

Soil moisture regimes in Mexico in a global 1.5°C warming scenario

Soil moisture regimes in Mexico

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Abstract

Purpose – This study aims to present the climate change effect on soil moisture regimes in Mexico in a global 1.5°C warming scenario.

Design/methodology/approach – The soil moisture regimes were determined using the Newhall simulation model with the database of mean monthly precipitation and temperature at a scale of 1: 250,000 for the current scenario and with the climate change scenarios associated with a mean global temperature increase of 1.5°C, considering two Representative Concentration Pathways, 4.5 and 8.5 W/m² and three general models of atmospheric circulation, namely, GFDL, HADGEM and MPI. The different vegetation types of the country were related to the soil moisture regimes for current conditions and for climate change.

Findings – According to the HADGEM and MPI models, almost the entire country is predicted to undergo a considerable increase in soil moisture deficit, and part of the areas of each moisture regime will shift to the next drier regime. The GFDL model also predicts this trend but at smaller proportions.

Originality/value – The changes in soil moisture at the regional scale that reveal the impacts of climate change and indicate where these changes will occur are important elements of the knowledge concerning the vulnerability of soils to climate change. New cartography is available in Mexico.

Keywords Climate change, 1.5°C warming scenario, Newhall simulation model, Soil moisture regimes

Paper type Research paper

1. Introduction

With the increase in mean global temperature, regional impacts and local capacity for adapting vary enormously from one region to another (Wang *et al.*, 2017). One of the key impacts will be on water resources (Arnell *et al.*, 2016). To reduce the impacts and risks of global warming in the different human and natural systems, the international community, in the Paris accord, established as an objective to restrict the increase in mean global temperature to 2°C above preindustrial levels, with an aspirational target of 1.5°C (UNFCCC, 2015).



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Limiting warming to 1.5°C would reduce the local impacts projected for 2°C, which for some regions would be disastrous with severe impacts on food production, water resources and ecosystems and would mean moderate to high-risk for human and natural systems (IPCC, 2014). This involves a new stage of actions against climate change, and thus, it is essential to study the characteristics of global and regional change under these warming thresholds. However, there is a small number of studies related to impacts associated with global warming to 1.5°C. For this reason, it is essential to study the characteristics of global and regional climate change at this warming threshold.

One of the main functions of soil is biomass production by supplying water, nutrients, air and physical support for plant growth, directly affecting the food chain. All the processes of this system depend largely on temperature, water availability and especially, biological activities that greatly determine soil characteristics and its functions for human societies and the environment. This function is severely threatened by climate change, which will change soil processes and characteristics and the goods and services this component of the natural environment provides (Blum, 2005).

Soil moisture is the main natural water resource for agriculture and natural vegetation (Heim, 2002). Consequently, determining changes in soil moisture is vital for evaluating the impacts of climate change on agricultural production and natural ecosystems (Kim and Wang, 2012). Different studies have investigated responses of soil moisture to climate change and have simulated soil moisture dynamics by global circulation models or land surface models because *in situ* measurements are scarce (Seager *et al.*, 2013).

Soil climate is the long-term register of seasonal and daily moisture and temperature patterns, which are perhaps the most dynamic soil properties and important components of the structure of the US soil taxonomy. With this register, large-scale climate maps can also be generated for multiple iterations of climate data to evaluate climate change (Winzeler *et al.*, 2013). Of central interest for the USDA(2012) climate change science plan are future biotic conditions that accompany climate change, particularly those regarding soil climate as they affect agricultural and forest productivity. Bonfante *et al.* (2011) explore several strategies to improve estimations of soil climate within soil taxonomy schemes and recommended simulation models as a viable approach. Among these strategies is the Newhall simulation model, which has been used with four decades of atmospheric climate records. This model has been used not only in soil taxonomy studies but also in studies of crop response to climate and of yield production (Jeutong *et al.*, 2000; Yamoah *et al.*, 2003; Waltman *et al.*, 2011). The Newhall simulation model is considered a meso-scale model and although it is valid only for well-drained soils, it is considered that in most cases it provides a reasonable approximation to average soil moisture through estimating the monthly number of humid and dry days. It requires monthly weather data on atmospheric precipitation and average air temperature to facilitate its implementation (Winzeler *et al.*, 2013).

Different studies have shown that climate change will affect developed and developing countries differentially, with major vulnerabilities in low latitude regions (Smith, 2012; Darwin and Kennedy, 2000). For this reason, the objective of this study was to estimate in Mexico the regional impact of an increase of 1.5°C in mean global temperature on soil moisture regimes and to analyze the implications for the different ecosystems of the country.

2. Methods

2.1 Soil moisture regimes of Mexico

The study was divided into three parts. First, the authors determined the soil moisture regimes with the database of mean monthly precipitation and temperature of the 594,995

areas of climatic influence (ACI) developed by [Gomez-Diaz et al. \(2011\)](#) at a scale of 1:250,000 and for the period of 1970-2000. The second part consisted of estimating the ratios of mean air temperature and mean monthly precipitation for the climate change scenarios associated with an increase in mean global temperature of 1.5°C for the country and applying them to the databases of ACI averages and then determine the soil moisture regimes for the climate change scenario. The third part relates to the different vegetation types of the country and the soil moisture regimes for current conditions and for climate change.

The soil moisture regime was determined using the Newhall simulation model modified by [Van Wambeke \(2000\)](#), which is programmable and allows various soils to be classified at the same time. The Newhall simulation model considers soil to be a water reservoir that extends from the surface down to the depth of an available water holding a capacity of 200 mm or the specific value according to the soil thickness. Water may be incorporated into the soil through rainfall; however, it may be lost by leaching or runoff if the retention capacity of the soil is exceeded or it may be removed by evapotranspiration. The model estimates evapotranspiration with the procedure established by [Thornthwaite](#) using data on average monthly temperature and duration of insolation ([Newhall and Berdanier, 1996](#)). The soil moisture regime is determined by moisture conditions in the moisture control section (MCS) over a period of one year or more. Moisture conditions of the MCS, in turn, are determined from moisture states of the entire soil moisture profile. The computer model calculates three moisture states per month from monthly precipitation and normal monthly potential evapotranspiration (PE) for each month of the selected climatic record ([Newhall and Berdanier, 1996](#)).

The database generated for all the ACI in Mexico was used for conditions of average monthly temperature and rainfall and duration of insolation was associated with the latitude of different places and data from the MCS of each of the soil classes of Mexico reported by the National Institute of Statistics and Geography ([INEGI, 2006](#)). The description of the groups and subgroups of soil moisture regimes is given in [Table I](#).

The soil moisture regimes of Mexico are related to different types of vegetation and land uses reported by [INEGI \(2017\)](#) in the land use and vegetation series VI. The digital map with information on vegetation types and land use was overlaid onto each soil moisture regime map for the current conditions and for each of the climate change scenarios of the study and changes in the soil moisture regimes for each of the land uses and vegetation was estimated.

2.2 Scenarios of climate change

For the climate change scenarios associated with an increase in mean global temperature of 1.5°C, two *Representative Concentration Pathways* (RCPs) of 4.5 and 8.5 W/m² were considered. The scenarios were determined using three general models of atmospheric circulation, namely, GFDL, HADGEM and MPI. The models were selected because they have been used in other studies in Mexico: in third, fourth and fifth national communications to the UNFCCC ([INE, 2006, 2012; SEMARNAT, 2009](#)); in national studies ([Conde et al., 2011](#)) or in sectorial studies ([Gomez-Diaz et al., 2011; Monterroso-Rivas et al., 2011](#)). In all cases, the models have shown good performance in the country and have had comparable results.

The models were provided by the Atmospheric Sciences Center of the National Autonomous University of Mexico and its scale was converted to a 0.5°. From the basic geographic unit used in this study, ACI, the center of the polygon (centroid) was calculated for each of the 594,994 ACIs throughout the country. From the geographic position of each centroid, model information for each polygon was extracted by applying the change ratio for each scenario to the mean monthly precipitation and temperature, with which the moisture regimes were determined in each polygon of the country using the Newhall simulation model.

Soil moisture regimes	Description
Aridic	The MCS is, in normal years moist in some or all parts for less than 90 consecutive days when the soil temperature at a depth of 50 cm below the soil surface is above 8°C
Extreme Aridic	The MCS is completely dry during the whole year
Typic Aridic	The MCS is moist in some or all parts for 45 consecutive days or less during the period that the soil temperature at 50 cm depth is more than 8°C
Weak Aridic	The MCS is moist in some or all parts for more than 45 consecutive days, but less than 90 consecutive days during the period that the soil temperature at 50 cm depth is more than 8°C
Xeric	The MCS is, in normal years, dry in all parts for 45 or more consecutive days in the 4 months following the summer solstice and moist in all parts for more than 45 or more consecutive days in the 4 months following the winter solstice. It is the typical moisture regimen in areas where winters are moist and cool and summers are warm and dry
Dry Xeric	Soils with xeric moisture regimes, which the MCS is dry in all parts for more than 90 consecutive days during the four months following the summer solstice
Typic Xeric	Other soils with xeric moisture regimes
Ustic	The Ustic soil moisture regime is intermediate between the Aridic regime and the Udic regime. The MCS is dry in some or all parts for 90 or more cumulative days in normal years. It is moist, however, in some part either for more than 180 cumulative days per year or 90 days or more consecutive days. If in normal years the MCS is moist in all parts for 45 or more consecutive days in the 4 months following the winter solstice, the MCS is dry in all parts for less than 45 consecutive days in the 4 months following the summer solstice
Aridic Tropustic	Soils with an Ustic moisture régime and iso-temperature regime with less than 180 consecutive days that the MCS is completely or partly moist when the soil temperature at 50 cm depth is more than 8°C
Typic Tropustic	Soils with an Ustic moisture régime and iso-temperature regime with 180 or more, but less than 270 consecutive days that the MCS is completely or partly moist when the soil temperature at 50 cm depth is more than 8°C
Udic Tropustic	Soils with an Ustic moisture régime and iso-temperature regime with 270 or more consecutive days that the MCS is completely or partly moist when the soil temperature at 50 cm depth is more than 8°C
Xeric Tempustic	Soils with an Ustic moisture régime and without iso-temperature regime in which the MCS is dry in all parts for more than 45 consecutive days during 4 months following the summer solstice, and where the MCS is moist in all parts for more than 45 consecutive days during 4 months following the winter solstice
Typic Tempustic	Soils with an Ustic moisture régime and without iso-temperature regime where the MCS is dry in some or all parts for more than 45 consecutive days during 4 months following the winter solstice, and where the MCS is moist for more than 45 consecutive days during 4 months following the summer solstice
Wet Tempustic	Soils with an Ustic moisture régime and without iso-temperature regime where the MCS is moist in all parts for more than 45 consecutive days during 4 months following the winter solstice, and where the MCS is not completely dry for more than 45 consecutive days during 4 months following the summer solstice
Udic Dry Tropudic	The soil MCS is not dry in any part for as long as 90 cumulative days in normal years Soils with a Udic moisture regime in which the MCS is dry in some or all parts for 30 or more cumulative days and with an iso-temperature regime
Dry Tempudic	Soils with a Udic moisture regime in which the MCS is dry in some or all parts for 30 or more cumulative days and without an iso-temperature regime
Typic Udic	Soils with a Udic moisture regime in which the MCS is dry in some or all parts for less than 30 cumulative days
Perudic	The MCS is not dry in some or all parts for less than 30 cumulative days and usually is completely moist

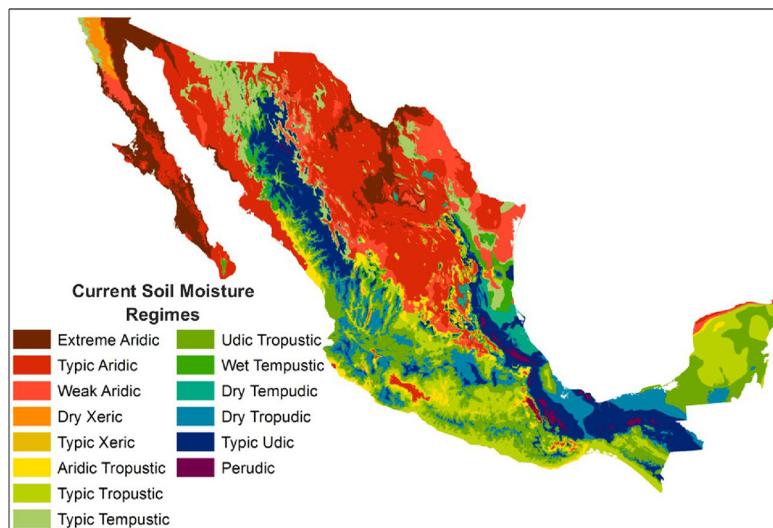
Table I.
Classes of soil
moisture regimes

Source: van Wambeke (1982)

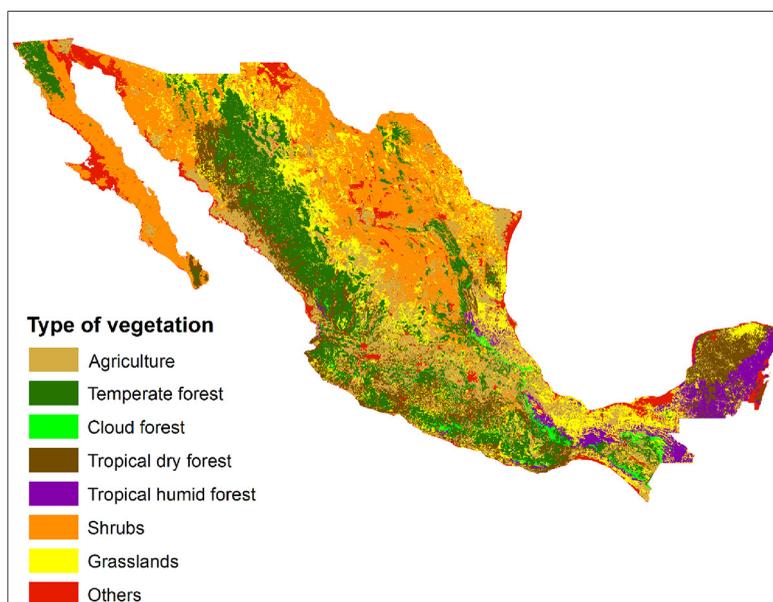
3. Results and discussion

3.1 Soil moisture regimes in Mexico in current conditions and land use and vegetation types

The geographic distribution of the current soil moisture regimes of Mexico is shown in Figure 1(a). Of the total area of the country (196,437,500 ha), 38.8 per cent of the soils has an Aridic moisture regime (Table II), of which 7.1 per cent corresponds to the subgroup



(a)



(b)

Figure 1. Soil moisture regimes under current conditions (a) and current vegetation types and land uses (b) of Mexico

Extreme Aridic, where the soil moisture control section is completely dry during the entire year. It is largely associated with the hyper-arid and arid climate areas delimited by [Gomez and Monterroso \(2012\)](#) following the criteria of the United Nations Convention to Combat Desertification, which are based on the aridity index and PE estimated by the Thornthwaite method. Within this regime, the largest proportion (23.9 per cent) of soils was Typic Aridic, and the subgroup Weak Aridic represents 7.8 per cent; the latter two subgroups are associated with areas of semiarid climate delimited by [Gomez and Monterroso \(2012\)](#).

The Xeric regime represents less than 1 per cent of the country and is dominated by the Dry subgroup. It is mostly located in the northwest on the Baja California peninsula.

The Ustic regime occupies 36.4 per cent of the area and is associated with the subhumid climates. Of this area, 28.0 per cent corresponds to the Tropustic subgroups, which are located mainly south of the Tropic of Cancer and in the coastal regions at latitudes above the Tropic of Cancer, where the difference between average summer and winter temperatures is less than 6°C. The Tempustic subgroup accounts for 8.4 per cent of the area, associated mainly to subhumid climates located in the continental areas north of the Tropic of Cancer, where average summer and winter soil temperatures differ by 6°C or more. The 3.1 per cent of the area corresponds to the subgroup Aridic Tropustic, the driest of this group, and is associated with marginally dry subhumid to semiarid climates. The Typic subgroups of this regime (Typic Tropustic and Typic Tempustic) account for 17.4 per cent of the area in Mexico; these subgroups are mainly associated with the subhumid climates of the country. The wettest subgroups of this regime are Udic Tropustic and Wet Tempustic, representing 15.9 per cent of the country's area; these regimes are associated with the more humid of the subhumid climates and also with the humid climates that have one dry period during the year.

The Udic soil moisture regime represents 24.1 per cent of Mexico's territory and are associated with the humid climates of the country. Of this area, 9.9 per cent corresponds to the subgroups that experience a short period of moisture deficit (Dry Tropudic and Dry Tempudic). The subgroup with low moisture deficit during the year is Typic Udic, which covers 13.5 per cent of the area of Mexico and are found in humid climate regions with very little moisture deficit throughout the year. Finally, the areas where water moves through the soil all year round and never freezes are Perudic, representing 0.7 per cent of the area of Mexico.

[Figure 1\(b\)](#) shows the distribution of the eight types of vegetation grouped in the Mexican land use and vegetation series VI ([INEGI, 2017](#)). Agricultural land is 16.8 per cent of the total area. Temperate forests include pine, oak and pine–oak forests and cover 16.9 per cent of the country's total area, almost half of which is moderately to highly perturbed. Cloud forest covers only 1 per cent of the area, but it is very important because of the great biodiversity it contains; three-fourths is moderately to highly perturbed. Tropical dry forests occupy 10.4 per cent of the country; two-thirds are moderately to highly perturbed. Tropical rain forests cover 5.4 per cent of the country and two-thirds are moderately to highly perturbed. Scrub vegetation comprises 27.6 per cent of the country's area; here desert microphyll and rosetophyll scrub predominate. Grasslands account for 16.1 per cent of the total area; two-thirds are induced or cultivated grasses. The group of Other land uses, which includes several types of vegetation, bodies of water and urban and rural areas defined as human settlements, represents 5.9 per cent of the country's area: 0.9 per cent is human settlements, 0.8 per cent is bodies of water, 1.5 per cent is halophyte vegetation, 1.2 per cent is sand desert vegetation and the rest is other types of vegetation such as palms, coastal dune vegetation and mangroves, among others.

3.2 Soil moisture regimes analysis

Table II details the areas and percentages of the different soil moisture regimes of Mexico for a 1.5°C increase and the RCP 4.5 and 8.5 W/m² estimated with the three models considered in this study.

The HADGEM and MPI models predict that in almost the entire country there will be a considerable soil water deficit and part of the areas of each moisture regime will shift to the next drier regime, in greater proportion for the HADGEM model. The GFDL model presents this trend, but in lower proportions; this is the model that estimates the smallest changes in the soil moisture regimes of Mexico. There are considerable differences in the area of the soil moisture regime subgroups among the three models under study. The GFDL model in the RCP of greater radiative force estimates a decrease in the area with greater water stress (Extreme Aridic), with increments in areas of the intermediate moisture regimes (Ustic) and a decrease in the area of the moistest regimes (Udic). The HADGEM model estimates an increase in the area of the subgroup with greater water stress (Extreme Aridic) and the Ustic and Udic regimes become drier with an increase in the deficit of available moisture. The MPI model presents a situation similar to that of the HADGEM model but with smaller reductions in the wettest regimes (Udic). The variations between the two RCP are small.

It is important to note that these results should be considered plausible projections of climate change in Mexico. In general, there is a marked increasing trend in soil moisture stress in Mexico, with a decrease in the wettest soil moisture regimes (Udic), which become intermediate humidity regimes (Ustic), while a portion of the Ustic regimes shifts to Aridic as the severe moisture restrictions increase. The estimated dates in which the mean global temperature increase of 1.5°C will occur are 2053 for the 4.5 W/m² RCP and 2042 for the 8.5 W/m² RCP (Gay and Sanchez, 2017). Temperature increases are different in different regions of the country (Figure 2). The GFDL model in the 4.5 RCP, estimates the smallest increase for the Yucatán Peninsula with values of 1.1°C-1.3°C and the largest increase is in the north, from the Gulf of Mexico coast to the Gulf of California, with values of 1.9°C-2.2°C. For the 8.5 RCP, the smallest increase is also for the Yucatán Peninsula with values of 1.7°C-1.9°C and the largest increases are also in the north with values from 2.5°C to 2.7°C [Figure 2(a)]. The HADGEM model estimates the largest temperature increases of the three models. For the 4.5 RCP, the smallest increases are for the southern part of the Baja California Peninsula with 1.4°C and the largest for northern Mexico with values of 2.1°C-2.4°C. For The 8.5 RCP, the smallest increases are also for southern Baja California Peninsula with 1.8°C and the largest increases in the north with 2.7°C-3.2°C [Figure 2(b)]. Model MPI in the 4.5 RCP predicts the smallest increase for the southern part of the Baja California Peninsula with values of 1.2°C and the largest in the northern part of the country with values of 1.8°C-2.1°C. For the 8.5 RCP, the smallest increases are also for southern Baja California with values of 1.4°C and the largest in the north with 2.2°C-2.4°C [Figure 2(c)].

Figure 3 presents the precipitation anomalies. The GFDL model in both RCP estimates that the precipitation will increase in most of the country including the Yucatán Peninsula, the south-southeast, the central part of the county and the northwestern coast. However, for the north-central and northeastern parts of the country, it estimates decreases in precipitation; the increases and decreases are larger in the RCP of greater radiative forcing for these regions [Figure 3(a)]. The HADGEM model estimates reductions in precipitation in most of the country except for the Baja California Peninsula, the southern part and areas of the central part of the country. The decrease will be greater in the 8.5 RCP [Figure 3(b)]. The MPI model estimates increases in precipitation in both RCP for the central part of the country, the southeast, and the Yucatán peninsula, while for the rest of the country, it estimates a decrease in precipitation [Figure 3(c)]. Moreover, the estimated increases and

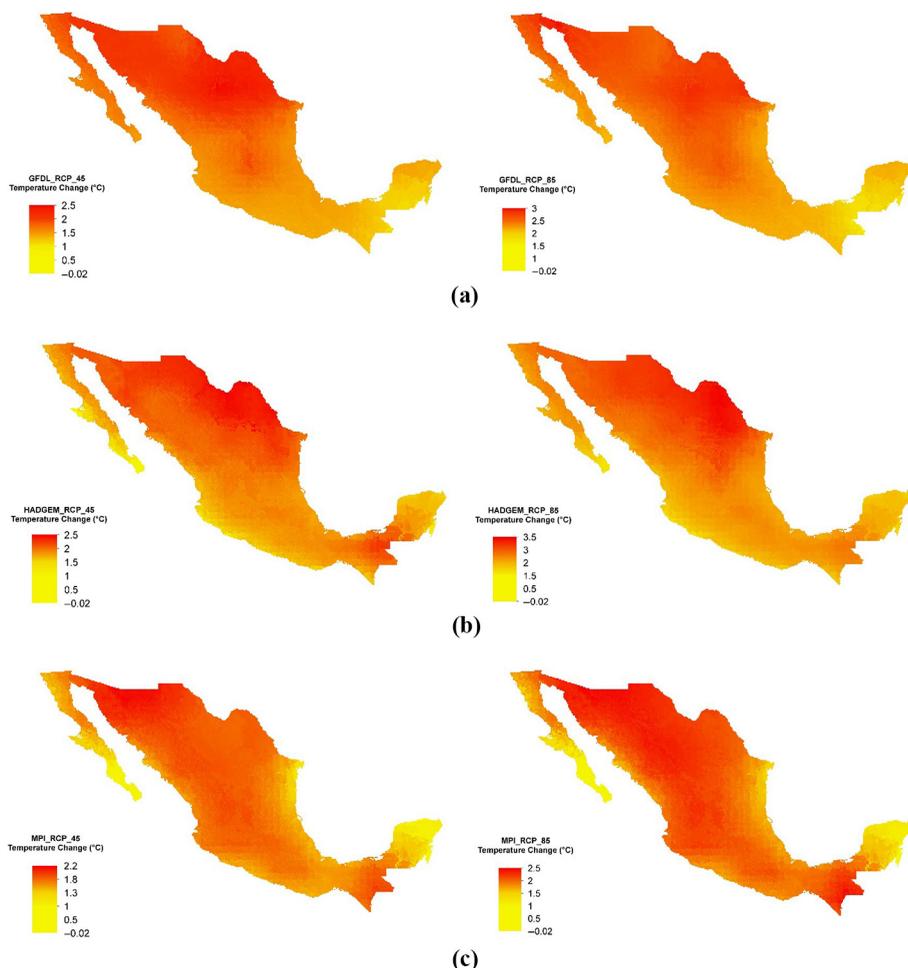


Figure 2. Changes in mean annual temperature for Mexico with an increase of 1.5°C in global mean temperature for the 4.5 and 8.5 W/m² RCP estimated with the models GFDL (a), HADGEM (b) and MPI (c)

decreases are larger for the 8.5 RCP, but the increase in precipitation is smaller than those estimated by the GFDL model for these regions.

The results regarding the increase in temperature and changes in precipitation are in agreement with the IPCC (2014) report for North America in which the CMIP5 assembly projects estimate that the temperature increases in the 8.5 RCP for Canada, the USA and Mexico will be above 2°C in most of the area of the three countries by the middle of the twenty-first century and will be more than 4°C by the end of this century with larger changes at higher latitudes of the region and small increases for southern Mexico. Moreover, it reports that in most of Mexico and part of southwestern and south-central US precipitation will decrease as of the mid-twenty-first century and will continue to decrease until the end of the century. Decreases will be greater in higher radiative forcing, and thus, most of Mexico will have an increase in the number of consecutive dry days (Sillmann *et al.*, 2013).

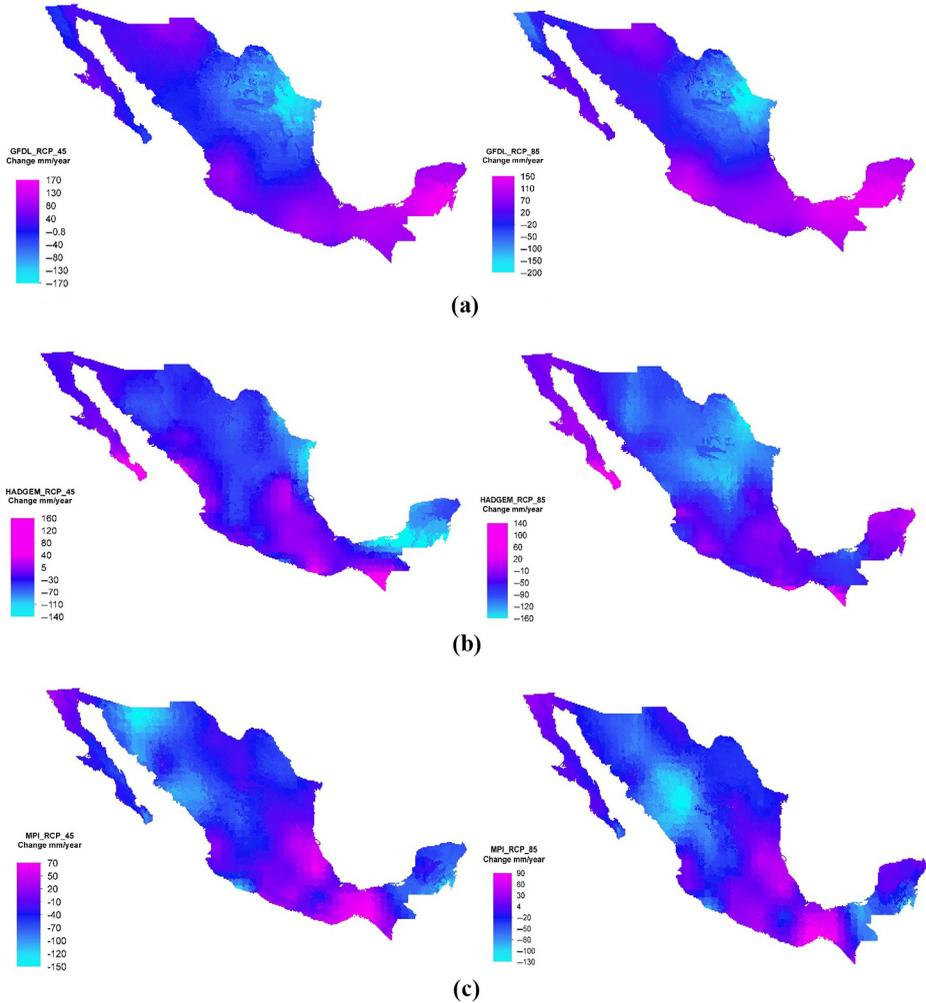


Figure 3. Changes in mean annual precipitation for Mexico with an increase of 1.5°C in mean global temperature for the 4.5 and 8.5 W/m² RCP estimated with models GFDL (a), HADGEM (b) and MPI (c)

The GFDL model estimations of increase in precipitation in most of the country fit those reported by the [Soil and Water Conservation Society \(SWCS\) \(2003\)](#) in a study of the implications of climate in soil erosion and runoff from farmland in the USA. This report has also projected that globally averaged temperature and intensity of rainfall events will increase in the future with increased greenhouse gases. Other simulation studies with GCM estimated that mean annual soil moisture will decrease in the near future (2012-2040) in California, NV, the Colorado River basin and Texas ([Seager et al., 2013](#)), which are regions that share climate systems with which precipitation and temperature conditions are associated in northern Mexico.

Many studies have investigated the responses of soil moisture to recent or future climate change ([Seager et al., 2013](#); [Yang et al., 2011](#); [Peng et al., 2017](#)) and the results revealed that

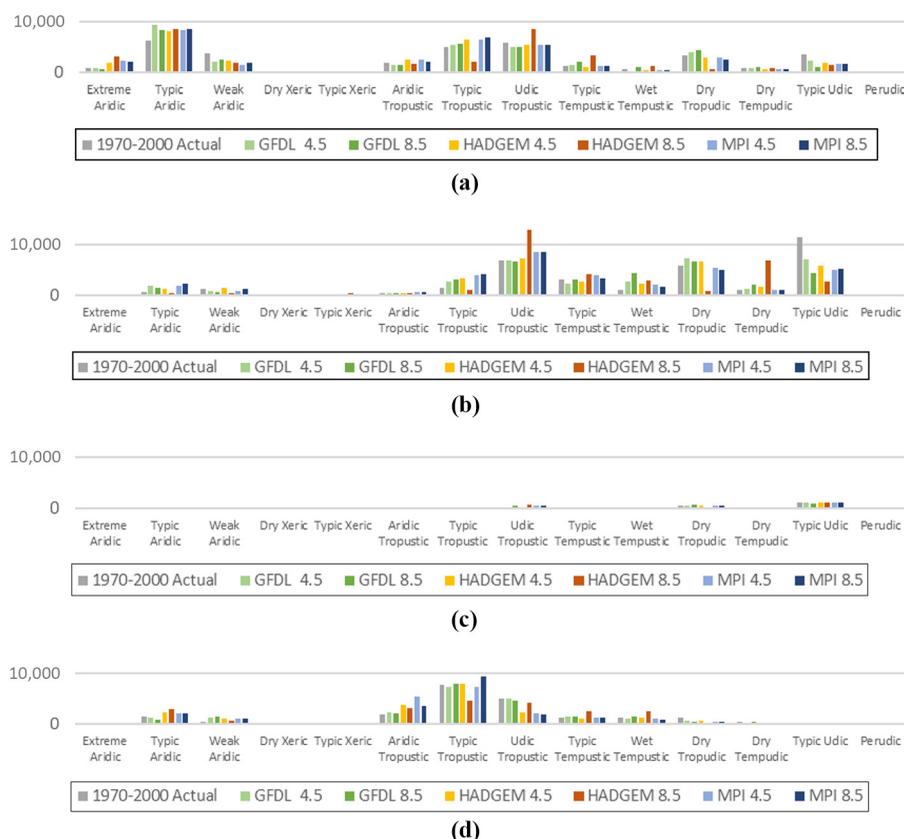
the annual mean soil moisture would decrease in the near future for some regions and increase for others. In the case of this study for Mexico, decreasing soil moisture dominates.

Physical impacts associated with climate change include altered precipitation regimes, a strong increase in heat extremes, higher risks of droughts and increasing aridity (Reyer *et al.*, 2017), situations that would increase the risk of wind erosion (Asensio *et al.*, 2015). Moreover, the mean intensity of tropical cyclones that can affect the country and the frequency of the more intense storms, is projected to increase (Knutson *et al.*, 2010). This trend toward precipitation occurring in more extreme events will increase soil erosion because most soil loss is caused by infrequent severe storms (Edwards and Owens, 1991).

3.3 Changes in soil moisture regimes for the different types of land use and vegetation

Figure 4 shows graphically the area of soil moisture regimes for the different types of vegetation land use under current conditions and with an increase of 1.5°C in mean global temperature for the two RCP and with the three models studied.

3.3.1 Agriculture. In the current conditions, 5.4 per cent of the country's total area with farmland use has an Aridic regime, 2 per cent of which is irrigated. The Ustic regime is 5.8 per cent and the Udic regime is 4.8 per cent. The GFDL model estimates an increase in the



(continued)

Figure 4. Area (thousands of hectares) of the soil moisture regimes for the different vegetation types and land uses in the current conditions and with an increase of 1.5°C in mean global temperature for the 4.5 and 8.5 W/m² RCP estimated with the GFDL, HADGEM and MPI models

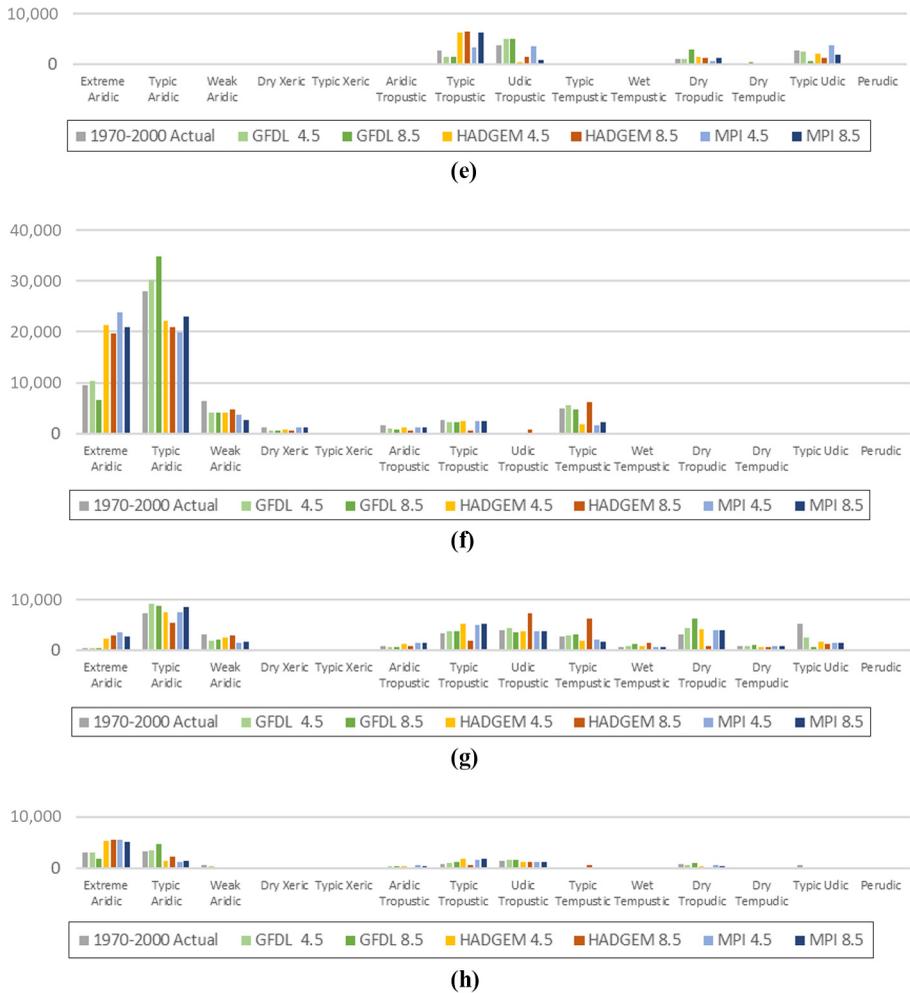


Figure 4.

Notes: Agriculture (a): Temperate forest (b): Cloud forest (c): Tropical dry forest (d): Tropical rainforest (e): Shrubs (f): Grasslands (g):Other land uses (h)

area with Aridic soil moisture regime for the two RCP, particularly in the Typic Aridic regime. Moreover, there will be a slight decrease in Ustic regimes in the 4.5 RCP and an increase in the 8.5 RCP, while the area with a Udic regime will decrease for the two RCP. The HADGEM and MPI models estimate increases in the area with Aridic and Ustic regimes and a decrease in the Udic regimes for the two RCP, but in a larger proportion in the 8.5 RCP.

3.3.2 Temperate forest. Of the area of the country with this type of vegetation, 6.5 per cent has a Ustic regime and 9.4 per cent has a Udic regime. In the current conditions, 0.9 per cent of the country's area has an Aridic regime, in the two less dry subgroups that support mainly oak forest communities. The Xeric regime is 0.1 per cent of the area and supports the pine-oak forest.

The area with the Aridic regime increases, according to the three models in both RCP. For the Ustic regime, the three models predict an increase, while the Udic regime decreases; the HADGEM model predicts these occurrences in greater magnitude.

3.3.3 Cloud forest. This type of vegetation is found only in Ustic and Udic soil moisture regimes. For the current conditions, the proportion is 0.1 per cent Ustic and 0.9 per cent Udic. The three models predict a slight increase in the area of Ustic moisture regimes arising from the area of Udic moisture regime in both RCP.

3.3.4 Tropical dry forest. In the current conditions, for this type of vegetation, 1.0 per cent of the country's area has an Aridic regime, in the two less dry subgroups. Also, 8.6 per cent with the Ustic regime and 0.9 per cent with the Udic regime. The three models predict increases in an area with Aridic regime in both RCP. The area with Ustic moisture regime does not change in the MPI model in either of the RCP or with the GFDL model, in 4.5 RCP it does not change, but increases in the 8.5 RCP. The HADGEM model predicts a slight reduction in area in both RCPs. The area with Udic regime decreases, according to the three models, and in greater proportion in the HADGEM model in the 8.5 RCP.

3.3.5 Tropical rainforest. Under this type of vegetation, in current conditions, 3.3 per cent of the country's area has a Ustic regime, most is Udic Tropustic, while 2.2 per cent has a Udic regime. The three models predict increases in the area of Ustic regime and a decrease in the area with a Udic regime in both RCP, while the HADGEM model estimates the same, but in a larger proportion in 8.5 RCP.

3.3.6 Shrubs. In the current conditions, 22.3 per cent of the country's area covered with shrub vegetation has an Aridic regime. In the Extreme Aridic and Typic Aridic regimes desert microphyll shrub – rosetophyll and sarcocaulis shrub – predominate. In the Weak Aridic regime desert rosetophyll shrub, desert microphyll shrub and Tamaulipas spiny shrub vegetation predominate. The Xeric regime, 0.6 per cent of the area of the country, supports mainly chaparral vegetation. The Ustic regime, 4.7 per cent of the country, has submontane shrub with some areas of desert rosetophyll shrub in the driest subgroup of this regime. The area with Aridic moisture regime will increase, according to the three models in both RCP. The HADGEM and MPI models predict that the area of Extreme Aridic will double. The area with the Xeric moisture regime will decrease slightly according to the GFDL and HADGEM models for both RCPs. The MPI model predicts no change in this regime for the 4.5 RCP but predicts increases for 8.5 RCP. In the case of the Ustic moisture regime, the three models predict a decrease in area.

3.3.7 Grasslands. In the current conditions, grasslands cover 5.4 per cent of the country with an Aridic regime and they are located mainly in the two least dry subgroups. In Extreme Aridic halophyte grasses predominate, while in the Typic Aridic regime there are natural and halophyte grasses, and natural grasses in Weak Aridic. In the Xeric regime, the area with this type of vegetation is insignificant. In the Ustic regime, 5.8 per cent of the country's total area, natural and induced grasses predominate. In the Udic regime, 4.8 per cent of the country, mainly induced grasses have replaced areas with tropical rainforest and are now used for livestock grazing. The three models predict increases in the area with the Aridic regime in both RCP, with considerable increases in Extreme Aridic, according to the HADGEM and MPI models. There will be an increase in the area of grasslands in the Ustic regime, according to the three models in both RCP, and the area with the Udic regime will decrease, in greater proportion in 8.5 RCP predicted by the HADGEM model.

3.3.8 Other types of land use and vegetation. In current conditions, 3.6 per cent of the country's area with other land uses and vegetation have Aridic moisture regimes. In the Extreme Aridic and Typic Aridic xerophyll halophyte vegetation and sandy desert, vegetation is predominate, and there are areas with no vegetation. The area with Ustic soil

moisture regime is 1.5 per cent; here, palm plantations and urban areas predominate. The areas with a Udic regime is 0.8 per cent and are also mainly urban areas. For the areas with this land use and with Aridic regime, the three models do not predict changes for 4.5 RCP, but HADGEM model for 8.5 RCP predicts an increase. Areas with a Ustic regime increase and areas with a Udic regime decrease, according to the three models and the two RCP.

The impact of climate change on the ecology is very difficult to evaluate because of the large number of interrelated factors involved (Markham, 1996). However, focusing on one of the relevant factors, such as the changes in soil moisture at a regional scale, is considered an important advance (Naden and Watts, 2001). Studies such as those presented here that reveal the impacts of climate change on specific changes in one of the soil properties and that indicate where the changes will occur contribute to the knowledge of the vulnerability of soils to climate change (Blum, 2005). These estimations are vital in establishing the impacts on agricultural productivity and of natural ecosystems (Kim and Wang, 2012; Seager *et al.*, 2013).

As the biomass production depends directly on the climatic conditions and soil water availability (Sinclair *et al.*, 2005), the increase in soil water stress will reduce agricultural and livestock yields, and also, species range shifts will threaten terrestrial biodiversity (Mantovani *et al.*, 2013). There is also a substantial risk of degradation of the country's natural and managed systems with continuing warming. Thus, determining changes in soil moisture are vital for assessing the impacts of climate change on agricultural production and natural ecosystems (Chamizo *et al.*, 2015; Mirelles *et al.*, 2002; Kim and Wang, 2012).

Several studies have concluded that the increase in soil temperature will have profound effects on soil processes, among which is the activity of the soil heterotrophic community. Consequently, it will impact turnover rates of C contained in soil organic matter and N mineralization rates, which increase in soils that have more available moisture and decrease in dry soils (Briones *et al.*, 2009; Harte *et al.*, 1996; Eastburn *et al.*, 2011; Pritchard, 2011). The three models of this study estimate a general increase in water stress associated mainly with increased temperature, which increases evapotranspiration. The models, except for the GFDL, estimate a reduction in precipitation in most of the country. For this reason, the scenario is one of higher temperature and lower available moisture, and thus, the activity of the soil heterotrophic community could decrease in most of the regions. However, soil organisms and the communities that are adapted to withstand wide fluctuations in temperature and available moisture in the current climate is unlikely to be significantly affected by climate change, in contrast with soil systems that have evolved in more stable environmental conditions (Pritchard, 2011). In this way, changes in available moisture and increases in temperature will directly affect the soil food web and will also affect soil organisms indirectly by altering the development of plant communities (Pritchard, 2011).

4. Conclusions

Temperature increments are different in different regions of the country, with higher values in the north and lower in the south and on the Baja California Peninsula. Moreover, the values differ depending on the general model of atmospheric circulation and the RCP: lower increments estimated by the GFDL model and higher by the HADGEM and MPI models, which also estimate larger increases in 8.5 RCP.

Precipitation anomalies are also different for the three models, but the pattern that was estimated is of increase in precipitation in the south and decrease in the north. The GFDL model in both RCP estimates the largest increases in precipitation and in a larger proportion of the country's area. The HADGEM and MPI models estimate greater reductions in precipitation in most of the country that are more accentuated according to the 8.5 RCP.

When temperature increases, it was observed an increase in soil moisture loss (evapotranspiration) that is associated with a reduction in precipitation, a considerable increase in water stress will occur in the soils of Mexico. This is because the soil moisture regimes of a region shift from a wet (Udic) to a transitional soil moisture regime (Ustic) or from a transitional to a dry soil moisture regime (Aridic). Of this regime, the area of the subgroup with greater moisture restriction increases.

These results related to changes in soil moisture regimens provide an indicative tool to be used in conjunction with knowledge of other factors in considering the potential future climatic limitations on, and opportunities for, ecological conservation and change. They also provide a base for developing strategies for adaptation to climate change that includes practices that favor preserving soil moisture and prevent its loss. In agricultural soils, for example, practices such as better growing periods identification considering optimal soils moisture conditions, conserving moisture with crop residues or even preventing the incidence of pests or diseases. In forest soils, all strategies for vegetation conservation and ecosystem rehabilitation should be strengthened. It is possible to design local actions always based on knowing the impact of climate change on soil moisture. It is urgent that local production plans include the risk of change in soil moisture, considering the potential changes and their implications in crop production or even in economic losses. Farmers, merchants, local politicians and non-governmental organizations can benefit from the results of promoting similar research.

Under these scenarios, the risk of land degradation will be far higher than present expectations, becoming a challenge for global ecosystems. Strict management and rational use of water resources are required and restoration of soil and vegetation to reduce ecosystem vulnerability. For this reason, plans of action are urgently needed.

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