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Environmental niche of *Pennisetum setaceum* (Forssk.) Chiov., 1923, invasive species in Mexico, and climate change scenarios

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ABSTRACT
Objective: The goal of this work was to know the potential distribution of *Pennisetum setaceum* (Forssk.) Chiov., 1923 in Mexico, at present and in the future, after its introduction as an ornamental species, which carries a risk of invasion. However, its presence has not been exhaustively monitored, and there are favorable environmental conditions for its distribution in México.
Design/methodology/approach: we used MaxEnt algorithm as the methodology of ecological niche modeling. For climate change models, the four SSP scenarios of the IPCC Sixth Report were used.
Results: The model generated for *P. setaceum* presents a potential environmental niche with high probability for the entire Pacific coast and in central Mexico; in general, the future scenarios maintain the central area of the country as the most likely distribution area. These results represent the first models for the potential environmental niche distribution of *P. setaceum* in Mexico.
Limitations on study/implications: However, it is necessary to increase the data from historical records.
Findings/conclusions: Monitoring the species could generate more fresh data to improve accuracy in futures models and start reasoning about containment measures, such as restricting its use or pursuing eradication.

Keywords: alien species, climate change, desertification, ecological niche.

INTRODUCTION

Pennisetum setaceum (Forssk.) Chiov. (1923) is a herbaceous plant belonging to the Poaceae family. It is cultivated as an exotic ornamental or forage plant in various parts of the world and has proven to be an aggressive coloniser (GIBD, 2021). It is native to North Africa, East Africa, and the Arabian Peninsula (EPPO, 2009) and grows in arid coastal and pre-desert areas of the Sahara (Williams *et al.*, 1995), reaching altitudes of up to 2,800

metres. Today, this plant is considered cosmopolitan, as it is found on all continents. It has a wide climatic range, provided that annual rainfall does not exceed 1,270 mm and temperatures do not fall below 0 °C (Pasta *et al.*, 2010). This triploid species has a lifespan of up to 20 years. It becomes productive from the second year, producing up to 100 seeds per inflorescence (Pasta *et al.*, 2010).

P. setaceum is highly resilient to the impact of fire due to its strong root system and rapid germination following a burning event (Alcamisi, 2019). It can adapt to degraded and infertile soils, as well as drought conditions, and has become invasive in several countries, reducing biodiversity, impoverishing the soil, and displacing native grass species (PIER, 2021).

This weed is an adaptable grass that is highly competitive and efficient in its use of water. These characteristics have endangered the biodiversity of tropical dry forests in Hawaii (Tunison, 1992; Wagner *et al.*, 1990) since its introduction as an ornamental plant. In this environment, *P. setaceum* competes with the native grass *Heteropogon contortus* (L.) P. Beauv. ex Roem. & Schult., utilising water more effectively during the rainy season (Williams & Black, 1994). Cordell and Sandquist (2008) reported that changes in land use, grazing and forest clearance enabled this species to become established, resulting in the conversion of Hawaii's tropical dry forests into monospecific grasslands. Richardson *et al.* (2000) concluded that *P. setaceum's* peculiarities make it a species capable of invading and modifying the ecological features of the territory it colonises. This species benefits from roads and motorways, as these facilitate the physical movement of seeds through air currents created by traffic. These tiny seeds germinate easily in poor and ruderal soils (Pasta *et al.*, 2010). Conversely, Georgen & Daehler (2001) state that the plant produces large quantities of seeds that can germinate within three to five days under optimal moisture conditions. Under adverse conditions, the seeds can maintain their germination potential for up to six years (Tunison, 1992).

Of the 1,100 recorded alien species in Mexico, 348 are considered invasive (CONABIO, 2021). *P. setaceum* is on the Ministry of Environment and Natural Resources' list of high-risk invasive alien species in Mexico. According to this agency, it was only found in the states of Baja California, Sonora and Nuevo León until 2016 (SEMARNAT, 2017).

A fundamental approach to understanding and managing species involves determining their current and potential distribution using tools such as ecological niche modelling (Guisan & Thuiller, 2005; Peterson *et al.*, 2012). ENMs contribute to predicting areas in which environmental conditions are suitable for species survival, describing potential distributions or fundamental environmental niches (Anderson *et al.*, 2003; Guisan & Thuiller, 2005; Simoes *et al.*, 2020). ENMs have been used to determine the ecological and spatial delimitations of native species (Martinez-Sifuentes *et al.*, 2021), alien species (Marcer *et al.*, 2012; Xue *et al.*, 2022), and, in one case, *P. setaceum* (Da Re *et al.*, 2020). The latter study used presence data related to invasion to determine the potential for adaptation to non-native habitats.

The aim of this study was to compile all available information on *P. setaceum* in Mexico, in order to create and analyse an ecological niche model for this species under current and future climate scenarios. This information is therefore crucial for assessing the potential invasion of this species in Mexico. These results will inform the development of invasion mitigation strategies in Mexico.

MATERIALS Y METHODS

Creation of the database

The database was generated using data from the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2021), the Global Biodiversity Information Facility (GBIF, 2023) and the correspondance author's personal collection data (VB). This data was collected in the Guadalajara metropolitan area using a random transect method, with georeferenced self-sown individuals identified in urban and peri-urban areas in 2021. A total of 313 points of interest georeferenced to *P. setaceum* were included in the database. Duplicate occurrences were removed to reduce the effects of spatial autocorrelation, with records within 5 km of individual occurrence points being filtered using the spThin package in R (Ailello-Lammens *et al.*, 2015).

The final database comprises 29 unique occurrence points, each at least 5 km from the next. These points are located in the Mexican states of Baja California Sur, Baja California Norte, Sonora, Chihuahua, Sinaloa, Nayarit, Jalisco, Coahuila, Nuevo León, Michoacán, Guanajuato, Guerrero, Puebla and Chiapas.

Accessible region M

Accessible region M (Barve *et al.*, 2011) was generated using a 100 km radius zone of influence around each occurrence point and subsequently overlaid on the World Wildlife Fund ecoregion shapefile (Olson *et al.*, 2001), according to the methodology proposed by Moo-Llanes *et al.* (2019) to avoid possible modelling bias related to model calibration. It was decided to use invasion area data rather than natural distribution data because it was thought that the prediction would be underestimated due to the significant difference in climate between Mexico and the Arabian Peninsula, as well as the species' high level of adaptability to new environments. In fact, the same position has been taken in several studies, with the intention of being able to more accurately approximate the model regarding biological invasion at the local level, when the invasive species has demonstrated a high capacity to adapt to climatic situations very different from its natural context (Marcer *et al.*, 2012; Xue Y *et al.*, 2022; Da Re *et al.*, 2020). The occurrence records were randomly divided into two subsets using the 'random k-fold' method: 70% for model calibration and 30% for assessments (Moo-Llanes *et al.*, 2020; Moo-Llanes *et al.*, 2021). This method randomly divides occurrence locations into a user-specified number of bins, as detailed in the Muscarella *et al.* (2014) protocol.

Bioclimatic variables

Fifteen of the 19 WorldClim bioclimatic variables (Fick & Hijmans, 2017) were used to construct the ecological niche models (ENMs). Variables combining temperature (Bio08 and Bio09) and precipitation (Bio18 and Bio19) were excluded (Escobar *et al.*, 2014; Moo-Llanes *et al.*, 2021). All variables had a spatial resolution of 1 km^2. Four sets of bioclimatic variables, each comprising 15 WorldClim variables, were used: a)

Set1: the fifteen bioclimatic variables from WorldClim (Moo-Llanes *et al*., 2021). b) Set2: the Jackknife method in MaxEnt was used to select different bioclimatic variables that contributed most to the model (>90%) (Moo-Llanes *et al*, 2013; Moo-Llanes *et al*., 2021), removing one variable per pair with Pearson's correlation ($r<0.8$). To select the variable to be eliminated, it was verified that the variable presenting the lowest spatial autocorrelation with the pair of variables to be evaluated and with other combinations of bioclimatic variables would be selected. c) Set 3: nine variables were established for constructing ecological niche models for different species (Moo-Llanes *et al*., 2013). Finally, Set4 (d): the variance inflation factor (VIF) was considered (Table 1).

This is a measure of the levels of multicollinearity between pairs of variables in the USDM package in R. VIF values greater than 10 indicate potentially problematic correlations with covariates and suggest that these should be carefully evaluated during model development (Estrada-Peña *et al*., 2013; Moo-Llanes *et al*., 2023). ENMs were projected for the current period (1970-2000) and for the year 2041-2060 using the Socio-Economic Shared Pathways (SSPs). The ENMs were projected using the four SSPs of the IPCC Sixth Assessment Report: SSP1-2.6 (445.6 ppm CO_2), SSP2-4.5 (602.8 ppm CO_2), SSP3-7.0 (867.2 ppm CO_2) and SSP5-8.5 (1135.2 ppm CO_2) (IPCC, 2021; Moo-Llanes *et al*., 2021; Moo-Llanes *et al*., 2023).

Ecological Niche Models

These models were constructed using the MaxEnt algorithm based on the kuenm package in R (Cobos *et al*., 2019). The generated models were projected onto region G, comprising the entire Mexican national territory, given that the species is cultivated as an ornamental plant in almost all of Mexico (personal observation).

Table 1. Sets of bioclimatic variables used for the construction of the ecological niche model of *Pennisetum setaceum* in Mexico.

Bioclimatic variables	Code	Set1	Set2	Set3	Set4
Average annual temperature	Bio01	X		X	X
Average diurnal range	Bio02	X			X
Isothermality	Bio03	X			X
Seasonal temperature	Bio04	X	X	X	
Maximum temperature of the hottest month	Bio05	X			
Minimum temperature of the coldest month	Bio06	X			
Annual temperature range	Bio07	X	X	X	
Average temperature of the hottest quarter	Bio10	X	X	X	
Average temperature of coldest quarter	Bio11	X	X	X	
Annual precipitation	Bio12	X		X	
Precipitation of the wettest month	Bio13	X		X	
Precipitation of the driest month	Bio14	X	X	X	X
Seasonal precipitation	Bio15	X		X	X
Precipitation in the wettest quarter	Bio16	X			X
Precipitation of the driest quarter	Bio17	X			

A total of 1,736 candidate models were obtained by combining four sets of environmental variables and 14 regularisation multiplier values (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0 and 5.0). These were then combined with the 29 possible combinations of the five entity classes (linear=l, quadratic=q, product=p, threshold=t and hinge=h) (Cobos *et al.*, 2019).

First, the best candidate models were selected for statistical significance: partial Receiver Operating Characteristic (ROC) and omission rate at 5% predictive ability. Secondly, they were selected for their performance based on Akaike's information-corrected criterion (AICc) for small sample sizes (Núñez-Penichet *et al.*, 2021). The number of parameters was determined by identifying all parameters with a non-zero weight in the lambda file produced by MaxEnt. This is a small text file containing details of the model produced by MaxEnt as part of the modelling process (Warren & Seifert, 2011). Finally, models with delta AICc≤2 were selected from those that were statistically significant and had omission rates below 5% (Cobos *et al.*, 2019).

After the calibration process, the final models were created using all occurrences with the selected parameter values and 10 bootstrap replications with logistic outputs for Mexico. In order to identify high-risk geographical areas for model transfer, the environmental distance between sites in general, and to the nearest portion of the calibration region M, was calculated using Mobility-Oriented Parity (MOP) analysis. The environmental amplitude of the predictors within region G (10% of the sampled benchmarks) was then compared for the total projection area. It should be noted that the extrapolation risk analysis defines areas with strict extrapolation (*i.e.* they represent the degree of similarity between conditions in M and G, where zero values correspond to areas of strict extrapolation) to avoid the risk of overprediction in non-analogue settings (Owens *et al.*, 2013).

RESULTS AND DISCUSSION

A total of 1,736 models were analysed, 1,254 of which were statistically significant. Five models that met the omission rate and AICc criteria were selected (Figure 1).

The model with environmental predictors (Set2), class (Threshold), multiple regularisation (N=0.9), partial ROC (1.39), omission rate at 5% (0.00), AICc (764.25), delta AICc (0.00), WAICc (0.16) and numerical parameters (N=9) was chosen as the best candidate (Table 2).

The model indicates that *P. setaceum* is likely to find favourable environmental conditions for establishment along the Pacific coast and in the central regions of Mexico (Chiapas, Oaxaca, Guerrero, Michoacán, Colima, Jalisco, Nayarit, Puebla, Mexico City, Guanajuato, Zacatecas, Sinaloa, Baja California Sur and Baja California Norte), as well as in the states of Veracruz, Hidalgo, San Luis Potosí and Coahuila (Figure 2a). However, care must be taken when interpreting the results for the areas corresponding to the Yucatán Peninsula, the Gulf of Mexico, San Luis Potosí, Durango, Zacatecas, Coahuila, Sinaloa, Sonora, Baja California Sur and Baja California Norte, as there is high standard deviation (Figure 2b).

In all four climate change scenarios (SSP1-2.6; SSP2-4.5; SSP3-7.0; and SSP5-8.5), the areas of potential *P. setaceum* invasion and standard deviation are minimal. As can be seen in Figure 3, the increase in the areas of encroachment is smaller in each of the different scenarios.

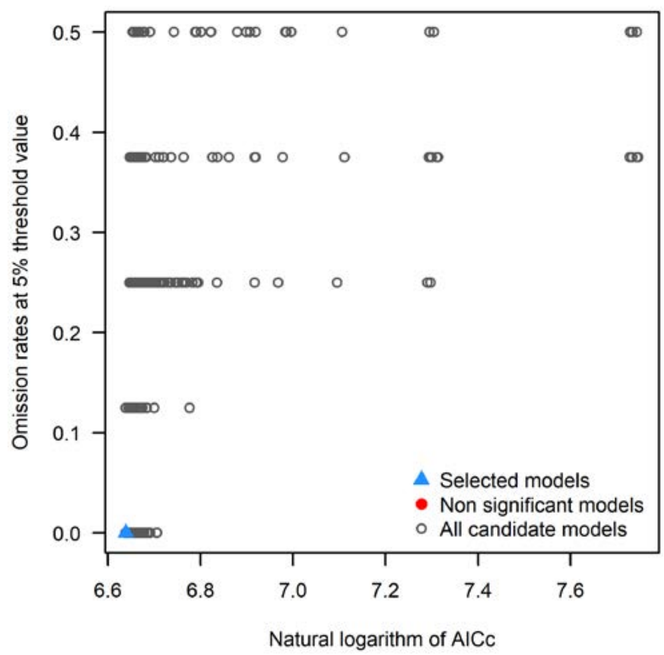

Figure 1. Distribution of selected models, those statistically non-significant and the total set, according to predefined criteria for *P. setaceum* in Mexico.

Table 2. Performance statistics for the selected models according to the criteria established for the construction of the ecological niche of *P. setaceum* in Mexico. *Features: T (Threshold), P (Product), L (Linear) y Q (Quadratic).

Classes*	Multiple regularisation	Set	ROC partial	Omission rate 5%	AICc	Delta AICc	W AICCc	# Parameters
T	0.9	Set2	1.39	0.00	764.25	0.00	0.16	9
PT	0.9	Set2	1.38	0.00	764.25	0.00	0.16	9
LPT	0.9	Set2	1.38	0.00	764.25	0.00	0.16	9
QPT	0.9	Set2	1.38	0.00	764.25	0.00	0.16	9
LQPT	0.9	Set2	1.38	0.00	764.25	0.00	0.16	9

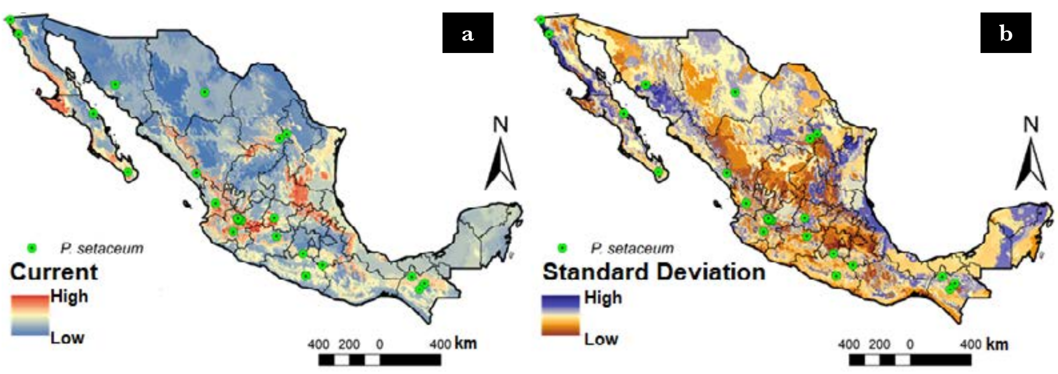

Figure 2. Ecological niche model for *P. setaceum* in Mexico. a) Shows the ENM of *P. setaceum* in Mexico, with the highest probability of distribution shown in red. b) Shows areas of uncertainty, with the highest uncertainty shown in blue.

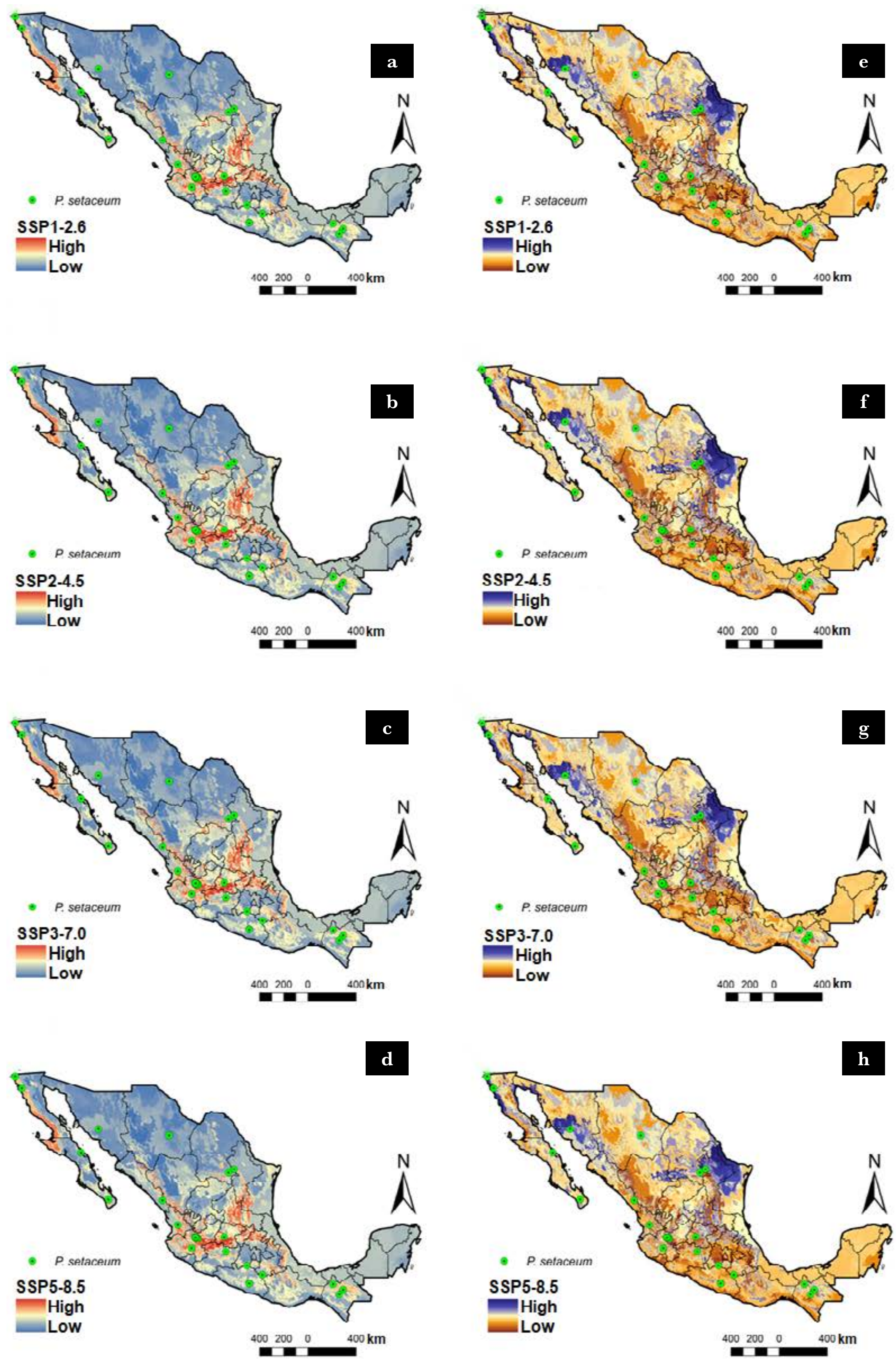

Figure 3. Climate change scenarios for the ENM of *P. setaceum* in Mexico. The left panel shows each of the four SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP4-8.5), while the right panel shows the uncertainty of the ENMs.

Overlapping the current scenario with the different climate change scenarios reveals that the zones where they overlap remain largely unchanged across Mexico, particularly in the centre of the country (Figure 4).

Depending on the scenario, there are exclusive areas of encroachment, as is the case with SSP370 in the Veracruz area. The areas that remain constant between the current period and the climate change scenarios are consistent across the four SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP4-8.5). The areas lost correspond mostly to parts of the Yucatán Peninsula, the Gulf of Mexico (Veracruz) and Baja California Sur, while the areas gained (areas of new invasion) correspond mostly to central Mexico (Figure 5).

The territorial scale of the data presented here is much larger than that of a similar study conducted by Da Re *et al.* (2020) on the island of Tenerife. In that study, it was shown that the entire coastal area was suitable for the spread of *Pennisetum*. In contrast, Mexico offers an extremely large territorial space with a wide range of climates, including tropical conditions that could be suitable for the species, which naturally occurs in arid zones, as seen in its natural distribution. The models analysed could be improved to better describe reality if new distribution records for this species in Mexico could be accessed. This work may therefore stimulate interest in generating new knowledge about this species in Mexico, as the field study demonstrates the severity of the invasion in the studied sites, particularly in the Guadalajara metropolitan area (Jalisco), resulting in biodiversity loss and desertification (Pasta *et al.*, 2010; PIER, 2021; Tunison, 1992). Having observed that the plant is being used on a national scale as an ornamental grass, we are keen to see the results of this work. The collection points used are those of self-propagated individuals, *i.e.* individuals that originated in urban and peri-urban areas due to the species' invasive potential after seeds were spread from ornamental plantings in city flower boxes.

Raising awareness of this specific problem in Mexico could encourage the implementation of effective measures to prevent situations like the one in Italy, where eradication is now economically impossible (Alcamisi, 2019). The species was first introduced to the botanical garden in Palermo, Italy, in 1939 for study purposes, as a forage and ornamental plant. It is

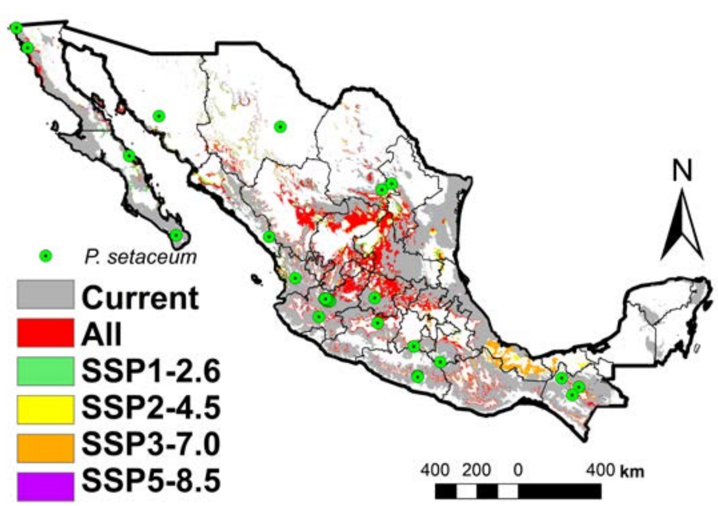

Figure 4. Areas of overlap of the four SSP scenarios based on the ENM construction of *P. setaceum* in Mexico.

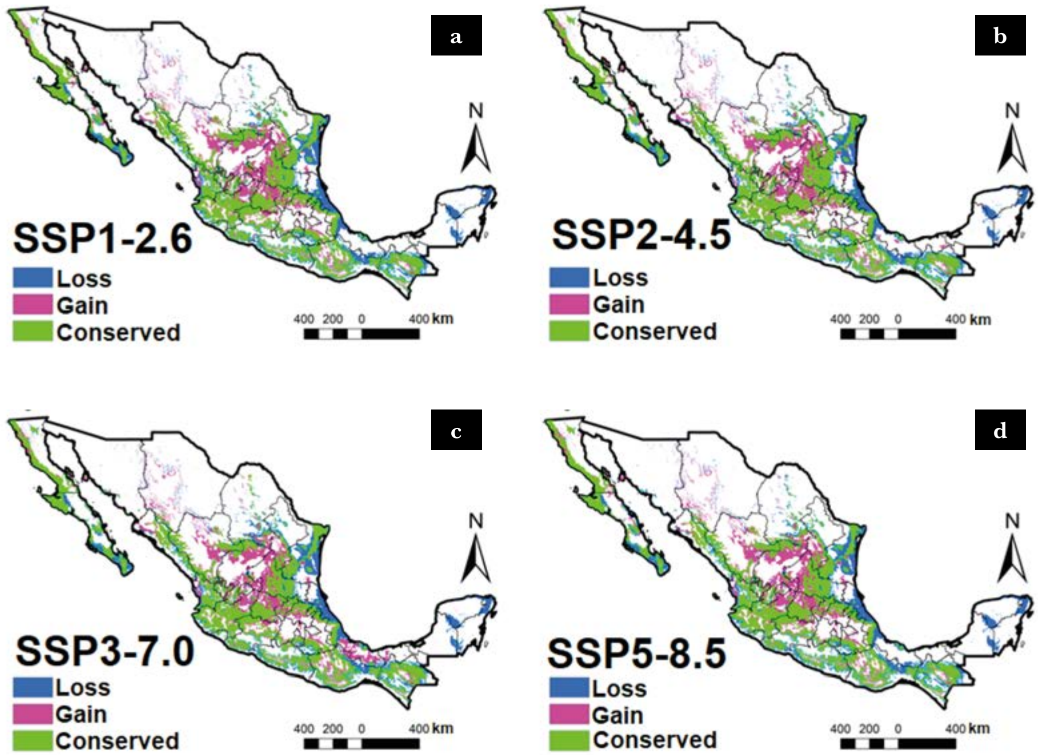

Figure 5. Areas of gain, loss and maintenance (conserved) of ENM of *P. setaceum*, according to each of the scenarios and the current period in Mexico.

now fully naturalised, having almost completely displaced local grasses such as *Hyparrhenia hirta* (L.) Stapf. (Pasta *et al.*, 2010; Giovanni Provenzano, personal communication; manager of the Monte Pellegrino Oriented Nature Reserve, Palermo). A similar situation could occur in some areas of Mexico if intervention is not carried out promptly and effectively.

Studies on possible increases in invasions depending on climate change scenarios on Tenerife warn of the potential expansion of this exotic species on the island, including the possible conquest of the high-altitude ecological niche of local pines. This could have serious consequences, including increased desertification and forest fires, as well as a loss of biodiversity (Da Re *et al.*, 2020). A similar situation could easily occur in the La Primavera Forest in Guadalajara, an area subject to frequent forest fires (Jardel-Peláez, 2021). The extensive root system of *P. setaceum* reduces the availability of water for neighbouring plants, stunting the growth of tree species (Cordell & Sandquist, 2008). It therefore limits the number of young trees in areas where it becomes established (Cabin *et al.*, 2002). Given the species' characteristics, we should not expect less aggressive results in Mexico than in previous studies conducted in other parts of the world. Currently, several cities in Mexico use this species for public landscaping, planting it in tree surrounds and roundabouts. There is strong support from citizens, who consider the species aesthetically pleasing. However, the risk of invasion is considered to be very high, and it has been observed that the species is reproducing spontaneously and colonising cracks in pavements, planters, and vacant lots in several areas of these cities (personal observation, Figure 6).

Figure 6. On the left, entrance to the city of *San Cristóbal de las Casas*, Chiapas, on the right, *Avenida de las Américas* avenue in the city of Guadalajara, Jalisco.

This situation is evident to a critical observer and deserves to be studied and reported, hence the need for this research. The models generated in this study demonstrate that there is indeed territory within the country susceptible to colonisation. Fieldwork data also show that the species is capable of colonising the Mexican environment independently. The large quantity of viable seeds produced by the species, its ecological niche and the complacency of the population, which propagates and sows the species unknowingly, could therefore generate a serious future problem.

CONCLUSIONS

This study is the first to model the environmental niche of *P. setaceum* in the Americas. It is expected to lay the groundwork for further research on this invasive species in Mexico. Specific censuses must be carried out in several metropolitan areas of the country to update databases and produce increasingly accurate models, providing an up-to-date view of the level of invasion and enabling the development of control and eradication plans.

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