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Adapted RCP 4.5 and 8.5 climate change scenarios for invasive *Sus scrofa* in Mexico

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Summary

Climate change is a common factor that contributes to the growth or decline of animal populations. The present study, conducted using the Species Distribution Model, highlights the fact that despite the recognized negative impact of wild boar (*Sus scrofa*) on semi-natural areas and agricultural systems worldwide, the species remains poorly studied. According to projections for Representative Concentration Pathways (RCP) 4.5 and 8.5, increased clusters of wild boar abundance are expected to emerge around fragmented species assemblages by 2070. *Sus scrofa* is an extremely destructive and rapidly spreading invasive species whose movement appears to be facilitated by humans. As a consequence, many endemic plants are threatened with extinction. Biological corridors between fragments with poor conservation status should be linked to priority areas for adequate protection. The creation of preserved landscapes in territories separated from semi-natural ecosystems is recommended. Additionally, these measures can help mitigate the negative impact of *S. scrofa* on local biodiversity. Continuous monitoring and adaptive management strategies will be crucial for long-term conservation of the affected areas. Environmental protection efforts must prioritize the restoration of natural habitats and the implementation of strict regulations to control the spread of this invasive species. Collaborations between conservation organizations, governments, farmers, and local communities are essential to ensure effective wild boar management and the preservation of arable land and forests. Moreover, public awareness campaigns about the environmental impact of wild boar and the importance of conservation efforts are critical for garnering broader support.

Keywords

biological conservation • climate change scenario • invasive alien species • species distribution model

1. Introduction

Invasive alien species (IAS) constitute a major cause of biodiversity loss worldwide and have significant negative impact on societies. Despite their importance, data on the monetary costs of IAS is scarce in most countries, though such data would be crucial for effective management. In Mexico, the costs of invasive species were estimated at 5.33 billion USD from 1992 to 2019 [Rico-Sánchez et al. 2021]. Furthermore, the vague systems of local entities in Mexico are often not recognized in conservation practices [Guibrunet et al. 2021].

Ecologically, the loss of natural capital due to the spread of invasive mammals in Mexico is increasing [Halecki and López-Hernández 2023]. Crops and soil ecosystems are particularly damaged by wild boar (*Sus scrofa*). However, scientists and wildlife managers often refer to these wild representatives inconsistently and inaccurately, even at the genetic level [Titus et al. 2022]. It it noted that wild boars have become invasive in countries where they were previously absent, such as Argentina [Ballari et al. 2022] and Cyprus [Hadjisterkotis et al. 2020]. Lethal removal of invasive species like *S. scrofa* is frequently the most effective method to mitigate their negative impact, although it can alter their spatial behavior [Westhoff et al. 2022]. For example, *S. scrofa* uproots large areas of native vegetation, disrupting soil ecosystems, and feeds on endangered species such as turtles, birds, and reptiles. Wild boars are omnivores, which enables them to exploit a broad range of food resources in various environments [Silveira de Oliveira et al. 2020]. They have a short reproductive cycle and large litters, facilitating rapid population growth [Brogi et al. 2022]. What is more, wild boars can adapt to diverse habitats, from forests to agricultural areas, aiding their expansion [Bosch et al. 2020, Johann et al. 2020]. These animals are capable of travelling long distances, which promotes their spread. They can also swim through small rivers, which contributes to their dispersal in the northern prairies of North America [Kramer et al. 2024]. Originally, these invasive species were introduced to Mexico for sport hunting and meat trade [De-la-Rosa-Arana et al. 2021].

While research on invasive *S. scrofa* has increased, along with the number of peer-reviewed studies, there remains a lack of comprehensive information on their biology, ecology, the extent of the damage they cause, as well as control options [Ruiz-Rodríguez et al. 2022, Barrios-Garcia et al. 2022]. Conservation programs should aim to coordinate and implement management strategies for invasive *S. scrofa*. There are conflicting viewpoints on *S. scrofa* management, ranging from conservation in order to increase their populations, to eradication in order to prevent environmental damage. The purposes of this study were to:

a. Identify the distribution of *S. scrofa* in Mexico,
b. Model a climate scenario with milder impacts (RCP 4.5) for 2050 and 2070,
c. Model an extreme climate scenario (RCP 8.5) for 2050 and 2070,

d. Implement conservation measures to protect area prone to invasion from mammalian invasive species in Mexico.

2. Materials and methods

2.1. Research area

The study modeled the current and future potential distribution of two species considered highly invasive in Mexico, in order to identify the area most susceptible to invasion. Different climate models used in the study was presented in Table 1. This method was applied to estimate the distance between the species. The niche of each species was predicted in high-resolution (1 km) climate scenarios in Mexico for the current and two projected future emission scenarios, one conservative (RCP 4.5) and one drastic (RCP 8.5), and for two time periods, one short-term (2050) and the other long-term (2070). The variables were compiled by the makers of CONABIO data bases (the Mexican Commission for the Knowledge and Use of Biodiversity) to determine and rank invasive species based on the level of damage they caused. Data was incorporated from each of the species identified by CONABIO (Attribution 2.5 Generic; CC BY 2.5). CONABIO collects and generates biodiversity information, develops humanity's capacity to produce biodiversity informatics, and is a public source of information and knowledge accessible to the entire public.

2.2. Modeling of current and future potential distribution

Potential distribution models were designed based on the reconstruction of the studied species' ecological niche by means of the distance from the center of gravity of the niche through the construction of a minimum volumetric ellipse. The map resulting from this modeling shows values from 0 to 1, representing an index of environmental favorability, as related to the abundance of the species [Qiao et al. 2016]. Values close to 1 indicate areas with high proliferation of the species. In contrast, values approaching 0 reflect areas with low species abundance. Calibration data from the WorldClim database from 1961–1990 were used to extract the values of climatic variables for each record (Table 1). Studies were conducted at a 10-minute spatial resolution (about 18.5 km at the equator). In the MaxEnt modeling system, the three most important environmental variables using the permutation method were identified. A multidimensional minimum-volume ellipsoid was constructed [Escobar et al. 2016] with the center of gravity as the average of the three variables, and its dimensions were calculated from the data covariance matrix. The ellipsoid, in effect, represents the ecological (climatic) niche of the species [Siller-Clavel et al. 2022].

The procedure used to model the potential distribution was determined by applying the centroid distance method. Records were collected from the database (201 observations for *S. scrofa*). The first was for calibration, and the second for validation at a ratio of 70:30. The species' current presence in Mexico was used to validate the models. Calibration was performed with the WorldClim database and MaxEnt modeling system using the permutation method and extracting the values of the climatic variables from each record [Giorgetta et al. 2013].

An ellipsoid with a minimum volume was constructed based on the covariance matrix of the data and the centroid as the mean. A species' ecological (climatic) niche is effectively represented by the said ellipsoid. By projecting the niche into geographic space, a potential map of global distribution was obtained, and the Roc-partial test was used to assess its validity. The area under the curve (AUC index) for *S. scrofa* was 1.36, with a p-value of 0.042. The ellipsoid represents the species' climatic tolerance limits, which approximates its basal ecological niche.

The land use and vegetation maps were applied in order to assign different impact values to the land use and vegetation categories employed in the model. The categories were grouped into classes relating to a specific biodiversity impact value as follows:

i. primary vegetation (snow, bare ground, primary forest cover) = 0,
ii. managed forest cover = 0.3,
iii. iii); primary grassland and scrub = 0.3,
iv. secondary forest cover = 0.5,
v. secondary non-timber vegetation = 0.5,
vi. forest plantations = 0.7,
vii. permanent grassland = 0.3,
viii. induced grassland = 0.9,
ix. permanent agriculture = 0.7,
x. intensive agriculture = 0.9,
xi. intensively irrigated agriculture = 0.95,
xii. urban areas = 0.95.

Values nearer to zero indicate low levels of interaction, while values near 1 indicate high levels of influence. Data from CONABIO (La Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad) was used to produce the final human biodiversity impact map.

The distribution was visualized using QGIS software version 3.22 Firenze. To understand the future invasion of *S. scrofa* in Mexico, the ellipsoid was projected onto the current climate scenario for the country (1961–1990, with a resolution of 1 km). A future climate scenario was projected on a range distribution model, with one short-term scenario 2050 (2041–2060), and another long-term scenario in 2070 (2061–2080), along with two models for atmospheric greenhouse gas concentrations, one conservative (RCP 4.5), and the other extreme (RCP 8.5). Future scenarios were obtained by averaging the results from the model.

3. Results

3.1. Nature protection status in Mexico

The study showed that protected areas in Mexico are fragmented (Fig. 1). Currently, protected areas are subdivided into zones. Majority of those are high-status nature conservation sites. There are hotspots in Mexico with extremely high protection status. The map (shown in Fig. 2) identifies more areas subject to various anthropogenic influences. The region addressed in the study incorporates areas of high status of protection with biodiversity elements of conservation value. The results regarding the spatial distribution of priority sites for biodiversity conservation in Mexico suggested that the most severe conservation needs occur in the northern and central parts of the country, in the Gulf of Mexico and in the Gulf of California and along the Pacific Ocean. Having said that, the region is also highly fragmented, with minor maintenance activity zones and low human impact.

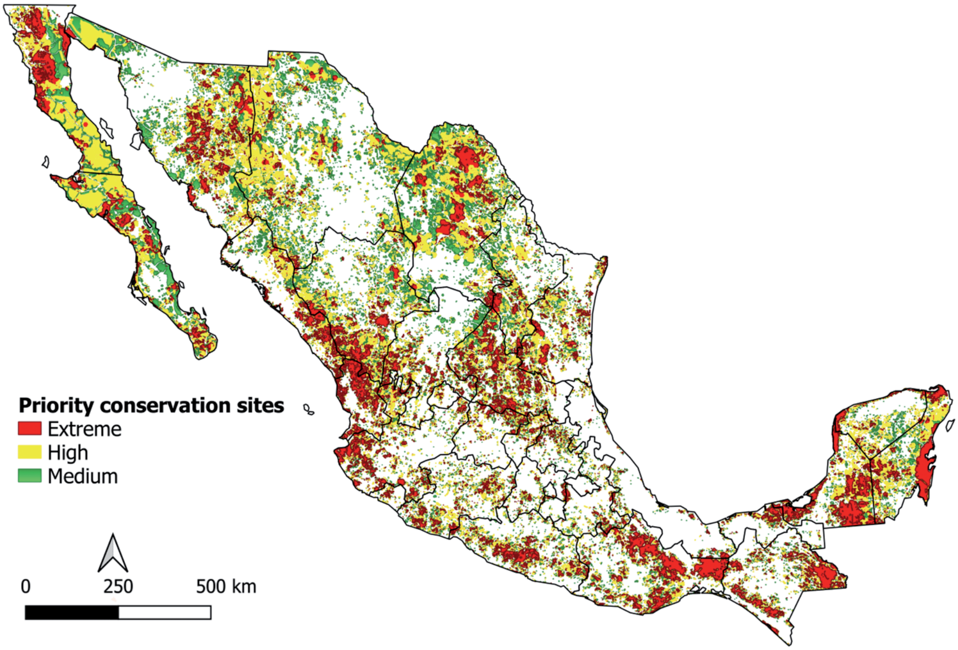
3.2. Climate change scenarios for *S. scrofa*

S. scrofa is currently distributed over much of the northern part of the country. The largest distribution is recorded in the state of Chihuahua (Fig. 3). The highest distribution ratio is 0.75. Other large clusters are found in the states of Tamaulipas and Nuevo León. The highest recorded distribution ratio ranged from 0.57–0.75. RCP 4.5 climate change scenario determined that by 2050, an extension of *S. scrofa* distribution ranges in the south of the country should be expected (Fig. 4). As the population grows until 2070, the distribution ratio will decrease to 0.70 (Fig. 5). Distribution ratio will remain approximately the same in 2050 under RCP 8.5 (Fig. 6). It is assumed that *S. scrofa* distribution will become thin by 2070 under RCP 8.5. A distribution ratio of 0.63 can be expected (Fig. 7).

Table 1. Targeted bioclimatic variables in research on *S. scrofa*

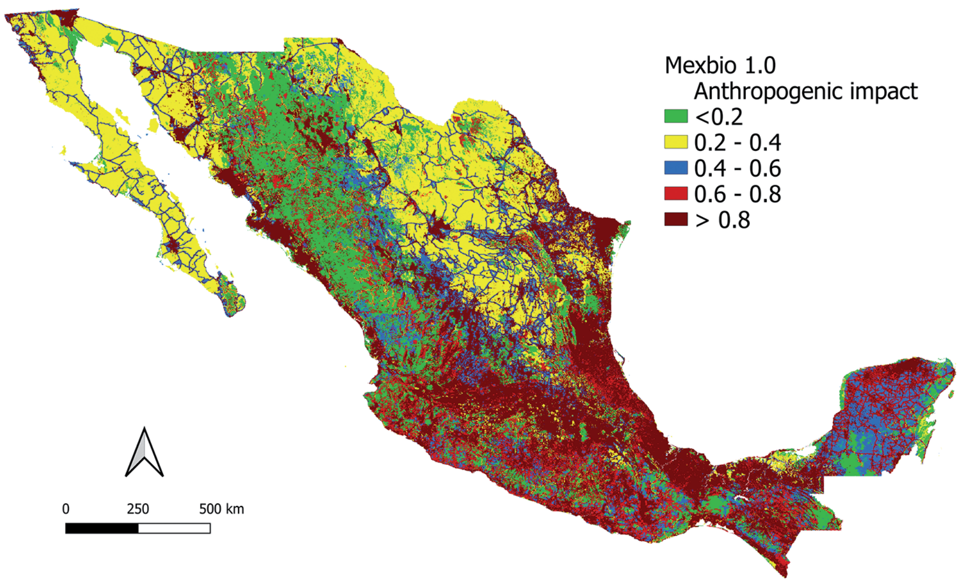
Bioclimatic variable	Description
BIO4	The amount of temperature variation over a given year (or averaged years) based on the standard deviation (variation) of monthly temperature averages
BIO5	Mean daily maximum air temperature of the warmest month (i.e. the highest temperature of any monthly daily mean maximum temperature)
BIO10	The quarterly index approximates the average temperatures observed during the warmest quarter data
BIO 12	Annual precipitation amount (i.e. accumulated precipitation amount over 1 year)
BIO 15	A proxy for the variation in monthly precipitation totals throughout the year – this coefficient is the ratio of the standard deviation of monthly precipitation to the average monthly precipitation (coefficient of variation)

Source: Cerasoli et al. [2022]



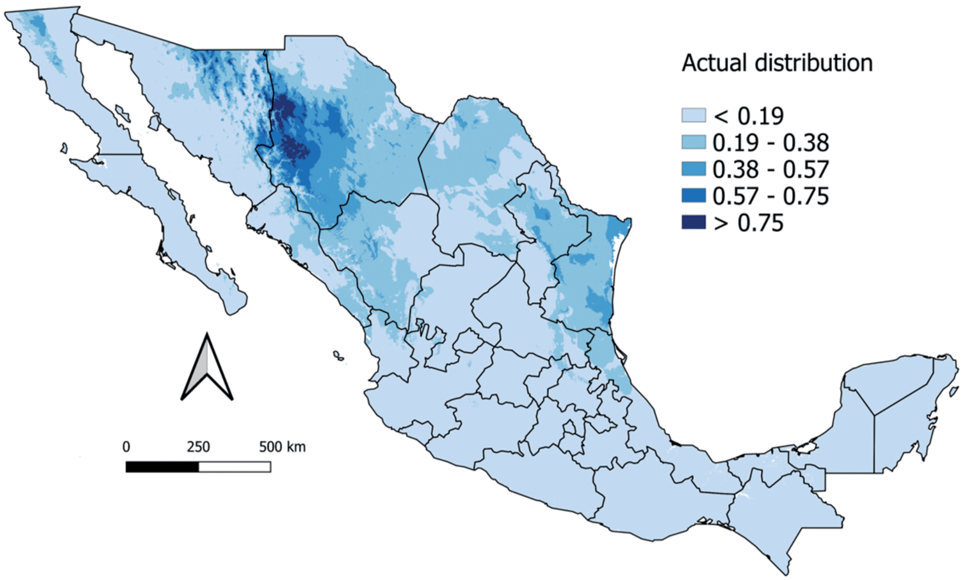
Source: CONABIO

Fig. 1. Protected areas in Mexico with high formal and legal status



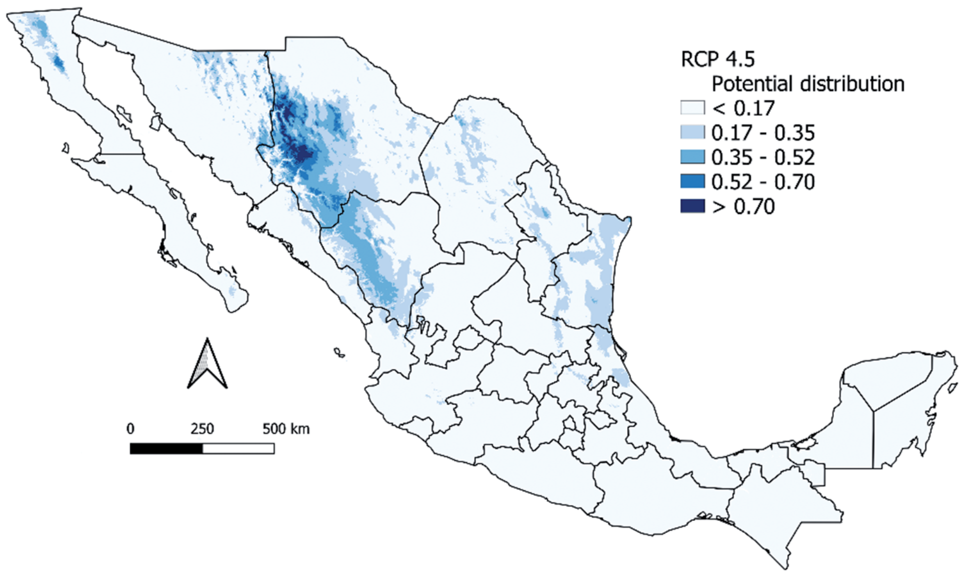
Source: CONABIO

Fig. 2. Anthropogenic index based on the Mexbio 1.0 model



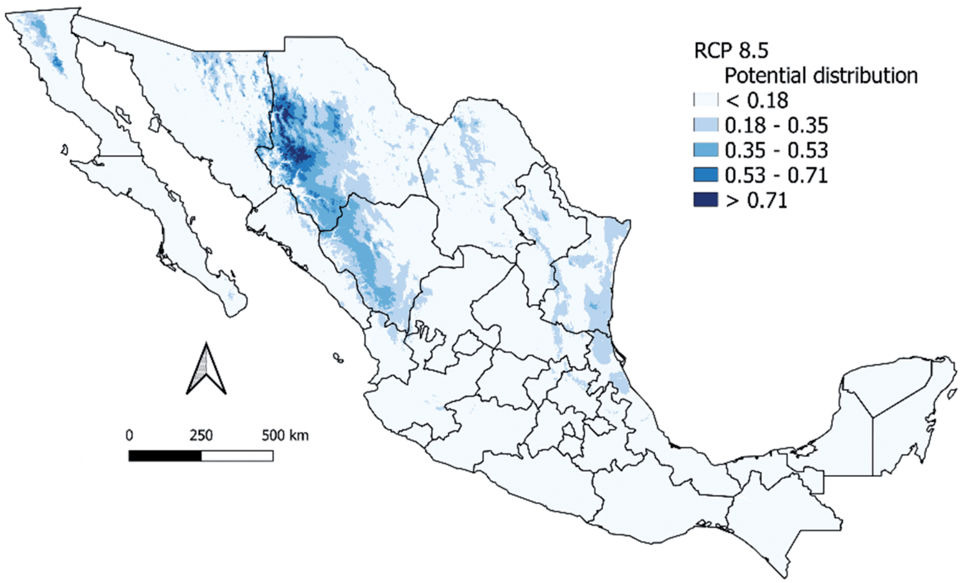
Source: CONABIO

Fig. 3. Current distribution of *S. scrofa* in Mexico



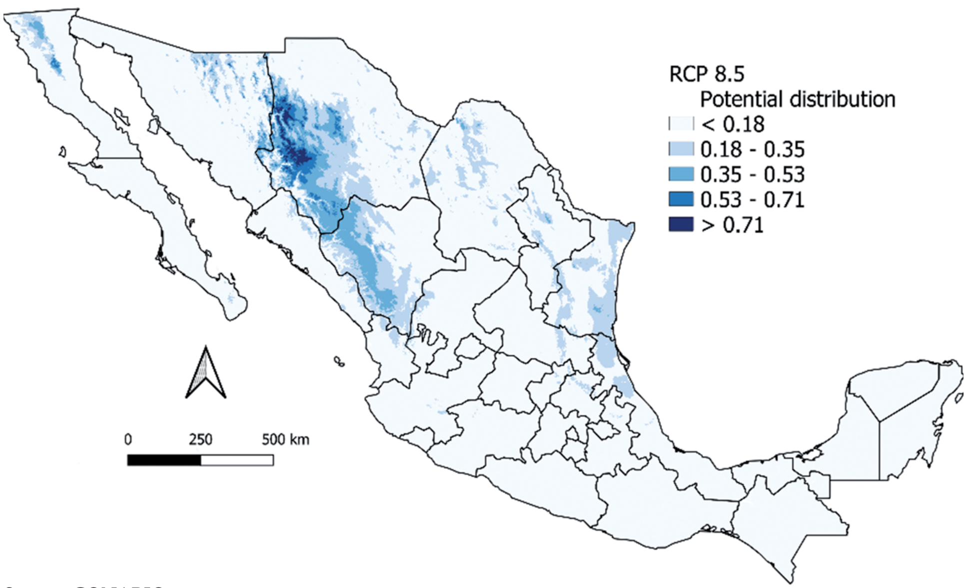
Source: CONABIO

Fig. 4. Projected distribution of *S. scrofa* in 2050 under RCP 4.5 scenario



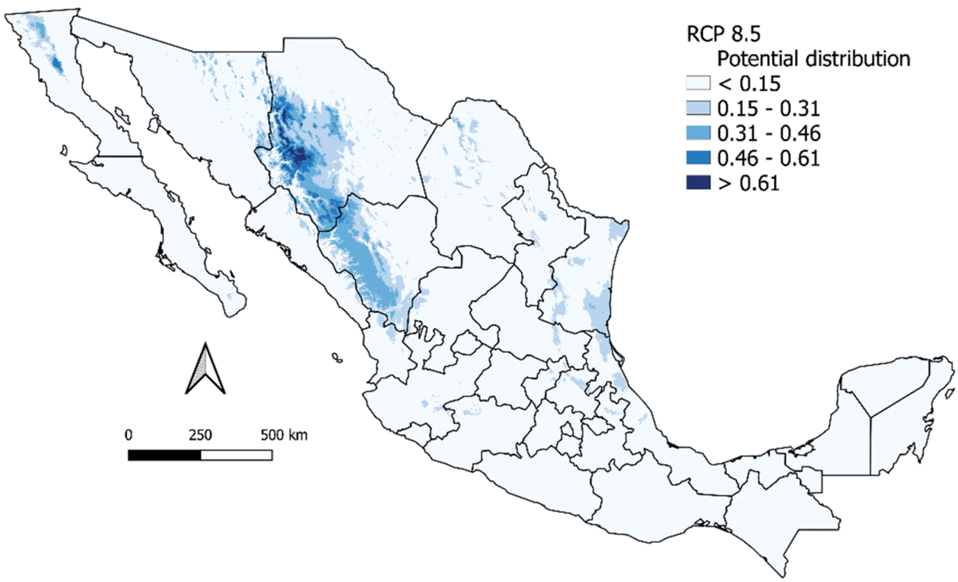
Source: CONABIO

Fig. 5. Projected distribution of *S. scrofa* in 2070 under RCP 4.5 scenario



Source: CONABIO

Fig. 6. Projected distribution of *S. scrofa* in Mexico in 2050 under RCP 8.5 scenario



Source: CONABIO

Fig. 7. Projected distribution of *S. scrofa* in Mexico in 2070 under RCP 8.5 scenario

4. Discussion

4.1. Protected area and invasive species in Mexico

Conservation efforts by government agencies must be directed toward disease surveillance at the IAS and wildlife protection agencies. Studies have shown that protected land in Mexico is highly fragmented; many protected areas are isolated (Fig. 2). Throughout Mexico, priority conservation areas are fragmented [Flores-Armillas et al. 2020]. Spatially, the largest centers of biodiversity are found in the south-central part of the country (Fig. 1).

The distribution of the *S. scrofa* is mainly noted in the north of the country (Fig. 3). Conservation and management efforts can be optimized for understanding social behavior in wildlife. *S. scrofa* is a prolific invasive species found in many regions of the world that causes extensive economic and environmental damage [De-la-Rosa-Aran et al. 2021]. Climate change may contribute to an increase in the range of *S. scrofa* (Fig. 4). *S. scrofa* cause damage to crops, and constitute vectors that cause infectious diseases in humans and livestock, therefore, managing populations of that species is essential for damage control. Since data on mammalian range and habitat selection is important for target species management, accurate spatial data could provide valuable information on how to set up a population management system to better understand the evolution of mammalian populations [Kappes et al. 2021].

4.2. Impact of *S. scofa* on ecosystem in Mexico

In the future, it is predicted that *S. scrofa* distribution will be larger, and clusters of abundance could be formed (Fig. 5). *S. scrofa* has established invasive populations throughout much of its introduced range (e.g., Australia, North America) through a combination of intentional introduction, escape and natural expansion, and removal is a key management strategy used to reduce the harmful effects of this animal on properties, livestock, sensitive habitats and native species [Aguirre-Muñoz et al. 2008, Lewis et al. 2019]. With the recent increase in the distribution and abundance of *S. scrofa* in North America, there has been a concomitant increase in the ecological and economic impact of *S. scrofa* on native and anthropogenic ecosystems [Tabak et al. 2017, Didero et al. 2020]. The expansion of this species' range is largely the result of deliberate introduction, free-range breeding practices, and the escape of domesticated pigs and wild boars from captivity. Domesticated *S. scrofa* can undergo frequent feralism or revert to a wild state. The *S. scrofa* exhibit highly plastic behavior, with matriarchal groups and solitary males, similar to *S. scrofa* in Europe. *S. scrofa* distribution will cover also the protected areas (Fig. 5). Climatic changes will increase the number of *S. scrofa*, however, population structure will be more diluted (Figures 6 and 7).

S. scrofa was introduced in the central Ñacuñán region of Argentina in the early twentieth century. The ecology of wild boar in a protected area in the Monte Desert biosphere in Argentina coincides with the feeding habits and impact of invasive risk behavior [Cuevas et al. 2010]. The movement of pigs is positively correlated with the number of households, the number of hunting farms, the amount of public land, the number of wild pigs harvested by hunters, and the number of collection points. *S. scrofa* has been introduced into Mexico for sport hunting and the meat trade for human consumption, but their role in disease transmission to humans or domestic animals is limited.

In future years, the number of *S. scrofa* risk assessments will increase. However, Mexico's ecological niche modeling scenarios include another source of uncertainty in the form of the threshold chosen for map construction. The most realistic scenario is RCP 4.5 predicted by 2050 (Figures 4 and 5). Habitat integrity and diversity are threatened by the insertion of alien species into newly formed ecosystems, whether intentional or accidental [Rosalino et al. 2022]. Despite their dual roles as destructive invasive species and popular game animals, there remains a distinct lack of consistency in how wildlife researchers, managers, and policymakers relate to these animals [Ureta et al. 2022].

5. Conclusions

S. scrofa is both a destructive invasive species and a popular game animal in many parts of the world. Successful control of populations deemed invasive will require informed public support and sound scientific management, which requires clear communication about the species among the research community, wildlife managers, and the general public. *S. scrofa* can infiltrate large regions. A portion of the population survives most eradication programs in invasive species management situations, and it is unclear how *S. scrofa* behave when not eradicated. Climate change actions could help mitigate the damage caused by the rapidly expanding and destructive *S. scrofa*. There are still significant data gaps in biological and environmental studies, including education on invasive species, that need to be addressed. Additionally, economic and ecological damage can be assessed through control strategies, and management strategies for biological risk control may be implemented on that basis. A detailed plan for eradicating invasive species in the region is needed, including a schedule of actions to highlight the impact of climate change. Meteorological variations are of particular importance. Additional research and technical advances in modeling should be developed to help address conservation policy issues.

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