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Article

Environmental suitability areas for [*Bouteloua curtipendula* (Michx.) Torr.] in Mexico due to climate change effect

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Abstract:

The grasslands are exposed to climate change effects that will be observed along the next decades. This will change the plant communities, modifying in turn the services and products supplied by these areas. The influence of the climate as a primary productivity determinant for ecosystems has led to research on the impact of climate change on plant communities with the use of simulation models. The species of *Bouteloua* genus are among the most important ones in Mexico's grasslands due to their quality as forage for livestock and their ecological characteristics —the most prominent being the sideoats gramma [*Bouteloua curtipendula* (Michx.) Torr.]—. The objective was to analyze the areas with environmental suitability for *B. curtipendula* as an effect of climate change in Mexico. The reference and the future climate were analyzed through the General Circulation Models (GCM) HadGEM and GFDL, with the RCP4.5 and RCP8.5 for the period 2041-2060 and 2061-2080; for the niches of potential distribution modelling, georeferences from 407 collection sites and 29 environment variables were used with the MaxEnt model. Both GCMs predict that the potential area for *B. curtipendula* will experience an initial decrease of 3.1 to 14.4 %, although later it will recover and even reach an increase of 1.4 %. The annual temperature, the May to October precipitation, and the December to April moisture index, were the main environmental variables accounting for the potential distribution of the species.

Key words: *Bouteloua curtipendula*, Environmental suitability, Descriptors, Ecological niche, MaxEnt, General circulation models, Climate change.

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Introduction

The grazing area in Mexico covers more than 45 % of the national territory, with a larger proportion in the northern region of the country where it reaches 70 %(1). However, these grassland areas are exposed to the effects of changing climate conditions that will occur in the following decades according to various studies, bringing about changes in plant communities, as well as the products and services they provide(2,3). The influence of climate as a determinant of primary productivity of ecosystems has led to studies in order to assess the impact of climate change on plant communities using simulation models. Some studies carried out in Mexico have shown that the ambient temperature will increase between 1.8 and 4.5 °C during the period 2040-2100, while the precipitation will decrease from 2 to 12 %(4,5,6).

The species of the genus *Bouteloua* are some of the most important ones in the grasslands of Mexico, due to their forage quality and their ecological characteristics, among which the grass known as sideoats gramma [*Bouteloua curtipendula* (Michx.) Torr.] is prominent; this species has been included in some programs for the improvement of pastures, due to its outstanding features as fodder, and improved varieties have been released in Mexico(7,8) and in the United States(9). In addition, *B. curtipendula* has a wide variability of the polymorphism that could give it an advantage in terms of adaptability to the effects of climate change(10).

Some studies have reported that the structure of the plant communities depends largely on the weather conditions, among which the precipitation and the temperature stand out as determinants(11,12,13); at the same time, it has been found that chronic drought strongly reduces the coverage of grasses while it increases the coverage of shrub species in some areas of the Chihuahuan Desert(13).

Other results[14] show that there is little evidence that changes in precipitation will influence the competitive effects of individual plants in a grassland area with dominance of *Bouteloua curtipendula*, *Bouteloua hirsuta* and *Schizachyrium scoparium*, and that their intraspecific and interspecific interactions are what can modify the colonization of spaces with inadequate agro-ecological characteristics. The objective of this research was to analyze the areas with environmental suitability for *B. curtipendula* by effect of climate change in Mexico; using two general circulation models (GCM) under the representative concentration pathway of greenhouse gases (RCP4.5 RCP8.5) for the periods 2041-2060 and 2061-2080.

Material and methods

Databases and environmental information systems

The research was based on the analysis of data of the baseline climate and modeling of future climates, obtained from the Global Climate Data portal of WorldClim.org. The data for the 1950-2000 period were used for the reference climate, and the data utilized for the future climate were those corresponding to the periods 2041-2060 and 2061-2080, henceforth referred to as periods 2050 and 2070, respectively, with a spatial resolution of 30 arc seconds[15].

The HadGEM-IS and GFDL-CM3 GCMs were utilized; the first was selected because one of the variables it considers is the vegetation type and includes the native grassland as part of the vegetation cover of the planet[16]; the second, because version CM3 not only includes emerging issues of climate change but also has an improved spatial resolution and pays special attention to the simulation of precipitation in tropical areas[17]. The simulation utilized representative concentration pathways (RCP) of greenhouse gases[18] 4.5 and 8.5 to analyze a low and a high scenario; the RCP2.6 was not used because the trends show that this scenario is hard to achieve[19]. The weather data were processed by the ArcGIS software; maps with climate and bioclimate variables were subsequently generated using the Idrisi Selva software and were utilized to analyze the areas with environmental suitability for *B. curtipendula* with Maximum Entropy Species Distribution Modeling (MaxEnt).

Potential distribution of *B. curtipendula*

The following adjustments were made in order to run the MaxEnt model: use of 25 % of the data for testing, the test 10 replications with cross-validation, and a maximum of 2,000 iterations. These adjustments used 410 geo-referenced data obtained from four sources: (a) direct collection, (b) collection from other researchers, (c) data contained in the herbarium specimens of the Biology Institute of the University Center for Biological and Agricultural Sciences of the University of Guadalajara, and (d) collections' data published on the website of the Global Biodiversity Information Facility[20].

The environmental variables utilized were: annual precipitation, May-October precipitation, November and April precipitation, December-February precipitation, precipitation in the wettest month, precipitation in the driest month, maximum annual temperature, maximum temperature May-October, maximum temperature between November and April, mean annual temperature, average temperature in May-October, average temperature in November-April, average temperature of the warmest month, average temperature of the coldest month, annual minimum temperature, minimum temperature in May-October, minimum temperature in November-April, May-October photoperiod, November-April photoperiod, annual humidity index, May-October humidity rate (estimated as the ratio of precipitation to evapotranspiration), November-April humidity rate, December-February humidity rate, annual thermal oscillation, May-October thermal oscillation, November-April thermal oscillation, December-February thermal oscillation, and soil texture.

Areas with probability of environmental suitability

The model for the prediction of areas with environmental suitability for *B. curtipendula* obtained with MaxEnt was used with the Idrisi system 17.0[21] with the generated a map with the threshold values corresponding to the 10^{th} percentile[22]. For the calculation of the surface with environmental suitability of the species, the areas occupied by the bodies of water and urban centers were not considered; these thematic layers were obtained by means of the use of the soil chart and the vegetation[23].

Fit of the model

The ecological niche model employed by MaxEnt predicts the rate of occurrence (Receiver operating characteristic, ROC) of the species as a function of the environmental predictors in each locality[24] represented by each cell of the mesh of approximately 900 x 900 m in the geographic scale of 30 arc sec.; in turn, the area under the curve (AUC) can be interpreted as the fit of the model, in which a value of 1.0 would be a perfect classifier and a random classifier would have a value of 0.5[25]; therefore, the values close to 1.0 show greater fit of the model to the data.

Results and discussion

Analysis of the potential distribution niche

The average AUC values obtained for baseline climate and climate change scenarios were higher than 0,933 in all cases (Table 1), which is why the data obtained are considered to have a high degree of reliability in assessing the environmental suitability for *B. curtipendula*(24,25). These results agree partially with those of a research conducted in grasslands of United States(26), where the analysis for *B. curtipendula* with 1,251 sampling data reflects a value of the AUC of 0.946; the higher value of the AUC of this study may be due to the use of a greater number of geographic references. On the other hand, in the 10 replicas of the model used in this investigation it was found that the lowest value of AUC was of 0.915 to a high of 0.976, the standard deviation was <0.013 in all cases; therefore, the results are believed to be reliable. Because both GCMs yielded similar data in the prediction of areas with potential suitability, subsequent investigations may use either one of them.

Table 1: Average values of the area under the ROC curve, obtained in 10 replications, and average standard deviation, in the analysis of potential distribution of *Bouteloua curtipendula* in Mexico

GCM	Average AUC	Higher AUC	Lower AUC	Standard deviation
Reference climate	0.934	0.955	0.920	0.011
GFDL-CM3 RCP4.5 2050	0.933	0.953	0.915	0.011
GFDL-CM3 RCP4.5 2070	0.955	0.966	0.928	0.013
GFDL-CM3 RCP8.5 2050	0.956	0.969	0.932	0.011
GFDL-CM3 RCP8.5 2070	0.935	0.953	0.920	0.011
HadGEM-ES RCP4.5 2050	0.957	0.975	0.932	0.012
HadGEM-ES RCP4.5 2070	0.937	0.960	0.923	0.012
HadGEM-ES RCP8.5 2050	0.956	0.976	0.928	0.013
HadGEM-ES RCP8.5 2070	0.934	0.951	0.920	0.010

GCM= General circulation models; AUC= Area under the curve.

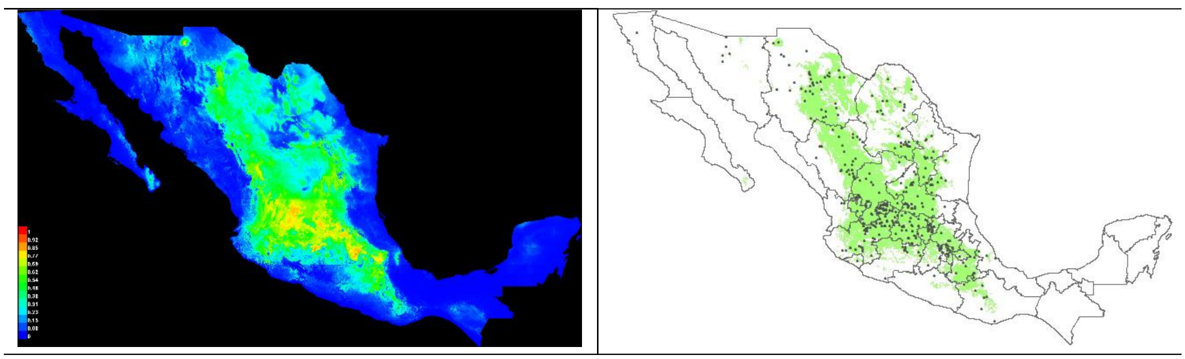
Changes in the mean annual temperature and accumulated precipitation

In the analysis of the average annual temperature, the two GCMs used in this research predict average increases of 2.8 and 3.4 °C for the 2050 period and of 3.4 and 5.0 °C for the 2070 period with the RCP4.5 and RCP8.5, respectively. With regard to the annual cumulative precipitation, the two models predict a decrease of 3.12 and 6.5 % in the 2050 climate, and of 7 and 14.4 % in the 2070 climate. It is important to note that changes in the temperature and the precipitation will be different in each geographical area, with a general trend toward a more accentuated change in arid and semi-arid areas than in temperate and tropical zones of Mexico.

Areas with environmental suitability for *B. curtipendula*

Figure 1 shows that the species is found naturally in an extension of 548,719 km^2 (Table 2), located in central and northern Mexico; from the southeastern part of the state of Chihuahua to the northern part of Michoacán and Guerrero, in the areas of native grassland located in the Mexican plateau and the Transversal Volcanic Axis. The low presence of the species and the scarcity of surfaces with environmental fitness in the low areas and coastal plains in the coasts of the Pacific Ocean, Gulf of Mexico and Caribbean Sea are notorious.

Figure 1: Current suitability area with environmental *B. curtipendula* in Mexico



Left side: a map of the MaxEnt model; the red color represents greater probability of occurrence, and the blue color, areas where occurrence is less likely. Right side: Map based on the previous one, with the surface of limited environmental fitness in the 10th decile of the value of probability; the dots indicate the sites of collection of the species.

The results obtained with the algorithm MaxEnt are influenced by environmental data used[27,28]; Figure 1 (right hand side) shows the homogeneous area with the greatest aptitude for the environmental baseline climate, while Figure 2 depicts the areas with environmental suitability for future periods and the analyzed RCP.

Table 2: Surface area with current environmental suitability for *Bouteloua curtipendula* in Mexico and variation with the general circulation models (GCMs)

Climate/MCG	Surface with environmental suitability (km^2)	% In relation to the reference climatology
Reference	548,719	100.0
GFDL-CM3 RCP4.5 2050	509,152	92.8
GFDL-CM3 RCP4.5 2070	505,516	92.1
GFDL-CM3 RCP8.5 2050	521,876	95.1
GFDL-CM3 RCP8.5 2070	557,293	101.6
HadGEM-ES RCP4.5 2050	506032	92.2
HadGEM-ES RCP4.5 2070	520457	94.8
HadGEM-ES RCP8.5 2050	528419	96.3
HadGEM-ES RCP8.5 2070	552,799	100.7

The GCMs converge in the prediction of a slight decrease of the surface area with environmental suitability for *B. curtipendula* for the two future climates (except in the RCP8.5 in 2070); the decline in the registered surface area is primarily located in the eastern part of the state of Chihuahua, north of Durango, in the northeast of Coahuila and in small areas distributed in the center and the south of the Mexican Republic (Figure 2). In the 2070 period, an average increase of 1.6 % of the surface area is predicted to occur in RCP8.5 (Table 2), located primarily in the northeast of Chihuahua and north-central Coahuila, in addition to small areas scattered in other areas adjacent to the area with current environmental suitability. This phenomenon can be influenced by the type of metabolism of the species and in this case the physiology of *B. curtipendula* is of type C4[26], which is more efficient in the use of water and high temperatures[3,29].

Ecological descriptors of the geographical distribution of *B. curtipendula*

The thermal oscillation and rainfall were the ecological descriptors that contributed most to the potential distribution of the grass *B. curtipendula* in Mexico (Table 3) in all environmental scenarios. Other studies have also shown the influence of precipitation and temperature in this species[3,13]. When analyzing the thermal oscillation separately from the other variables (Figure 3), a sharp increase in the probability of occurrence of *B. curtipendula* with 14 to 20 degrees of difference between maximum and minimum temperatures (the thermal oscillation) was observed.

Figure 2: Areas with environmental suitability for *B. curtipendula* and changes estimated for the periods 2041-2060 and 2061-2080, with RCP4.5 RCP8.5, and in relation to the baseline climate

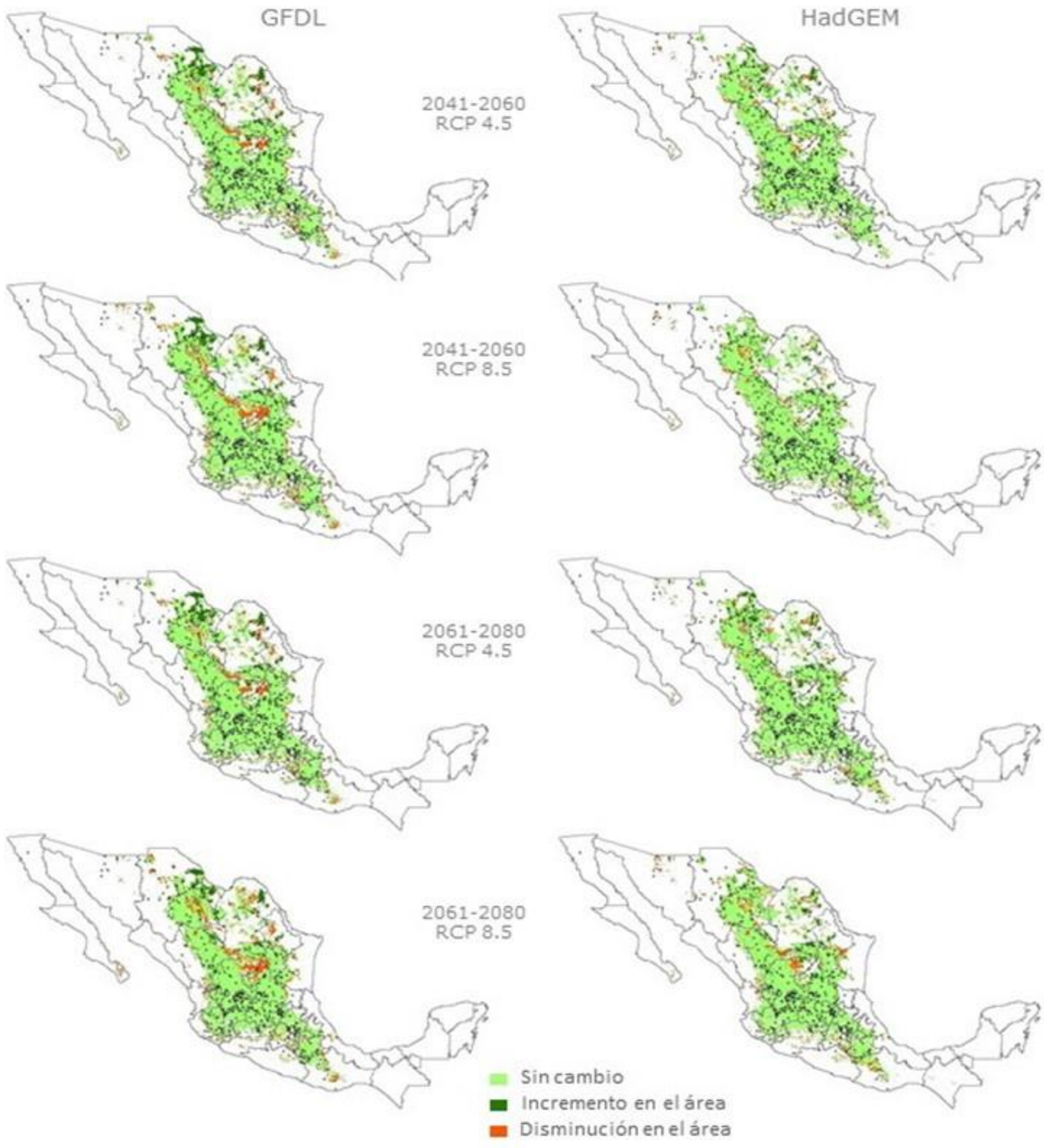
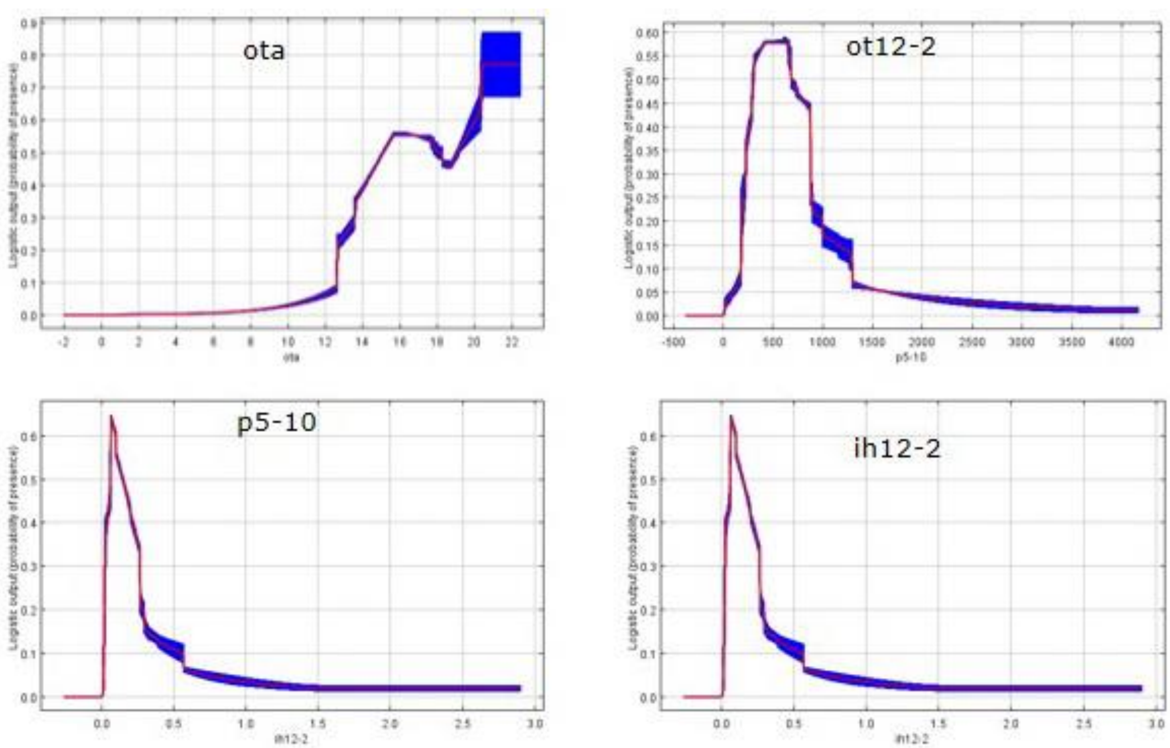


Table 3: Relative contribution (%) of the environmental variables that have the greatest influence on the environmental suitability for *Bouteloua curtipendula* in Mexico

Environmental variable	**Reference climate**	**RCP 4.5**				**RCP 8.5**			
		2050 1	**2050 2**	**2070 1**	**2070 2**	**2050 1**	**2050 2**	**2070 1**	**2070 2**
ATO	29.9	21.5	22.8	20.8	23.8	27.8	31.6	32.1	30.5
Nov-Apr PP	14.6	9.2	8.4	8.4	8.3	7.9	7.6	7.2	6.7
May-Oct PRE	11.1	17.1	15.6	18.8	14.6	19.3	23.8	20.1	25.5
Dec-Feb TO	8.2	10.3	12.8	11.8	12.6	11.2	13.9	11.5	14.3
Dec-Feb IH	7.2	9.8	8.0	11.1	9.8	13.7	8.6	13.9	11.1
May-Oct MT	2.6	3.7	1.6	2.2	1.8	2.5	1.7	2.3	1.5

ATO= annual thermal oscillation; PRE= precipitation; PP = photoperiod; TO= thermal oscillation; IH= index of humidity; MT= minimum temperature.

Figure 3: Environmental variables that influence the probability of presence of *B. curtipendula*



The left-hand side: changes in the prediction of each variable in the sample average. Right side: changes in the prediction of environmental variables separately. The shaded area represents the standard deviation. (ATO, annual thermal oscillation; p5-10, May-Oct precipitation; TO12-2, Dec-Feb thermal oscillation; IH12-2, December-February humidity rate).

The annual precipitation in was one of the main ecological descriptors in the distribution of *B. curtipendula*, not directly but indirectly, through the rate of annual and seasonal humidity, which are the variables that contribute to explain the presence of the species. Based on Figure 3 it can be inferred that *B. curtipendula* is more likely to occur in areas with indices of annual humidity of 0.2 and 0.5, above which point this likelihood decreases quickly as the index approaches a value of 1.0; depending on these levels of humidity, *B. curtipendula* is distributed naturally in arid and semi-arid zones(30,31) and is less frequent in sub-humid and humid areas of Mexico. The contribution of the moisture content in the months of December to February indicates that *B. curtipendula* requires moisture in order to stay in its own ecological niche, as may be corroborated by the fact that the precipitation in the period between December and February contributed to the 5.4 % in the species' distribution, to even a greater extent than the annual cumulative precipitation which reached a value of 3.0 %. In this regard, in a research on *B. curtipendula* conducted in the Chihuahuan desert, precipitation was the key factor accounting for the net primary productivity, mainly when the rain is distributed in small but frequent events during the summer(32). A similar situation has been presented with respect to other species, as reported in a study carried out in Western Africa to model the occurrence of 302 species of grasses, according to which precipitation is the variable that most often affects the distribution of grass species in grasslands(11). Other studies also report that the precipitation is the determining factor in the distribution of grasses at the local and regional scales(33); they also mention that for 30 species native to the Great Plains of the United States the environmental descriptor that contributed the most to the probability of occurrence of *B. curtipendula* was the mean annual temperature(26), which may be explained by taking into account the latitude that causes very low temperatures with respect to the areas of distribution of this species in Mexico. When the contribution of annual rainfall is analyzed separately, the greatest probability of occurrence of this grass is on the sites with precipitations of 450 to 750 mm¸ smaller or larger precipitations reduce the likelihood of the occurrence of this species.

With regard to the photoperiod, the contribution was 9.0 and 14.6 %, in the months from May to October and November to April, respectively (Table 3), with higher probabilities of presence in ranges from 12:30 to 13:00 h in the months of May to October, and from 1100 to 1130 h in the months of November to April (Figure 3); it should be noted that *B. curtipendula* has a wide genetic variation that allows it to adapt to a variety of settings(33,34), which explains its present in sites as extreme as Canada and Argentina(29,35).

Conclusions and implications

The two models agree in the prediction that for the periods 2050 and 2070, there will be an increase of 2.8 to 5.0°C in the annual average temperature, and a decrease of 3.1 to 14.4 %

in accumulated precipitation. The effect of these changes on the surface area with environmental suitability for *B. curtipendula* will have slight negative long-term consequences, because the species will have a lower presence in the period 2050 for both RCPs, and in the 2070 climate, only for the RCP4.5. However, it will recover in the 2070 period in the RCP8.5 and a mean increase of 0.9 % of the surface area with environmental suitability has been predicted in relation to the reference climate. The decline in the area with environmental suitability is located primarily in the states of Chihuahua, Durango and Coahuila and, to a lesser extent, in small areas of central and southern Mexico. The expected increase in area with environmental suitability will occur primarily in the northeast of Chihuahua and in north-central Coahuila. The environmental variables that contributed the most to explain the presence of *B. curtipendula* in Mexico were: annual thermal oscillation, precipitation in the period from May to October, thermal oscillation in the period from December to February, and humidity from December to February.

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