

Wiktor Halecki^{1*}, Nuria Aide López-Hernández²

¹Nano-Tech Environmental Polska sp. Z o.o. al. Mickiewicza 21C/2 31–120 Kraków, Poland; *wiktormailmix.pl

²National Center for Disciplinary Research in the Relationship between Water, Soil, Plant, and Atmosphere (CENID RASPA) of the National Institute of Agricultural and Livestock Forestry Research, Km. 6.5 margen derecha Canal de Sacramento, C.P. 35079, Gómez Palacio, Durango, Mexico; lopez.nuria@inifap.gob.mx

Ecological implications: nature capital loss and the spread of invasive European wild rabbit in Mexico

Introduction

Protected areas (PAs) are crucial for preserving tropical biodiversity, but they face diverse threats. In Mexico, some PAs have experienced significant forest loss and fires, while others contend with elevated levels of mining and population density (Godínez-Gómez, 2020). These regions undergo fragmentation and have restricted maintenance zones. For example, La Montaña in Guerrero, Southern Mexico, faces social-ecological vulnerability with extreme poverty and deteriorating ecosystems, leading to challenges such as crop reductions and limited information access. The Oaxaca region in Southern Mexico, renowned for its high biodiversity, lacks officially designated protected areas (Robson, 2007). In the Yucatan Peninsula, the Punta Laguna Nature Reserve (also known as Otoch Ma'ax Yetel Kooh) stands out as a pristine haven with kilometers of untamed rainforest, providing an ideal setting to encounter the diverse wildlife of the Yucatan. This 5,000-hectare reserve is home to over 600 species, including spiders, howler monkeys, pumas, crocodiles, coatis, white-tailed deer, and various tropical birds (García-Frapolli et al., 2013). The Natural Protected Areas (NPAs) in the Yucatan Peninsula, Mexico, have witnessed a transformation in resource management practices by Yucatec Mayan communities. Despite benefiting from robust social organisation, these communities must proactively address the challenges of climate change and implement structural improvements to enhance their resilience (Galicia-Gallardo et al., 2023). This global phenomenon underscores the urgent need for rigorous monitoring, comprehensive evaluation, and strategic management of introduced species to effectively mitigate their potential ecological impact.

The European wild rabbit, *Oryctolagus cuniculus* L., has become established in the natural environment of Mexico, presenting both a pest and a conservation concern, particularly in areas heavily grazed. Originally native to the Iberian Peninsula, southern France, and North Africa (Wilson, Reeder, 2005; Burgin et al., 2020), this species has been successfully introduced to South America since 1936. Presently, it is found to a limited extent in Chile, Argentina, the Falkland Islands, and the Caribbean (Burgin et al., 2020). Recognising the potential environmental impact of European wild rabbits in new regions is essential for enhancing habitat and conservation initiatives (Parada-Díaz et al., 2022).

This study pursued two primary objectives: initially, to quantify the loss of natural capital over a thirty-year period (1), and subsequently, to explore the impact of European wild rabbits on habitat degradation and landscape alteration in the context of climate change scenarios (2).

Material and methods

Short characteristic of study species

The body length of *Oryctolagus cuniculus* (syn. *Lepus cuniculus* L.) is 360–380 mm (excluding the tail), tail length 65–70 mm, ear length 70–80 mm, hind foot length 80–89 mm; body weight 1.5–3 kg (Schai-Braun, Hackländer, 2016). Its back is brown-grey, steel-grey or yellow-grey, and the underside of the body is white-grey or ash-grey (Ophoven, 2006).

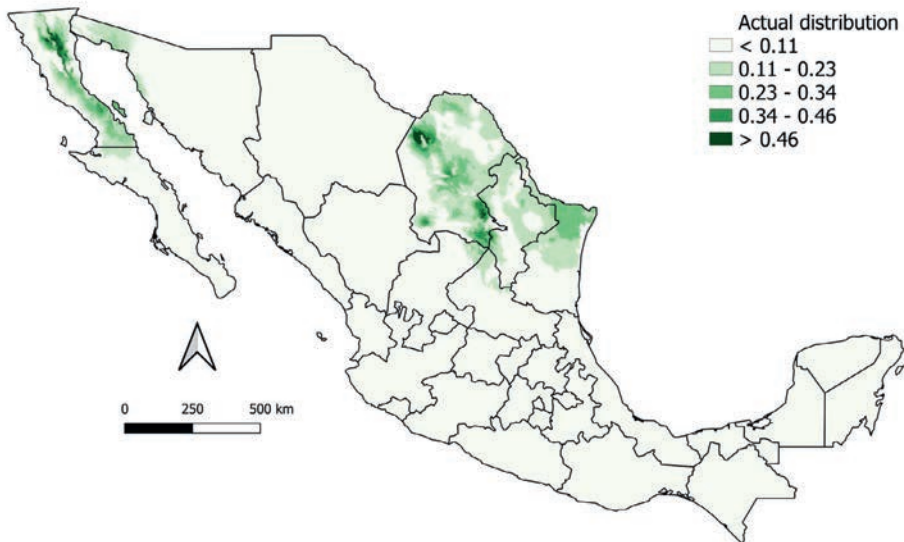


Fig. 1. Current distribution of *Oryctolagus cuniculus* L. in Mexico

The short tail is black on top and white on the bottom. The tips of the rabbit's ears are brown, and the ears tips of the European hare, with which it is sometimes confused, are black. The European hare also has longer ears and hind legs (Reichholf, 1996).

Ancient introductions of the subspecies of the typical European wild rabbit probably during the Roman Empire spread it throughout Europe, and it is now found in most of western, central and eastern Europe and on the Mediterranean and Macaronesian islands. In the 20th century, it was released in the Black Sea steppes of Ukraine and Russia (Northern Caucasus). It was introduced to Australia in 1788 and again in 1859, where it is now widespread (Burgin et al., 2020). In many regions it is considered an invasive species, dangerous to natural native habitats (Fig. 1).

Methods

The Natural Capital of a country is defined by the natural physical environment. The Natural Capital model incorporates the essence of resources that allow a country to be completely self-sustaining: land, water, climate, biodiversity, food production and capacity, and energy and mineral resources. In addition, the level of depletion or degradation of those resources that could endanger future self-sufficiency are taken into account to reflect the full picture of the available natural capital. The Natural Capital Index (NCI) is based on 33 quantitative indicators, forming six clusters – water, other natural resources, biodiversity, food security, infrastructure and nature, and exposure to climate risks. This concept harmoniously fuses factors related to species composition, structure, and function, drawing from a wealth of research (Mora, 2019). Series 7 of the NCI provided valuable insights into the abundance and health of ecosystems during the years 1985, 1993, 2011, and 2021. This compilation was centred around the ecological integrity indicator and drew from the extensive dataset of natural landscapes, meticulously derived from the INEGA (Instituto Nacional de Estadística, Geografía e Informática) 7 series of vegetation and land use. The NCI was a result of rigorous calculations, taking into account the count of surviving natural landscapes and the ecological health of intricate predator-prey dynamics. Notably, the NCI seamlessly integrated geographical data, illuminating the condition and coverage of each 1 km² habitat pixel. It's important to mention that these data were last updated in 2022.

Mexico's assessment of ecological integrity scrutinises the conditions of habitats that dictate and sustain intricate systems of interactions between apex predators and their prey. This exhaustive evaluation leverages interaction networks involving a multitude of species, comprising 43 top predators (comprising 9 mammals and 34 birds of prey) and a comprehensive array of their primary prey (amounting to 210 species). These invaluable data sources were retrieved from the esteemed Portal de Geoinformación – *Sistema Nacional de Información Sobre Biodiversidad* (SNIB), and they are made available

under the Creative Commons Atribución 4.0 Internacional license, which harmonises seamlessly with the data utilisation guidelines stipulated by datos.gob.mx.

NCI serves as a revealing metric, delineating the portion of dwindling natural areas, and their quality, all gauged by the Ecological Integrity Index determined by PCA (Principal Component Analysis) review of high protection status sites. Utilising PCA conducted with records from a database of endangered sites in Mexico, the species' climatic tolerance limits and approximation of its fundamental ecological niche were determined. Biodiversity survey sites were selected based on essential environmental and geographic information. Although species distribution data isn't mandatory, its reliability can be useful to assess site effectiveness. The use of block-like partitioning in the two-dimensional environmental space ensures a more uniform selection of survey sites. The tool assesses species abundance through cluster measures. In addition, diversity was assessed using presence-absence matrices (PAMs) with the aid of R-Studio, a free and open-source data science software (*R Core Team, 2022*).

Sites across Mexico selected for comprehensive monitoring of the species. Clusters in this representation indicate areas that should be included to monitor changes in biodiversity. The figure within the cluster illustrates the quantity of sites with similar nature values, facilitating more homogeneous surveys in monitoring. Block-like partitioning

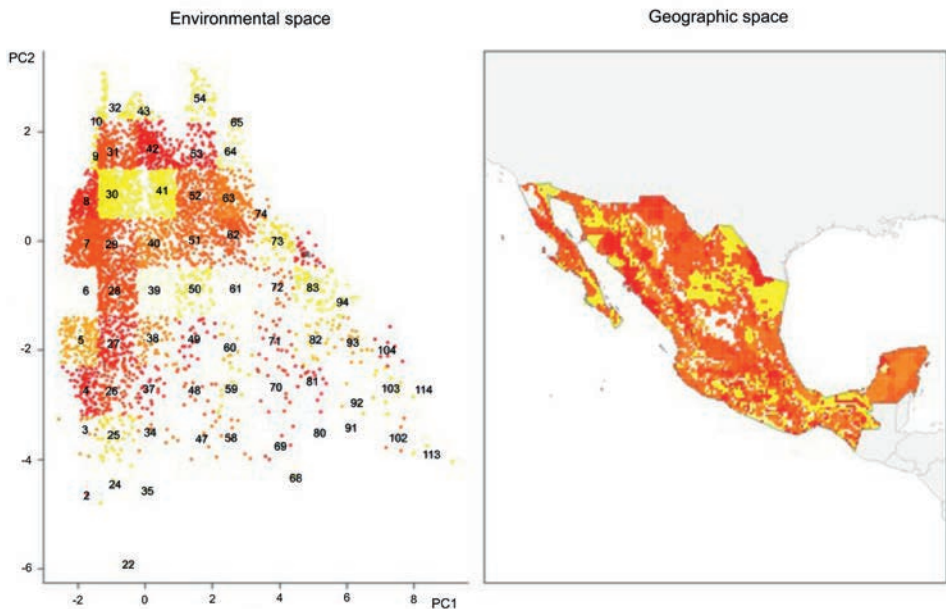


Fig. 2. Spatial visualisation as determined by PCA review of high protection status site in Mexico; geographic space was visualised by repositioning hotspots, with red indicating high species abundance and yellow indicating lower abundance

in PCA space is used to enhance uniform sampling site selection. Geographic space corresponds to the surface of Mexico, while environmental space involves multidimensional environmental variables.

Results and discussion

Nature conservation in Mexico

A computational model revealed that strategies integrating traditional activities supported conservation and enhanced household resilience in terms of income and food availability. This underscores the significance of local practices for resilience and the effectiveness of computational modelling in synthesising information from various sources (García Jácome et al., 2020). Socio-economic conditions are also important (Calderón-Contreras, White, 2020). To safeguard these unique areas, future conservation efforts should focus on establishing natural protected areas (Arenas-Navarro et al., 2023). PCA (Principal Component Analysis) indicated locations with a high diversity of species (Fig. 2) both in the northern and southern parts of the country (Fig. 3).



Fig. 3. Administrative divisions in Mexico. Source: Free Spatial Data (DIVA-GIS)

During 30 years, the Natural Capital Index (capital of ecosystems) has declined significantly in the central part of Mexico and in urbanised areas (Figs. 4–5 – Appendix 1). In 1985, the value of natural capital was high, with most rural areas at a level of 0.8 (Fig.

4A– Appendix 1). This state persisted until 1993 (Fig. 4B). It was not until 2011 that certain areas near cities and some rural regions dropped to 0.20. In the central part, values ranged from 0.4 to 0.6 (Fig. 5A – Appendix 1). Coastal regions, on the other hand, witnessed a notable decline in natural capital, possibly due to deforestation. From 2021, the values of areas with high potential and natural capital have been decreasing (Fig. 5B – Appendix 1). The average values of the Natural Capital Index (NCI) predominantly coalesce within the central core of the nation. Values as diminutive as 0.2, and those falling within the limited spectrum of 0.2 to 0.4, are currently evident, extending their presence beyond urbanised environments to encompass unblemished, untouched natural expanses. Areas distinguished by their considerable economic affluence should be seamlessly integrated with established conservation areas.

Floods and droughts, major disasters, required state public policies to build resilient communities. In response to CONAGUA's request (Comisión Nacional del Agua), virtual forums and digital surveys in Baja California Sur were employed to understand community perception. This analysis highlighted the need for improved information and increased community involvement in climate adaptation, reducing vulnerabilities (Imáz-Lamadrid et al., 2023).

Climate change: a scenario for *Oryctolagus cuniculus*

O. cuniculus is currently widespread in the northern part of Mexico, with the largest populations concentrated in the states of Baja California, Coahuila, Tamaulipas, and Nuevo León (as shown in figures 1, 3). The suitability index is calculated to be 0.46. According to the modelling results, most of the suitability values fall within the range of 0.34 to 0.46. Under the RCP 4.5 scenario, it is predicted that by 2050, *O. cuniculus* will expand its range southward (Fig. 6A – Appendix 1). Climate changes projected by 2070 are expected to lead to even larger ranges, although the suitability is anticipated to be lower, ranging from 0.26 to 0.34 (Fig. 6B – Appendix 1). When considering the RCP 8.5 scenario, *O. cuniculus* is also projected to expand its range by 2050 (Fig. 7A – Appendix 1). However, according to the scenario projections for RCP 8.5, the presence of *O. cuniculus* is expected to decrease and possibly disappear entirely in Tamaulipas. By 2070, concentration centres for rabbit populations may appear in specific locations, with a high suitability index ranging from 0.65 to 0.79 (Fig. 7B – Appendix 1).

Impact of lagomorphs on ecosystems

In various parts of the world, the introduction of new species has emerged as a significant concern (Somerville, Sugiyama, 2021). This issue gives rise to ecological challenges due to the diverse applications these species have in landscape-scale therapy (Kerr et al., 2021). A notable example of this problem can be observed in Australia, where the introduction of wild rabbits triggered a consequential biological invasion (Alves et al.,

2022). In Mexico, eight endemic lagomorph species are found, with several of them listed as endangered. Diets can serve as a valuable reference point for comparing the diets of other Mexican hares (Farias, 2004). Studies in both native and introduced ranges have highlighted the substantial spatial variability of rabbit abundance at local and landscape scales, influenced by various factors such as habitat diversity (Delibes-Mateos et al., 2012). In European hares (*Lepus europaeus* Pallas), 17 potentially infectious pathogens have been detected (La Sala et al., 2021). Research has shown a positive correlation between rabbit abundance and temperature, while a negative correlation exists between rainfall and rabbit abundance (Bello-Rodriguez et al., 2021). Therefore, rabbits alter their habitat, favouring less palatable or even invasive alien species, while limiting or even eradicating many native and endemic species (Cubas et al., 2021). Many factors may have contributed to its success including parasite reduction and its spread. Other rabbits are sensitive to environmental stress. For example, faecal cortisol metabolites have been measured in Vulcan rabbits (*Romerolagus diazi* Ferrari-Pérez) living in a naturally protected area (Rizo-Aguilar et al., 2014).

The *Oryctolagus cuniculus* dominates in the north of the Mexico (Fig. 6 – Appendix 1). The range of the *O. cuniculus* will be wider in circumference compared to now (Fig. 7A – Appendix 1). A trophic cascade makes it difficult to maintain (in its native range) or eradicate (in its introduced range) this species. Therefore, the new range of this taxon is found to exhibit extreme environmental plasticity (Tate, Marco, 2014). *O. cuniculus* is one of the most successful invasive mammals in Mexico. Consequently, predictions of a wide range of complex effects, such as stress on climatic factors, should be described. Climate change, as predicted by the model, has shown that by 2050 there will be an increase in the *O. cuniculus* range (Fig. 6A – Appendix 1). *O. cuniculus* can be considered an excellent model for demonstrating the influence, that an introduced mammalian species can have on the ecosystems into which it is introduced. This impact may be exacerbated by climate change between 2050–2070 (Fig. 6B – Appendix 1).

It may be useful to measure species distribution to get a clearer picture of spatial patterns and prioritise actions, especially in regions where rabbits have become invasive (Marín-García, Llobat, 2021). Alternatively, repopulation of control areas can be strongly influenced by the characteristics of individuals left in the area and/or recolonising (i.e., an ideal despotic distribution). The removal of dominants or sub-dominants can impact how quickly an area recolonises (Flores-Armillas et al., 2020). Knowledge and interest in domestic rabbits are associated with families that participate in agricultural activities and animal husbandry. Agricultural and livestock activities, hunting, and meat have been traditionally consumed since pre-Hispanic times (Somerville, Sugiyama, 2021).

The islands harbour a disproportionate amount of the Earth's biodiversity, but much of it has been lost largely due to the impact of invasive mammals. Island conservation in western Mexico provides an effective approach that can easily be applied to other

archipelagos where conservation efforts have been limited (Aguirre-Muñoz et al., 2008). The San Jose brush rabbit has the smallest distribution of any lagomorph species. *Sylvilagus mansuetus* Nelson is threatened by feral cat populations and by human activities, including illegal hunting, the development of tourist areas, and a salt mine. Human activities can severely affect San Jose Island, in the Gulf of California (restricted areas in Mexico) and threaten the survival of this species (Lorenzo et al., 2011). As a result of this tolerance, the hare has become a successful invasive species in Mexico (Aguirre-Muñoz et al., 2008).

Due to its remarkable environmental tolerance for subantarctic to equatorial temperatures and its ability to persist at such low numbers, the European wild rabbit has remained an invasive species for over a century. Consequently, rabbits are reshaping the landscape in these new habitats, preferring less palatable or even invasive alien plant species, while limiting or even exterminating many native and endemic plants (Lees, Bell, 2008).

Traditional production systems, such as homes and community gardens, have been maintained throughout history and have contributed to the survival of rural populations. The home garden is a low-risk agricultural system that allows families to mitigate the effects of periods of scarcity through the continued production of crops for consumption or commerce. In Mexico, the home garden is highly distributed and acts as a mainstay of the country's cultural identity. The changes that are taking place in the lifestyles of families, especially in their diets, favour the occurrence of *O. cuniculus* (De Guevara et al., 2019).

Increased temperatures, annual precipitation, and wind speed have been additional factors affecting the occurrence and impact of hares (Anderson et al., 2009). For conservation reasons, it is necessary to better identify important dietary food species and obtain data on their availability in the face of climate change. This results may be useful for nature conservation. For example, eastern cottontail (*Sylvilagus floridanus* J.A. Allen) is quite selective in consuming certain species of herbs and grasses. Since the vegetation record only poorly represents the rabbits' diet, a more targeted approach is suggested for future studies, as these lagomorphs chose specific plant species even when they became scarce during the dry season (Hudson et al., 2005). High-impact conservation: invasive mammal eradications from the islands of western Mexico. Dispersal of *O. cuniculus* populations has important implications for the availability of suitable, habitat under current (Fig. 1) and future climate scenarios (Fig. 6–7).

This article highlights the status of *O. cuniculus*, which is endangered in its native range. In Mexico, though, this was a very successful invasion. For example in Ukraine, the landscape has undergone significant transformation due to factors like urbanisation, industrialisation, which resulted in a decline in the rabbit population (Zagorodniuk, 2023).

The European wild rabbit is a keystone species in Iberia, and the survival of many endangered predator species, including the Iberian lynx (*Lynx pardinus* Temminck) and the Spanish imperial eagle (*Aquila aldaberti* C.L. Brehm), depends on the recovery of rabbit populations. High snowfall heights in heathland and grassland ecosystems are very important for the survival of *O. cuniculus* (Lees, Bell, 2008; Cabezas-Díaz et al., 2009). *O. cuniculus* appears to be distinct in this context, as no other mammal simultaneously serves as an endangered keystone species within one habitat while also causing detrimental exclusion in another.

Conclusions

[1] Spatial visualisation through the Natural Capital Index (NCI) serves as an informative metric, providing a clear depiction of the extent of our diminishing natural landscapes and their quality, as assessed by the Ecological Integrity Index. Over 30 years, the Natural Capital Index (NCI) has significantly declined in the central part of Mexico and urbanised areas. In 1985, the NCI was high, with most rural areas at a level of 0.8. This state persisted until 1993. However, by 2011, certain areas near cities and some rural regions had dropped to 0.20. This precise spatial information offers invaluable insights for establishing robust population management systems and enhancing our understanding of mammalian population dynamics; [2] Continued advancements in research have the potential to fill critical knowledge gaps, facilitating a deeper understanding of the ecology and management of *Oryctolagus cuniculus*. It emphasises the significance of considering the long-term ecological consequences associated with introducing new species, even when they serve valuable purposes in specific contexts. The populations of *O. cuniculus* may be greatly impacted by a fluctuating climate. It is necessary to develop a comprehensive plan to reduce the number of this invasive species in the region, including a schedule of actions to counteract the effects of climate change.

Conflict of interest

The authors declares no conflict of interest related to this article.

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Appendix 1

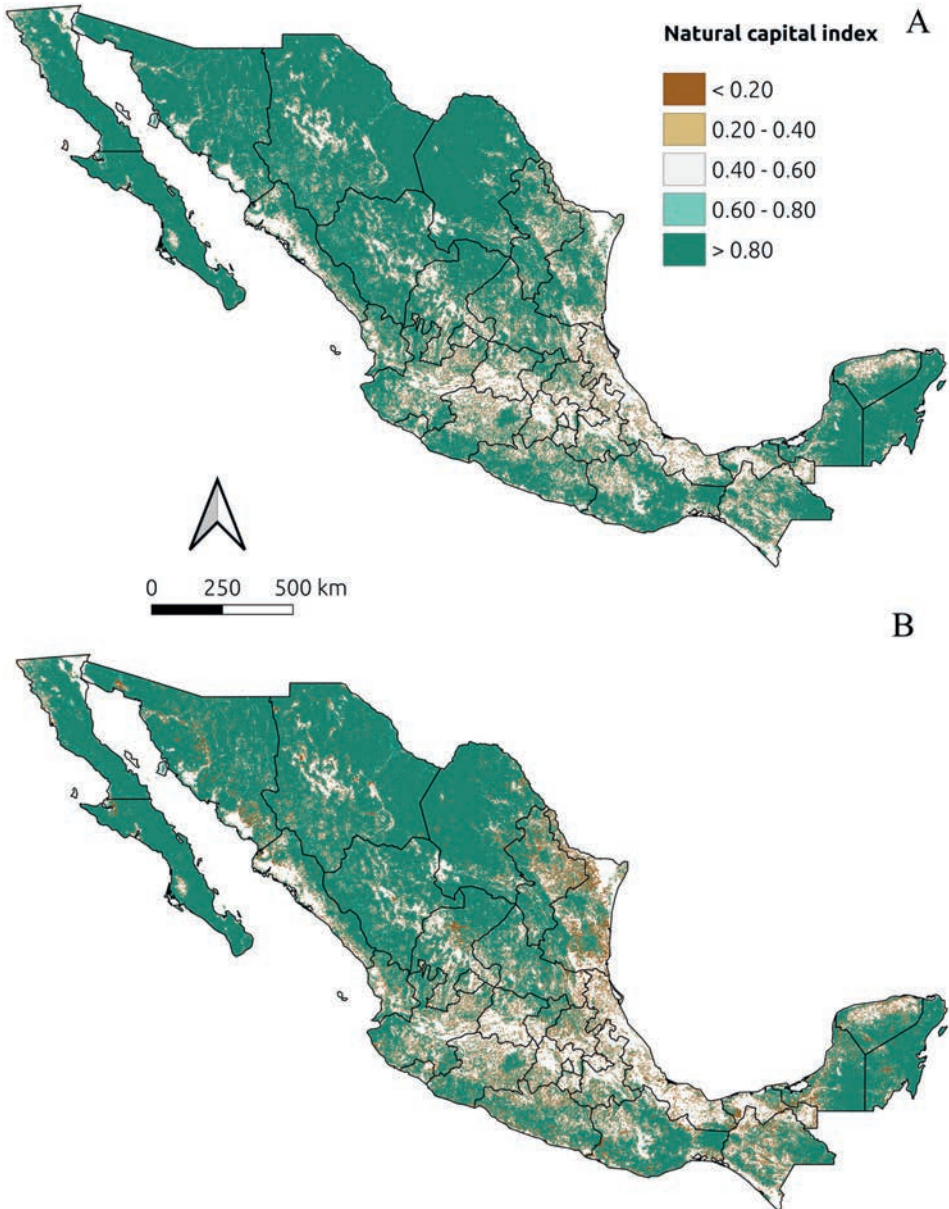


Fig. 4. Natural Capital Index in Mexico: A - 1985, B - 1993

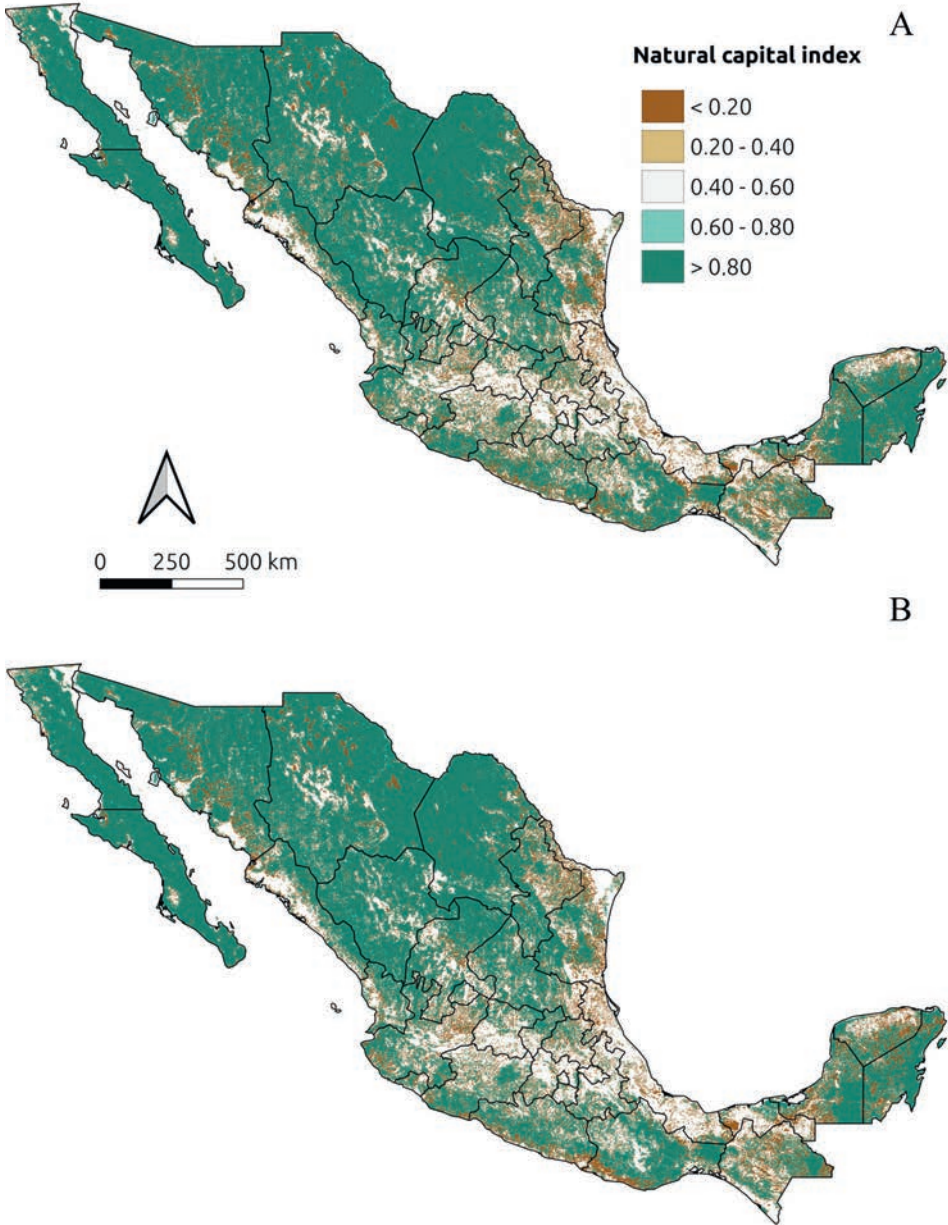


Fig. 5. Natural Capital Index in Mexico: A – 2011, B – 2021

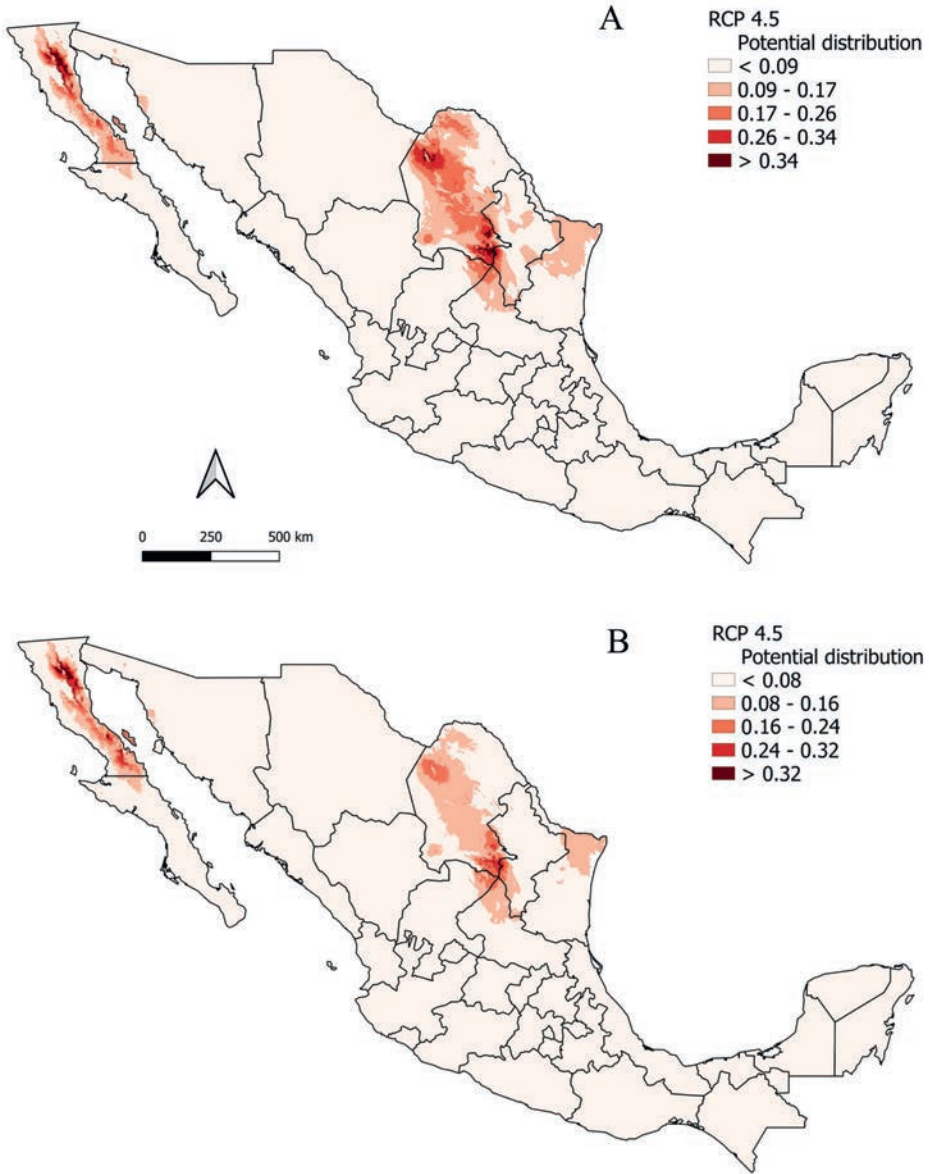


Fig. 6. Projected distribution (predicted habitat suitability) of *Oryctolagus cuniculus* L. under RCP (Representative Concentration Pathway) 4.5 scenario in: A – 2050, B – 2070

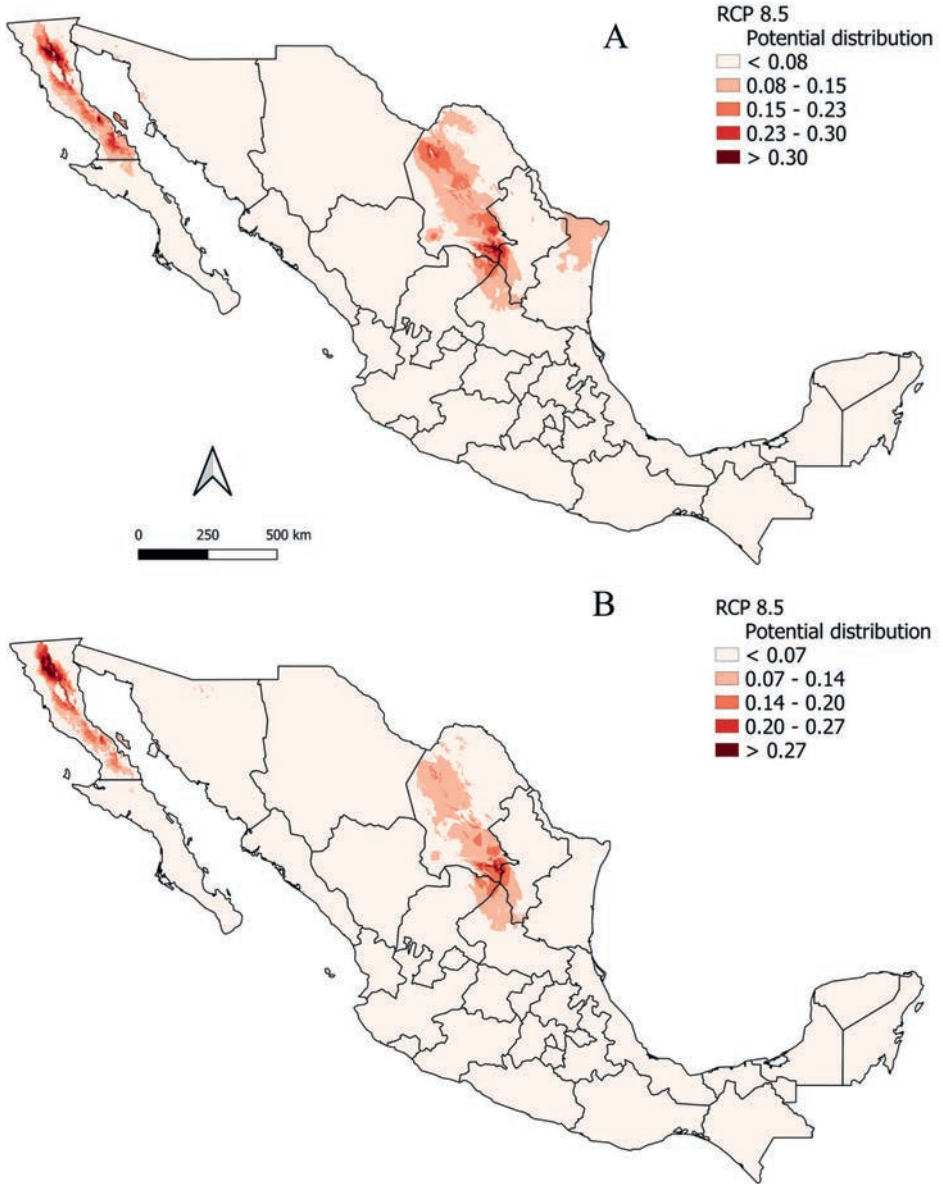


Fig. 7. Projected distribution (predicted habitat suitability) of *Oryctolagus cuniculus* L. under RCP (Representative Concentration Pathway) 8.5 scenario in: A - 2050, B - 2070

Abstract

Ecological integrity, a pivotal concept, characterises the capacity of an ecosystem to perpetuate an interwoven, sustainable, and adaptable ecological system that encompasses the entire spectrum of elements and processes one would anticipate in the natural backdrop of a given region. This article also sheds light on the status of the wild European rabbit (*Oryctolagus cuniculus* L.), which faces endangerment in its native habitat. Conversely, in Mexico, it has proven highly invasive. The presence of European rabbits in Mexico can lead to direct competition with native herbivores, potentially reducing their populations and altering the species composition of plants. Efforts to mitigate the ecological implications of invasive European rabbits in Mexico may include the implementation of control and eradication measures, the restoration of native habitats, and increased public awareness, education about the impact of invasive species on ecosystems. These actions are essential to safeguard Mexico's biodiversity and Natural Capital Index. A practical recommendation in this research is to fortify the protection ranges of isolated priority areas. *O. cuniculus* distribution may increase in the future. Eliminating rabbits from certain sites can generate more problems than it solves.

Keywords: climate change, ecological paradox, nature conservation, projected distribution

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Ekologiczne implikacje: Utrata kapitału naturalnego, a rozprzestrzenianie się inwazyjnego królika europejskiego w Meksyku

Streszczenie

Ekologiczna integralność, to pojęcie kluczowe. Charakteryzuje zdolność ekosystemu do utrzymania spójnego, zrównoważonego i elastycznego systemu ekologicznego, który obejmuje pełen zakres procesów w ekosystemie. Artykuł ten opisuje status dzikiego królika europejskiego (*Oryctolagus cuniculus* L), który jest zagrożony w swoim rodzimym środowisku, a w Meksyku staje się gatunkiem inwazyjnym. Obecność królików europejskich w Meksyku może prowadzić do bezpośredniej konkurencji z rodzimymi roślinożercami, potencjalnie zmniejszając ich populacje i zmieniając skład gatunkowy roślin w regionie. Działania mające na celu złagodzenie ekologicznych konsekwencji obecności inwazyjnych królików europejskich w Meksyku, mogą obejmować wdrożenie środków kontroli i likwidacji, przywracanie rodzimych siedlisk oraz zwiększenie świadomości publicznej i edukację, dotyczących wpływu gatunków inwazyjnych na ekosystemy. Te działania są niezbędne do ochrony bioróżnorodności i poprawy indeksu kapitału naturalnego Meksyku. Praktyczna rekomendacja tych badań dotyczy ochrony przyrody dla izolowanych obszarów priorytetowych. Rozprzestrzenianie się *O. cuniculus* według prognoz będzie w przyszłości postępować. Jednak całkowite usunięcie królików z niektórych miejsc, może generować więcej problemów, niż skutków pozytywnych.

Słowa kluczowe: zmiany klimatyczne, paradoks ekologiczny, ochrona przyrody, predykcja rozmieszczenia

Information on the authors

Wiktor Halecki <https://orcid.org/0000-0001-7802-2849>

He is deeply interested in ecohydrology and cutting-edge ecological science. He explores the intricacies of Earth's water systems, specifically delving into intricate patterns and their implications.

Nuria Aide López-Hernández

She is passionate about agroecology. Currently, she is actively engaged in a creative project focused on ecological protection and the sustainable utilisation of natural resources.