the destination of production are export consumer markets. Together they represent the most relevant agricultural indicators such as: higher volume of production, higher crop yield and greater diversification of the crop map, include mostly perennial farms such as guava, citrus, walnut and apple tree.

In agricultural practices with social approach, production is mostly for domestic consumer markets or self-consumption. Their contribution to agricultural economic indicators is less than those of business practices, productivity is conditioned on the rain cycle.

Because of climate change effects, economic and social impacts on the primary sector will become increasingly severe as water availability and climate variability worsen. Some of the obvious effects are: variations in the biological cycles of pest organisms (vertebrates, fungi, phytoplasmas and bacteria), drought condition, air quality (volume of particulate matter and presence of contaminants such as carbon dioxide, sulphur dioxide and nitrogen compounds), occurrence of extreme meteorological phenomena (hailstorm, shower and hurricane, heat wave), wildfires, and progressive despondency of the water table.

Other types of impacts are those associated with meteorological conditions. It is proposed to group them into three categories: those associated with air temperature, those associated with the rain cycle and those associated with sustainable practices. Those associated with air temperature are, for example, drought condition, heat wave, accumulation of heat units and cold units, duration of the growing season of crops and rate of evapotranspiration. Those associated with rainfall cycle identify geographic regions by the volume of rain received, the discrepancy is in the time that occurs and in time that returns. Those associated with sustainable practices have application on natural capital management, conservation agriculture, genetic resource improvement, precision agriculture, hydraulic infrastructure works and water harvesting.

Climate change as state policy

In its futuristic vision for 2025, the organization Tierra Futura identified seven major challenges to be faced: synergy and water trade, energy, food production, decarbonization of socioeconomic systems, appraisal and biodiversity governance (Bauer *et al*., 2012), functioning of the ecosystem and environmental services and social resilience on the route to sustainable development. Oriented to the geographic space of Mexico, they are outlined in Figure 1.

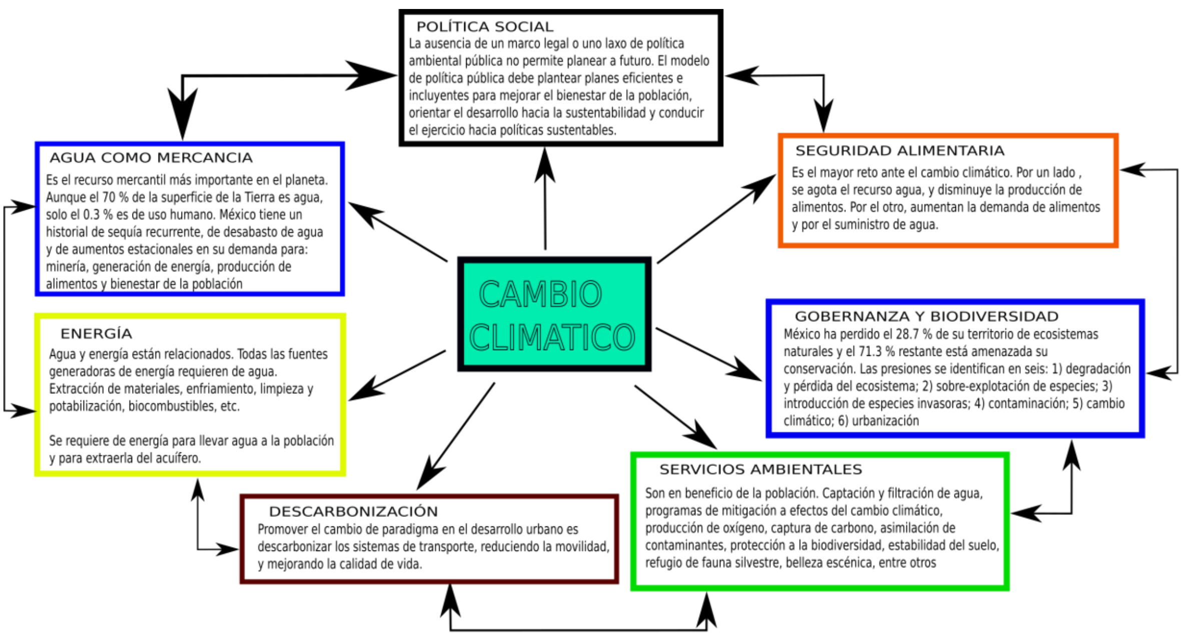

Figure 1. Interrelationships of climate change as state policy.

From Figure 1, it is highlighted that renewable energies have a regionalized potential development: in the north the generation of solar energy is promoted, in the center and northwest the geothermal and in the south wind energy (Impacto Social Consultores, 2021). Regarding food security, Mexico is the fourth largest maize producer in the world, but it is also a major importer and consumer. Demand for white maize in the domestic consumption market is covered, but the country has deficit in yellow maize production. Insufficiency is covered by imports from the United States of America, Brazil and Argentina. The imported volume of maize is observed with an upward trend, with an average annual growth rate of 5.8% (CIMA, 2020). Emphasize that corn grain is a key to food security and that the drop in historical yield in major producing states is related to extreme meteorological events such as frost, hailstorm, water shortage and hurricanes.

Mexico is a fossil fuel-dependent country, whose production and energy supply are mostly covered by gas and oil. The most recent energy balance showed that 85% of gross domestic supply was covered by hydrocarbons that, during 2018, decreased their share by 1.36 percentage points. Natural gas and condensates contributed 47% of the total supply, followed by petroleum and petroleum products with 38% (SENER, 2019)

It is estimated that at some point in the period 2040-2050 petroleum will be completely displaced by alternative energies, especially renewable and clean energy, therefore its energetic use would be significantly reduced (Senado de la República, 2003; Del Río *et al*., 2016; Cherif *et al*., 2017). Two factors that encourage technological innovation could lead to the consolidation of the third energy revolution: the energetic and economic cost of extracting petroleum and international pressures to reduce greenhouse gas emissions.

Mexico's National Climate Change Policy is conceived as the set of public interventions developed by the three government levels that contribute to reducing emissions of gases and greenhouse compounds and moving towards a low-carbon economy, as well as reducing vulnerability and strengthening adaptation of population, ecosystems and productive systems to the effects of climate change (México ante el cambio climatico, 2021). However, action programs on climate variability, vulnerability and greenhouse gas emissions are not an ideally permanent policy, state policy should focus on proposing mitigation and adaptation strategies, on cost-benefit ratio and on promoting actions towards sustainability.

The implementation of regional strategic policies ensues in better results in terms of managing the impact of climate change. Success could be attributed to the necessary inter-institution coordination at the three levels of Government. The regional scope of competence would include shared policies on: 1) air quality; 2) transport systems (air, sea and land); 3) tax support, such as loans, exemptions in the payment of taxes, granting subsidies to production, and guarantee prices; 4) research and education; 5) construction materials; and 6) conservation and use of the water resource (superficial and underground). The main point is to promote a state policy focused on achieving common objectives for the benefit of the population.

The population must have a prominent participation in the delimitation of regional policies, because of their knowledge of the territory. It is clear that the impacts of climate change are greatest in the most vulnerable sectors, which makes it necessary to implement an integral and inclusive political strategy. Early warning systems are the ideal tool to announce the proximity of extreme meteorological events (frost, hurricane, hailstorm, shower, drought) and for them to be communicated through Information and Communication Technologies (ICT), the drought condition in the world is permanent since the last century and its severity is regionalized.

In this context, INIFAP's institutional offer through the National Laboratory of Modeling and Remote Sensors seeks to reduce the period between decision-making and its impact in the short, medium and long term. It includes a certain number of web products and services, related to climate characterization and the application of forecast models, of regional and national scope. For example: the short-term numerical forecast, which is a re-scaled solution at 8 km, is updated every 24 hours, covers a five-day period, and is presented in daily and horary mode.

This product consists of 17 meteorological variables: air temperature (minimum, average and maximum), equivalent potential temperature, dew point temperature, soil temperature (0-10 and 10-40 cm), accumulated rainfall, among others. For more information, images are seen and downloaded by entering the links (https://clima.inifap.gob.mx/lnmysr/pronostico/pronosticodiario) and https://clima.inifap.gob.mx/lnmysr/pronostico/pronosticohorario).

X-ray of the climate change in Mexico

The spatial border of Mexico's natural capital is under constant pressure due to the growth of population cores and climate variability. As a result, the area of transition ecosystems has increased. In Mexico the main production cycle is spring-summer and covers up to 86% of the cultivated area. Alterations to the primary sector that are best associated with climate change in Mexico are summarized in Figure 2.

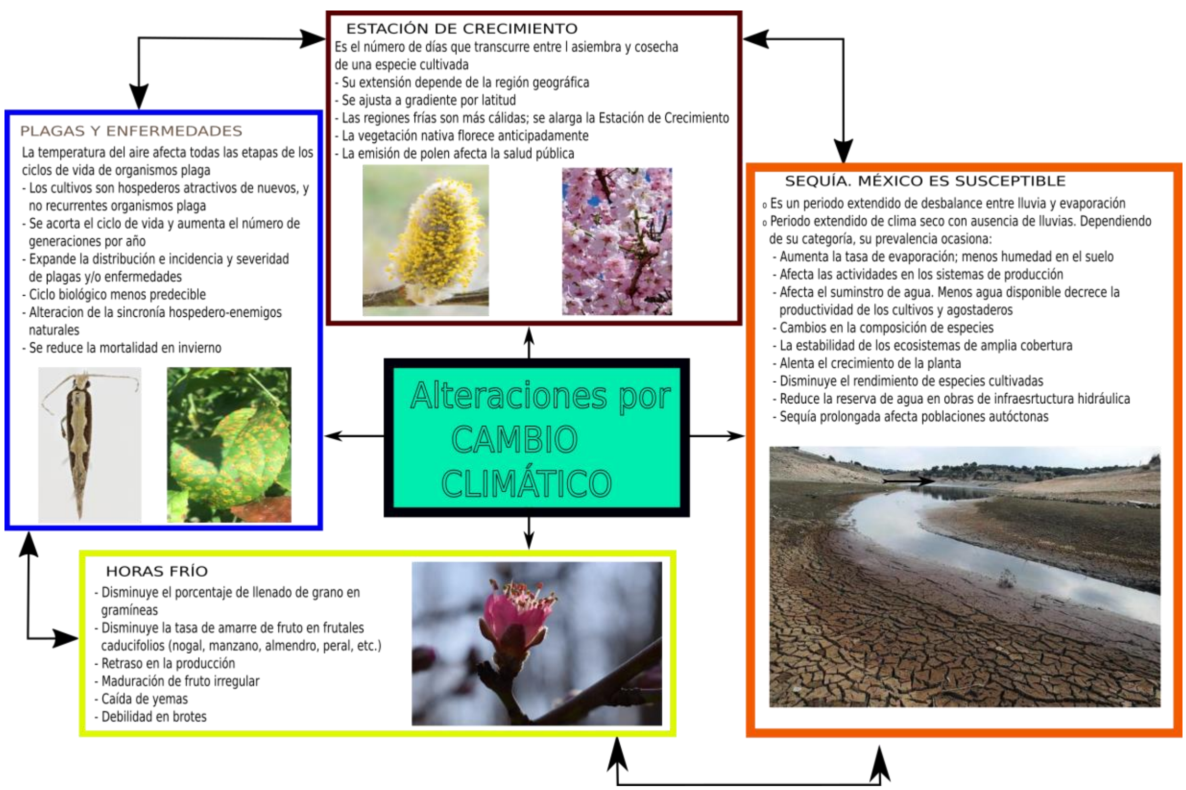

Figure 2. Alterations to the primary sector attributed to climate change. Pests and diseases, growing season, drought and cold hours.

In open ecosystems, the main threat is the destabilization of the food chains, of extensive livestock and the modification of flight paths of migrant species; extensive livestock in Mexico covers approximately 109.8 M ha. The length of the growing season is contrasting. It is strongly influenced by: air temperature, number of days with frost, availability of water, and the period of insolation. It has been documented that in the western region of Mexico, it has spread up to 2.2 days per decade since 1991, while in the east region the variation is 1 day for the same period. An increase in the number of days of the growing season results in crop diversification, but also in the invasion of weeds and an increase in water demand.

The drought condition in Mexico has been a constant of recent years. INIFAP, through the National Laboratory of Modeling and Remote Sensors, has implemented the logistic regression technique to assign the class value to the expected drought type. The drought forecast results from the associative analysis between the North American Drought Monitor's categorical database and the monthly rainfall accumulated obtained from times series of the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). Maps can be found in the institutional web portal https://clima.inifap.gob.mx/lnmysr/pronostico/sequía.

Periods of drought and their intensity are associated with the condition El Niño. El Niño, which is the warm condition in the sea surface temperature, causes droughts mainly in southeastern states of Mexico such as Oaxaca, Guerrero and Chiapas, while the opposite condition, of cold temperature, also called La Niña, corresponds with intense periods of drought in northern Mexico. A categorical characterization by drought condition is the basis for outlining water-efficient use programs in agricultural, industrial and urban sectors.

The characterization of geographic space in Mexico

Given the remarkable evidence of climate change and its regionalization, geographic space can be characterized based on three monthly databases: the quantity of accumulated rainfall expected (Figure 3), the expected precipitation anomaly with respect to base climatology (Figure 4) and the probability of drought occurrence (Figure 5).

In Figure 3, the map is a product in the process of validation. It results from implementing a data analysis architecture for time series using ML. The historical series is based on the accumulated volume of monthly rainfall obtained from CHIRPS, at national level. Figure 4 shows the precipitation anomaly with respect to the base climatology.

From Figure 4, critical areas, where a deficit in the volume of precipitated rain is expected to occur, are identified. This regionalization of drought condition could lead the set of mitigation actions as a component of public policy. The time series is predicted by comparing the accumulated monthly rain scenario (Figure 3) against the base climatology 2010 published by CONAGUA. Figure 5 shows the drought forecast.

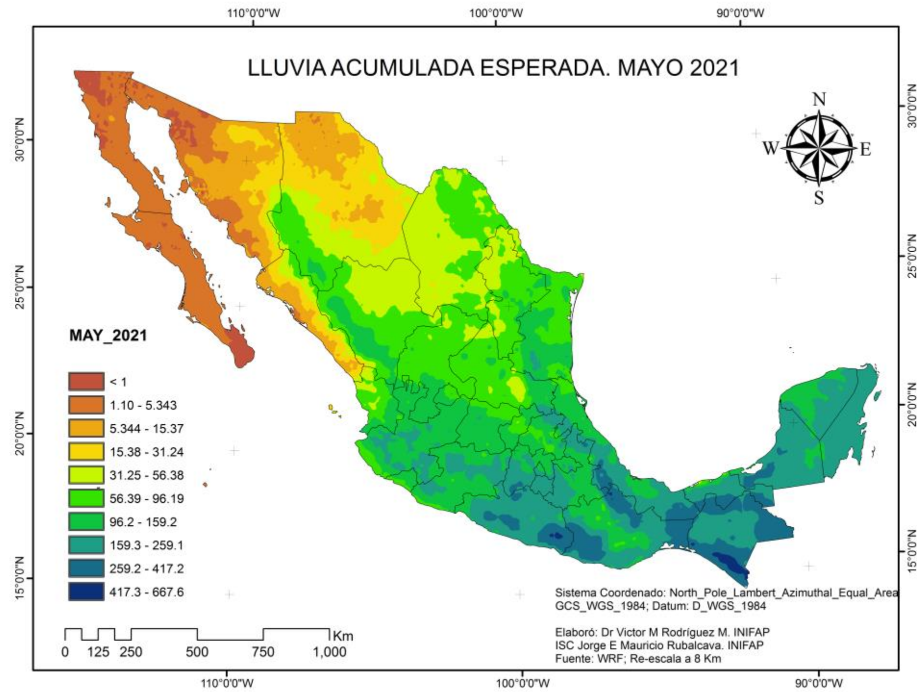

Figure 3. National distribution of accumulated monthly rainfall expected for the month of May 2021.

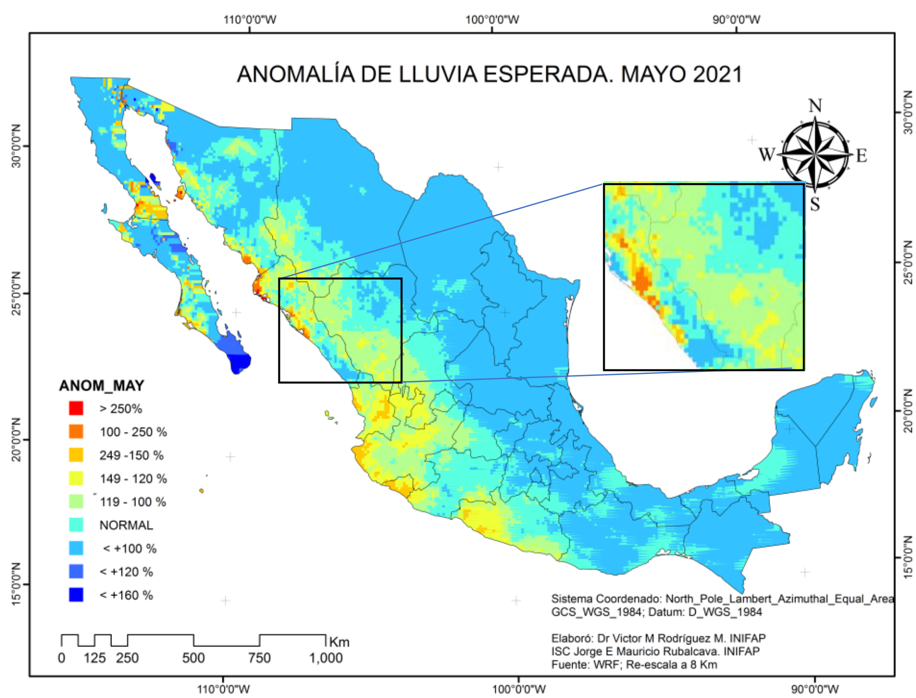

Figure 4. Monthly forecast of accumulated rain anomaly (%). May 2021.

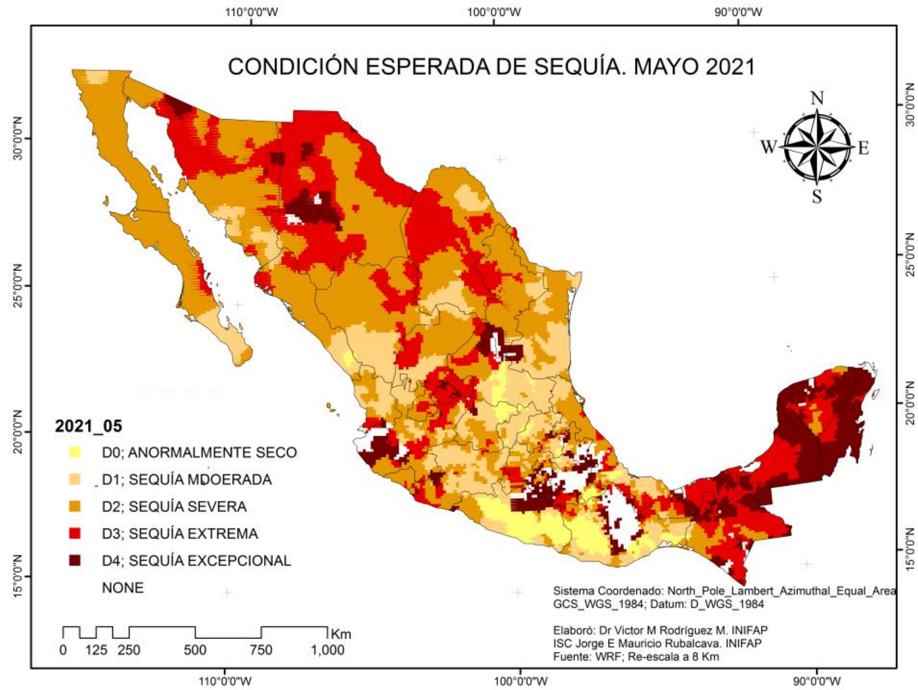

Figure 5. Drought condition expected for Mexico. May 2021.

Through the logistic regression analysis technique (will occur/will not occur), the monthly forecast of drought condition at the country level was obtained. The maps obtained have an individual pixel scale solution (1 km).

The water resource in Mexico

Water availability has a geographic component. The northern region has less water available, concentrates the largest number of inhabitants and includes the states that economically contribute the most to gross domestic product (GDP), 77% of the population lives in areas that produce 87% of Mexico's GDP, but where they only have 31% of the available water. The South region is where there is more water available, fewer inhabitants and it is the one that contributes the least to GDP (CONAGUA, 2018), 69% of Mexico’s water resources is here, 23% of the population live here and they produce 13% of the national wealth.

Compact agricultural regions concentrate the water resource and are intended for agribusinesses (Garatuza-Payan *et al*., 2011), while the demand for water by cities increases in the same proportion to the number of inhabitants. Increase in water demand is a threat to the ecosystem sustainability due to overexploitation of aquifers and change in land use. Highlights include mining and agribusiness that hoard water (Oswald-Spring, 2014).

In this manuscript, a series of numerical indicators, that support that Mexico is vulnerable to the effects of climate change, were described. The institutional proposal of INIFAP was highlighted, which proposes solutions to this complex problem with the use of effective techniques for the management of large databases and for the generation of numerical forecasts and their communication through web services. The proposal highlights the effects of climate variability in the primary sector and how through data science, thematic products that combine synergies between specific design databases, ICTs and data forecast models are obtained.

ML tools can play a key role in identifying areas of opportunity on local and regional trends in climate change impact indicators and in outlining mitigation programs that integrate heterogeneous response and exploration models on the interaction of environmental and social factors.

It can be inferred that the predicted climate factors of accumulated rain, rain anomaly and drought condition do not fully meet strategic planning expectations to lead a state policy; however, they are the product of data integration and promise to be benchmarks given the trend towards the adoption of cloud computing systems.

Mitigating the impacts of climate change requires effective political coordination and a common agenda. Large databases and process systematization are the most effective union for harmonizing scientific knowledge and directing future research. The proposed model is a castle of knowledge (Mauser *et al*., 2013) that includes three stages: a) co-design of the investigation; b) co-production of knowledge; 3) co-dissemination of the results. A common agenda or research program of local, regional and national scope is co-designed with the participation of researchers, decision makers and recognized characters of the population. The results are properly translated into a language understandable by all participants and communicated through web services, virtual or face-to-face workshops and technical publications.

Conclusions

It is necessary to highlight the obligation to update the legal framework that regulates the processes of monitoring and directing social policy on the impacts of climate change in Mexico.

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