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ORIGINAL PAPER

# Climate change and non-native species in the Spanish Network of National Parks

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**Abstract** The Iberian Peninsula is a primary entry point for non-native species (NNS) into Europe via maritime routes, and is a significant tourist destination. This positions the highly diverse Spanish National Parks at high risk from invasive species, necessitating proactive adaptation and mitigation strategies. We present a comprehensive analysis of the risks posed by NNS to the network of 15 continental and marine National Parks in Spain under climate change, aiming to align management strategies with international Global Biodiversity Framework (GBF) targets. We identified 200 NNS across the network of National Parks, including 78 listed in national NNS regulations. Park managers helped identify 22 priority NNS, including the water hyacinth, American mink, Cape fig and wakame, among others. Over half of the 22 priority NNS (55%) were classified as having a "Major" impact on native biodiversity according to EICAT standards, with another 23% considered "Massive". Distribution models suggest that rising minimum temperatures could enable NNS to expand in altitude within the parks, particularly in high-mountain parks. Species like the barbary sheep, water hyacinth and largemouth bass may particularly benefit from global warming. Our findings prioritize national parks most vulnerable to the double threat posed by climate change and invasive species, such as Islas Atlánticas, Doñana and Archipelago de Cabrera. We conclude that, in order to progress towards achieving GBF goals, it is essential to: (i) coordinate NNS management efforts across administrations (national and regional), (ii) integrate resources and expertise in a unified strategy against invasion across the network and (iii) enhance public awareness about the risks of introduction and impact of NNS.

**Resumen (in Spanish)** La Península Ibérica es el principal punto de entrada de especies exóticas invasoras en Europa a través de las rutas marítimas, además de un importante destino turístico. Esto sitúa a los Parques Nacionales españoles, de extraordinaria diversidad, en una situación de alto riesgo frente a las invasiones biológicas, lo que requiere estrategias proactivas de adaptación y mitigación. En este estudio presentamos un análisis exhaustivo de los riesgos que suponen las especies invasoras para la red de 15 Parques Nacionales de España, con el objetivo de alinear las estrategias de gestión con los objetivos internacionales del Marco Global de Biodiversidad (GBF). Identificamos más de 200 especies exóticas presentes en la red de Parques Nacionales. Si bien no todas han

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de ser dañinas, al menos 68 está incluidas en el Catálogo Nacional de Especies Exóticas Invasoras. El personal técnico de los parques nos ayudó a identificar 22 especies exóticas invasoras de preocupación para la Red de Parques, como el jacinto de agua, el visón americano, la uña de gato y el wakame, entre otras. El 55% de las especies de preocupación se clasificó como de impacto "Mayor" sobre la biodiversidad autóctona según los criterios de la EICAT, y otro 23% se consideró "Masivo". Los modelos de distribución sugieren que el aumento de las temperaturas mínimas podría permitir a las especies exóticas invasoras expandirse en latitud y altitud dentro de los parques, especialmente en las zonas de alta montaña. Especies como el arruí, el jacinto de agua y la carpa americana podrían beneficiarse especialmente del calentamiento global. Nuestros resultados ayudan a priorizar las especies exóticas y los parques nacionales de mayor riesgo, como Islas Atlánticas, Doñana y el Archipiélago de Cabrera. Concluimos que para avanzar hacia la consecución de los objetivos del GBF, es esencial: i) mejorar la coordinación entre las administraciones competentes en la gestión de especies invasoras (nacionales y regionales), ii) integrar recursos y la experiencia ganada en los distintos parques hacia una estrategia de lucha contra las especies invasoras de aplicación en toda la red y iii) trabajar en la divulgación y concienciación pública respecto a los riesgos de introducción y el impacto sobre la biodiversidad de las especies invasoras.

**Keywords** Climate change · Non-native species · National parks · Species distribution models · EICAT · Biodiversity conservation · Global Biodiversity Framework

## Introduction

The Iberian Peninsula operates as a primary stepping stone for non-native species (NNS) into Europe, particularly through maritime routes, positioning it as a hotspot for invasive species (Leprieur et al. 2008; Maceda-Veiga et al. 2017; Ascensão et al. 2021). Its role as a major tourism destination further amplifies the risk of introducing NNS into the continent (Anderson et al. 2015). At the same time, the Iberian Peninsula is expected to experience increased aridity and a higher frequency of extreme weather events, making it one of the most vulnerable regions in Europe to climate change (Fonseca et al. 2016; Cardoso Pereira et al. 2020). Heatwaves, cold spells and droughts lead to declines in body condition, life history traits, abundance, distribution and recovery of native animal species, whereas impacts on non-native animals are significantly lower (Gu et al. 2023). These three factors –NNS, tourism and climate change—constitute major threats to biodiversity conservation in protected areas, and their combination is especially alarming in the Iberian Peninsula, a global biodiversity hotspot harbouring a significant portion of European plant and terrestrial vertebrate species, along with a high level of endemicity (Myers et al. 2000; Araújo et al. 2007; Chappuis et al. 2012; Molina-Venegas et al. 2015)

The Spanish Network of National Parks plays a crucial role in preserving the natural heritage of the Iberian Peninsula (Araújo et al. 2007), and with 14 million annual visitors, it is also an important tourism attraction (OAPN 2022). With the recent addition of Sierra de las Nieves in 2021, the 16 national parks in the network encompass a wide array of habitats across the country, including mountain ranges, forests, wetlands, grasslands and meadows, arid and semiarid environments, Mediterranean scrublands, island and marine ecosystems. National Parks play a crucial role in protecting numerous endemic and protected species in Spain, particularly in the Canary and Balearic Islands. Given the compounded risks associated with climate change, rising tourism, and the introduction of NNS, the Spanish Network of National Parks requires the implementation of evidence-based, proactive mitigation strategies. These strategies should prioritize efforts on invasive species and areas at the highest risk, thereby effectively contributing to the achievement of the Global Biodiversity Framework's (GBF) objectives.

The GBF establishes ambitious targets aimed at the conservation of native biodiversity. These targets are critical for maintaining ecosystem resilience, ensuring the provision of essential ecosystem services, and safeguarding the genetic diversity necessary for adapting to changing environmental conditions. For example, well-preserved protected areas facilitate the progressive adaptation of communities to temperature increases (Gaüzère et al. 2016), and act as a biological filter against the advance of NNS (Foxcroft et al. 2011; Gallardo et al. 2017). This is particularly important considering that climate change and NNS are likely to interact, with climate change allowing NNS to move faster, farther and exacerbating their impacts (Rahel et al 2008, Walther et al. 2009, Bradley et al. 2024). In terms of addressing NNS, meeting the GBF targets involves a focused, strategic effort to identify and address the most vulnerable ecosystems and the NNS that pose the greatest threat, leveraging current research and predictive modelling to inform decision-making. By concentrating resources on high-risk areas and NNS, the Spanish Network of National Parks could more efficiently ensure the conservation of native biodiversity and its resilience against the escalating challenges posed by climate change and human activities.

In this framework, the objectives of this study are to: 1) compile information on the number of NNS reported in the Spanish Network of National Parks; 2) prioritize a short-list of current and future prospective NNS of concern for the majority of parks; 3) evaluate the potential impacts of selected NNS on native species; 4) model the potential distribution of selected NNS under current and future climate scenarios for 2050. The novelty of this research lies in the development of a database and models that will enable monitoring the progress of the Spanish National Network of National Parks towards achieving GBF Targets.

## Methods

This study encompasses 15 National Parks of the Spanish Network, excluding Sierra de las Nieves, which was declared in 2021. This is because part of the research was conducted in 2020 and 2021 before the park was officially declared, and the lack of systematic information about the presence of species in the new park comparable to that available for the rest of the parks. Additionally, restrictions on human activities in Sierra de las Nieves may have differed until its declaration from the rest of the parks. These variations in monitoring and management could have a substantial impact on the trends in NNS introduction, spread, and management within this park.

The methodological approach was structured into five steps. Each step builds upon the previous, ensuring that the research outcomes offer practical insights and actionable recommendations to advance towards meeting GBF targets within the Spanish Network of National Parks.

### Step 1: Identify NNS present in the Spanish Network of National Parks

First, we collected all available evidence of NNS reported within the limits of 15 National Parks (Suppl. Info 1, Table S1). For each National Park, we collected the following information: year of declaration, dominant habitat (wetland, mountain, Mediterranean forest, shrubland, sea), total surface (ha), and the number of visitors in 2022 (OAPN, 2022).

We collected all information available on the presence of non-native species in the annual technical reports of the National Parks (http://www.mapama.gob.es/es/red-parques-nacionales/nuestros-parques/), regional databases (e.g., ExoCat, https://mediambient.gencat.cat/, Invasara https://www.invasara.es/, Redexos https://www3.gobiernodecanarias.org/), reports in the news, Google Scholar, and the Spanish journals Quercus (www.revistaquercus.es), Limnetica (www.limnetica.net) and Ecosistemas (www.revistaecosistemas.net). We used as keywords, Topic = "national park" AND "Spain", AND Topic = "invasive OR exotic OR introduced OR non-native" in English and Spanish. We chose Google Scholar as our primary search tool because many important records regarding non-native species within the Spanish National Parks are published in Spanish, often in technical reports and documents. However, we acknowledge that other academic search engines such as Web of Science or Scopus may reveal additional sources of NNS information.

Our approach to compiling this list was liberal; we did not distinguish between widespread and abundant invaders, those with very restricted invasions, or even NNS with temporal populations or that have already been eradicated. This inclusivity follows the precautionary approach, aiming to identify all species with potential to access and establish in the parks. In spite of these limitations, the database offers a baseline to monitor future changes in the total number of NNS reported within the network (Suppl. Info 1).

We used ANOVA and Pearson correlation tests to look for significant relations between the number of NNS and the basic characteristics (year of declaration, dominant habitat, total surface and number of visitors) or the parks.

Step 2: Select a subset of NNS of concern for the Spanish Network of National Parks

We collaborated with park managers to identify a subset of NNS of concern for further investigation. We organized a workshop and invited directors and technicians from the 15 National Parks and OAPN (*Organismo Autónomo de Parques Nacionales*), the national authority coordinating the network. A total of 22 representatives of 10 parks and OAPN attended the workshop, held in April 2020. Parks that were not represented in the workshop were also consulted by email. We discussed the challenges posed by NNS and climate change to the conservation of biodiversity and ecosystems in the parks. We collectively identified NNS of concern for further investigation with the following criteria: (1) NNS identified by park managers as a threat, (2) NNS relevant for a wide variety of National Parks (not specific to a single park), (3) availability of data on the species to conduct the analyses described in the next steps. Park managers followed the legal definition of invasive species under national regulation (Reg. 42/2007 on the conservation of biodiversity), where invasive species are those non-native organisms introduced or established in natural or semi-natural habitats, which are a driver of environmental change, and threaten the conservation of native biodiversity. Accordingly, NNS identified for this study are restricted to those listed in the Spanish Catalogue of NNS or the Union List of invasive species of European Concern in 2020. We ensured a balanced representation across different taxonomic groups (plants and animals), habitats (terrestrial, freshwater, and marine), and stages of invasion; ranging from species widely established across the country to those in the initial stages of invasion that may benefit from climate change in their expansion. We acknowledge that the selection of NNS was based on expert judgment, which inherently introduces some level of bias and limits the replicability of the process. However, this approach ensured that the species selected for further investigation aligned with the concerns of park managers.

Step 3: Impacts of NNS of concern in the Spanish Network of National Parks

We used the Global Invasive Species Database (https://www.iucngisd.org/gisd/), CABI-Invasive Species Compendium (https://www.cabidigitallibrary.org/product/QI) and the fact sheets of the Spanish NNS Catalogue (https://www.miteco.gob.es/es/biodiversidad/temas/conservacion-de-especies/especies-exoticas-invasoras/ce-eei-catalogo.html) to extract information regarding the taxonomy, geographic range (native and non-native distribution), pathways of introduction, habitat, population tendency in Spain, impacts and management options (Suppl. Info 2).

We used information about impacts to classify NNS of concern in terms of the magnitude of their detrimental impacts on native biodiversity, based on the IUCN Environmental Impact Classification of Alien Taxa (EICAT, https://www.iucn.org/resources/conservation-tool/environmental-impact-classification-alien-taxa). This tool is desinged to support the prioritization of invasive species for management and guide conservation efforts (Kumschick et al. 2024).

EICAT uses semi-quantitative criteria to assign each NNS to five categories of risk: Minimal Concern (MC), Minor (MN), Moderate (MO), Major (MJ) and Massive (MV), based on the highest level of impact observed on native biodiversity (Hawkins et al. 2015). The types of impact considered by EICAT are based on various mechanisms, including competition, predation, hybridization, disease transmission, parasitism, toxicity or presence of poisonous substances, biofouling, herbivory, flammability, among others. The EICAT guidelines includes clear criteria to classify each impact reported in the literature into MC, MN, MO, MJ or MV depending on its severity and reversibility. For instance, if the invasive species leads to declines in the population size of native species, but does not cause any population extinction, then the impact is classified as "Moderate". But if the NNS results in the local extinction of at least one native species, it is classified as "Major". The NNS is assigned the highest observed impact across all impacts recorded in the literature. Although EICAT is originally designed to conduct assessments on a global scale, here it was applied at the local to regional level.

Step 4: Model the potential distribution of NNS under present and future scenarios

We estimated the risk of establishment of the selected NNS of concern in the 15 National Parks using Species Distribution Models (SDMs). These models use data on the environmental conditions of sites currently inhabited by a species globally (native + invaded ranges), to identify areas that meet the same conditions and therefore may be susceptible to invasion in the medium or long term. Occurrence data was extracted from the: (i) *Global Biodiversity Information Facility* (GBIF) for continental NNS, (ii) *Ocean Biogeography Information System* (IOBIS) for marine NNS, iii) the study of Gallardo et al. (2017) that included all of the species investigated here. We cleaned occurrence data to remove erroneous or low-resolution records and resampled data at a resolution of 30 arc-second (approximately $1 \times 1$ km at the equator) for continental species and $10 \times 10$ km for marine species, to match the resolution of environmental variables used as predictors.

As predictors of NNS establishment in continental environments (terrestrial + freshwater), we used the bioclimatic variables of WorldClim-Global Climate Data portal, version 2 (https://www.worldclim.org/). Predictors used for marine species are described below. Continental bioclimatic variables are based on records of temperature and precipitation between the 1970 and 2000, and represent inter-annual trends, seasonality, and climatic extremes that can limit the survival of living organisms (Hijmans and Graham 2006). From the 19 available bioclimatic variables, we chose the four most significant to explain the large-scale distribution of the selected species according to Gallardo et al. (2017): the maximum temperature of the warmest month (Bio 5), the minimum temperature of the coldest month (Bio 6), precipitation of the wettest month (Bio 13), and precipitation of the driest month (Bio 14). We also included altitude as an important predictor for freshwater species that are usually concentrated at low altitudes where waterbodies tend to be concentrated, irrespective of temperature (Gallardo and Aldridge 2018, Gallardo et al. 2015). Additionally, to account for the human influence on the distribution of invasive species, we included "accessibility". This variable, developed by the University of Oxford (Weiss et al. 2018), represents the time (in hours and days) it would take to reach the nearest city with > 50,000 inhabitants from each pixel on the map. Thus, the variable integrates data related to transport infrastructure and population density, two key aspects for explaining the introduction of NNS on a global scale. While the accessibility variable may be better interpreted as "isolation" (since a high value indicates a long travel time), we chose to keep the original name for consistency with the literature. In all cases, the resolution of continental predictors was 30 arc-seconds (1 x 1 km aprox.). For the two invasive marine species, following Gallardo et al. (2017), we used the following variables as predictors of their potential spread: bathymetry, salinity, annual range of air temperature, annual maximum and range of sea surface temperature, and accessibility. Marine predictors are obtained from Bio-Oracle (Ocean Rasters for Analysis of Climate and Environment, http://www.oracle.ugent.be/, Tyberghein et al., 2012) at the highest resolution available, which in this case is 5 arc-minute ($10 \times 10$ km aprox.).

For continental future scenarios, we used two General Circulation Models (GCMs): the Community Climate System Model, version 4 (CCSM4), and the Centre National de Recherches Météorologiques-Coupled Model, phase 5 (CNRM-CM5). For each GCM, we chose a pessimistic emission trend (RCP = 8.5), and two temporal horizons: 2041–2060 (hereafter: 2050) and 2061–2080 (hereafter: 2070). Future scenarios for marine predictors included the UKMO-HadCM3 developed by the Hadley Centre for Climate Prediction and Research (Gordon et al. 2000), and three greenhouse emission trends: A1B, A2 and B1. Marine future scenarios correspond to 2041–2060 (hereafter 2050), and 2087–2096 (hereafter 2090). We assumed that the variables altitude, accessibility and bathymetry, which do not have future scenarios constructed to date, remain constant under future conditions. However, we can expect that the time spent to reach the nearest city (aka accessibility) will decrease as the construction of transport infrastructures and urban development continue, thereby promoting the expansion of NNS (Seebens et al. 2015).

To estimate the potential distribution of the selected NNS, we used ensemble models (Araújo and New 2007). This technique involves calibrating several replicas of a model using alternative modelling settings that are then combined into a final model. This allows us to account for the inherent uncertainty of the statistical model. In this study, we chose four of the algorithms most frequently used in SDM: Generalized Linear Models, Generalized Boosted Models, Random Forest, and Generalized Additive Models. This means that for each species, four models are calibrated, each using a different algorithm, which are then combined by calculating their weighted average based on the quality (True Skill Statistic, TSS) of each model. As input data, the model uses the coordinates of sites invaded by each species that are randomly divided into two sets: 70% of the occurrences for calibrating the model, and the remaining 30% to test the predictive capacity of the model. To evaluate the predictive capacity of the model, the indicators ROC (Area Under the Receiver Operating Characteristic Curve) and TSS (True Skill Statistic) were used. A model is considered to have good predictive capacity when ROC > 0.80 and TSS > 0.7.

After calibration, the models are projected onto the Iberian Peninsula, Balearic Islands, and Canary Islands for the current and four climate change scenarios. Subsequently, the prediction corresponding to each of the 15 National Parks was extracted. The result is a map of environmental suitability that reflects how similar each pixel is to the localities invaded by the species worldwide in a 0 to 1000 scale. This allows us to assess the NNS expansive or contractive trend in each National Park. In addition to the maps of suitability, SDMs also provide a simplified prediction optimized to reduce type II errors (probability of presence/absence: 0/1). By simply adding up these binary maps, we can calculate the potential richness of invasive species within each park and its evolution under future scenarios. We used paired t-test to investigate if differences in the predicted number of NNS with suitable habitat in each park changes under future scenarios.

It must be noted that models reflect suitability, that is, probabilities of invasion in the event of an introduction, and not absolute survival limits. A high suitability does not necessarily mean the species will establish, but simply that conditions are ideal. Environmentally suitable areas may never be occupied because of historical, dispersal or biotic limitations (Jimenez-Valverde et al., 2011), particularly in the case of aquatic species. For the purpose of preventing species invasions it is nevertheless preferable to overestimate rather than to underestimate their potential distribution. It is also important to recognise that IAS have the capacity to occupy wider niches than those predicted from their existing range (Gallardo et al. 2013), and so models may underestimate potential ranges that could be eventually occupied.

Step 5: Integrated risk assessment and prioritization

We integrated the results obtained in the previous steps to support the prioritization of NNS and parks under highest threat. Such an exercise is fundamental to minimize the threat posed by invasive species within protected areas, thereby advancing towards meeting the GBF targets. For this purpose, we transformed the data collected in previous steps into a semi-quantitative scale that allows us to calculate a risk index. Specifically, we evaluated the risk of introduction, establishment, impact, and management feasibility of each invasive species in each Park on a scale of 1 to 4, using the following rules (Table 1):

*Introduction* To assess the risk of introduction of each NNS in each Park, we used two main sources of information: 1) the vectors and pathways of introduction of the species, listed in our EICAT fact-sheets, and 2) the current presence of the species in or around the park. With the support of the park managers who attended our workshop on IAS and climate change, we considered the vulnerability of each individual park to the vectors and pathways of invasion of each specific NNS.

*Establishment*: Once introduced (intentionally or accidentally), the species requires minimum environmental conditions to survive and reproduce successfully. We used the median value of the species suitability within the Parks as a reference, using results from the SDM. However, it should be noted that other factors, such as the presence of competitors or natural predators, may limit establishment at the local scale. Also, that establishment can be possible under suboptimal climate conditions if microrefugia exist or propagule pressure is very high.

*Impact*: The impacts associated with NNS are diverse and depend on the characteristics of the species (type of feeding, ability to alter the habitat) and the protected area (presence of habitat or vulnerable species). We used the maximum impact information collected in the EICAT fact-sheets as reference, which means that a particular NNS will have the same

**Table 1** Semi-quantitative evaluation of the risk of introduction, establishment and impact of non-native species in the Spanish Network of National Parks. Also included, management feasibility of non-native species 660 within the limits of the park, considering potential restrictions

| | Introduction | Establishment | Impact | Management |
|---|---|---|---|---|
| Low Risk | The species is not present in the park or its surroundings. Unlikely vectors of introduction | Climatic suitability for the species < 200. Establishment cannot be discarded if micro-refugia exist or propagule pressure is very high | The species is classified as Data Deficient, Least or Minimal Concern (DD, MC or MN). It does not significantly affect the population of native species | The species can be easily eradicated using standard techniques. There are experiences of successful eradication within the network of parks |
| Medium Risk | The species is not present in the park but widely spread in Spain. Vectors and pathways of distribution of the species are likely to facilitate its introduction in or around the park | Climatic suitability for the species between 200 and 500. Establishment cannot be discarded if micro-refugia exist or propagule pressure is very high | The species is classified as Moderate (MO). The species generates changes in the population of native species without affecting the entire community | The species can be contained by standard techniques, but population monitoring will still be necessary in the medium to long term to avoid reinvasion |
| High Risk | The species is already present in the surroundings of the park. Consequently, there are vectors and pathways of distribution allowing the species to reach the region | Climatic suitability for the species between 500 and 700. Establishment is possible if the necessary habitats are available | The species is classified as Major (MR). It can produce changes at the community scale, reversible if managed appropriately and in time | Control is expensive and would require continuous management over time to keep populations under control |
| Very High Risk | The species is already present in the park. Consequently, there are vectors and pathways of distribution allowing the species to reach the Park | Climatic suitability for the species > 700. Establishment is very likely if the species accesses the park | The species is classified as Massive (MV). It can lead to changes at community scale that are not reversible even if the species is managed | The species cannot be controlled because of the characteristics of the species (e.g. aquatic species and micro-organisms that are very difficult to eradicate completely), or because of the lack of effective management techniques that can be applied in the park |

impact score for all parks. In practice, this means that we assessed the potential impact of the NNS in the event that the species becomes established and reaches its maximum potential.

*Management feasibility*: The management of NNS and their impacts is critical for assessing the risk associated with biological invasions. To judge this section, we used information available in the literature and consulted park managers to obtain their expert opinion. Management feasibility considered aspects related with the efficacy of treatments, economic cost, need to continue actions to avoid re-invasion, as well as potential restrictions in protected areas (e.g. phytosanitary products that may not be allowed).

Once the aspects in Table 1 have been assessed, we use the following formula to calculate the risk associated with each of the 22 NNS (NNS1 to NN22) in each National Park (NP1 to NP15):

$$\text{Risk}\left[\text{NNS}_1\text{NP}_1\right] = \mathit{Introduction}_{1,1} + \mathit{Establishment}_{1,1} + \mathit{Impact}_{1,1} + \mathit{Management}_{1,1}$$

The possible values of this formula range from 4, for a case where the risk associated with the investigated NNS is very low in the park and eradication feasible; to 16 when the risk is of introduction and establishment are high, control options almost non-existent, and the consequences for native biodiversity serious and likely irreversible. We then used individual scores to prioritize: 1) NNS of concern for the overall network of national parks; and 2) national parks that are most affected by biological invasions.

*Prioritisation of non-native species*: To calculate the risk associated with each NNS for the Spanish Network of National Parks as a whole, we added the scores obtained for each species in each of the 15 parks individually. Scores were rescaled to a 0–100% scale to facilitate interpretation.

*Prioritisation of National Parks*: To calculate the total risk associated with a given National Park, we added the values obtained for the 20 NNS (22 in the case of the three Parks with marine habitats). Scores were rescaled to a 0–100% scale to facilitate interpretation.

## Results

### NNS present in the Spanish Network of National Parks

We found evidence of presence of 200 NNS within the Spanish Network of 15 National Parks (Suppl. Info 1). 39% of them are listed in the Spanish Catalogue of NNS (https://www.miteco.gob.es/es/biodiversidad/temas/conservacion-de-especies/especies-exoticas-invasoras/ce-eei-catalogo.html). The park showing the highest number of NNS was Islas Atlánticas ($N = 69$), whereas Ordesa showed the lowest ($N = 2$), (Table 2, Fig. 1A). The majority of NNS registered were terrestrial plants, with animals accounting for only 30% of NNS (Fig. 1B). The maximum monthly temperature is expected to increase in all parks under future scenarios, with special intensity in parks dominated by Mediterranean forests and shrublands (Monfragüe, Cabañeros), wetlands (Tablas de Daimiel) and mountains (Sierra de Guadarrama, Ordesa and Agüestortes); all of them showing increases of + 3 degrees Celsius (Table 2). At the same time, precipitation is expected to decrease or remain similar in the majority of parks (Table 2), a combination that will result in increased aridity. The number of visitors in 2022 ranged between 79,000 in Archipelago de Cabrera, to 4.2 million in Teide (Canary Islands) (Table 2).

There were no significant differences in the number of NNS between parks with distinctive dominating habitats (ANOVA, $F = 2.09$, $P > 0.05$), and no significant correlation between the number of NNS and the year of declaration, area, number of visitors or temperature of the park (Pearson test, $df = 13$, $P > 0.05$ in all cases).

### NNS of concern for the Spanish Network of National Parks

Attendants to our workshop on invasive species in protected areas identified a total of 34 NNS of concern in their parks. After discarding species that are not legally considered invasive in Spain, or that were relevant to one park only, we finally selected 22 priority NNS: 12 terrestrial, 8 aquatic continental and

**Table 2** Characteristics of parks in the Spanish Network of National Parks. Year: year of declaration of the park

| National Park | National Park characteristics | | | Max. Monthly Temperature (ºC) | | | Min. monthly rainfall (mm) | | | Visitors in 2022 | NNS | Risk Score | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Habitat | Year | Area (ha) | 1970–2000 | 2050 | 2070 | 1970–2000 | 2050 | 2070 | | | Current | 2050 | 2070 |
| Islas Atlánticas | Island-sea | 2002 | 8480 | 23.1 ± 0.1 | ↑1.9 | ↑2.4 | 30 ± 1 | ↓9 | ↓11 | 490461 | 70 | 69 | + 3 | + 3 |
| Doñana | Wetland | 1969 | 54,252 | 30.7 ± 0.4 | ↑2.0 | ↑2.4 | 7 ± 0 | ↓4 | ↓4 | 206944 | 56 | 69 | − 4 | − 5 |
| Archipiélago Cabrera | Island-sea | 1991 | 10,021 | 28.7 ± 0.1 | ↑1.8 | ↑2.2 | 1 ± 0 | = | = | 79592 | 27 | 67 | − 2 | − 2 |
| Tablas de Daimiel | Wetland | 1973 | 3030 | 34.0 ± 0.1 | ↑3.2 | ↑3.9 | 48 ± 6 | ↓3 | ↓4 | 107788 | 17 | 65 | − 5 | − 7 |
| Monfragüe | Medit. forest & shrubland | 2007 | 18,396 | 33.6 ± 0.4 | ↑3.0 | ↑3.8 | 69 ± 11 | ↓4 | ↑2 | 415359 | 15 | 64 | − 6 | − 7 |
| Cabañeros | Medit. forest & shrubland | 1995 | 40,856 | 33.0 ± 0.9 | ↑3.1 | ↑3.9 | 6 ± 1 | ↓2 | ↓3 | 83126 | 31 | 61 | − 4 | − 5 |
| Teide | Island-mountain | 1954 | 18,990 | 22.5 ± 1.2 | ↑0.8 | ↑0.8 | 4 ± 0 | = | = | 4264268 | 21 | 54 | + 3 | + 3 |
| Garajonay | Island-forest | 1981 | 3984 | 24.6 ± 0.4 | ↑0.8 | ↑0.8 | 0 ± 0 | = | = | 661446 | 46 | 53 | 0 | 0 |
| Sierra Nevada | Mountain | 1999 | 85,883 | 24.0 ± 1.3 | ↑2.7 | ↑3.1 | 74 ± 3 | ↑1 | ↑12 | 621221 | 30 | 52 | + 5 | + 5 |
| Sierra de Guadarrama | Mountain | 2013 | 33,960 | 24.0 ± 1.3 | ↑3.6 | ↑4.4 | 11 ± 3 | ↑5 | ↑5 | 2147418 | 7 | 51 | + 8 | + 7 |
| Timanfaya | Island-mountain | 1974 | 5107 | 27.0 ± 0.0 | ↑0.8 | ↑0.7 | 1 ± 1 | ↓1 | ↓1 | 1482625 | 18 | 60 | − 1 | − 2 |
| Picos de Europa | Mountain | 1918 | 67,127 | 21.5 ± 1.6 | ↑1.7 | ↑2.0 | 1 ± 1 | = | = | 1798533 | 6 | 49 | + 6 | + 6 |
| Caldera de Taburiente | Island-forest | 1954 | 4690 | 22.8 ± 1.6 | ↑0.8 | ↑0.9 | 1 ± 1 | = | = | 356968 | 29 | 48 | 0 | 0 |
| Ordesa | Mountain | 1918 | 15,696 | 15.8 ± 3.0 | ↑3.4 | ↑3.9 | 24 ± 2 | ↓4 | ↓3 | 572905 | 2 | 47 | − 1 | 0 |
| Aigüestortes | Mountain | 1955 | 14,119 | 14.2 ± 1.6 | ↑3.4 | ↑3.9 | 8 ± 0 | ↓3 | ↓4 | 206944 | 9 | 45 | 0 | 0 |

Year: year of declaration of the Park, Values of temperature and precipitation correspond to the median ± SD within the area of the park. Values for 2050 and 2070 correspond to the increase (↑) or decrease (↓) in the median value. NNS: Total number of non-native species reported in the park until 2024. Risk Score: probability of introduction, establishment, impact and management in each park of 20 terrestrial or aquatic NNS

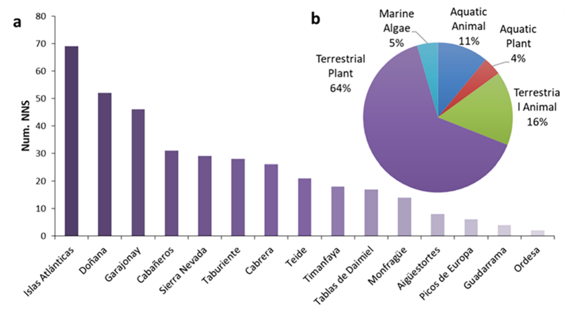


**Fig. 1** a. Total number of Non-Native Species (NNS) reported in the Spanish Network of National Parks. b. Type of NNS present in the Park Network

2 aquatic marine (Table 3). Some priority NNS were already present in many of the parks (e.g. *O. ficus-indica, N. glauca, O. pres-caprae*) and were regarded as an important threat to the rest of the parks in the network (Table 3). Other priority NNS were still absent from national parks (e.g. *M. coypu*, *P. lotor*) or present in only one park (e.g. *Vespa velutina, Eicchornia crassipes*, Table 3). 23% of the priority NNS were classified as having a Massive impact on native biodiversity according to EICAT standards, which implies the irreversible loss of native populations. Another 55% were classified as Major, which also lead to a loss of native biodiversity that may be reversible if the invader is managed in time (Table 3, Suppl. Info 2).

## Model the potential distribution of NNS under present and future scenarios

Species distribution models calibrated with the global occurrence of the 22 priority NNS showed very high accuracy scores (TSS from 0.72 to 0.94; AUC from 0.95 to 0.99; Sensitivity between 65 and 82%, Table 3). NNS showing the highest suitability within the Park Network included three plants: *O. ficus-indica, N. glauca, O. pes-caprae*; one animal, the racoon *P. lotor*; and one marine weed, *C. cylindraea*.

Accessibility was the most important predictor of most NNS, followed by minimum monthly temperature. Trends in potential NNS richness across the current and future (2050 and 2070) scenarios differ across three major groups of parks. In the case of high-mountain parks, NNS richness is expected to increase significantly in Sierra Nevada, Sierra de Guadarrama and Picos de Europa (Figs. 2A, 3A). In contrast, NNS richness significantly decreases in parks located in the lowlands and dominated by wetlands, Mediterranean forests and shrublands (Figs. 2C, 3B). Parks located in islands showed varying trends: Teide, a mountainous park located in the Canary Islands showed a significant increase in NNS richness in congruence with high-mountain parks, whereas NNS richness decreased in the Archipelago de Cabrera, a marine park (Fig. 2B). Two examples of changes in NNS potential richness are represented in Fig. 3. Results for each individual National Park can be consulted in Suppl. Info. 3.

## Integrated risk assessment

The National Parks with the highest risk score include Islas Atlánticas, Doñana and Archipiélago de Cabrera (Table 2). In contrast, the parks least vulnerable to biological invasions according to this ranking are Caldera de Taburiente, Ordesa and Aigüestortes. Under climate change scenarios, the scores of high-mountain parks increase considerably, particularly in Sierra de Guadarrama, Picos de Europa and Sierra Nevada. In contrast, the scores of parks located in the lowlands, such as Tablas de Daimiel, Monfragüe and Cabañeros, tend to decrease (Table 2).

The scores for the NNS investigated were highest for the Pampas grass (*C. selloana*), and lowest for the wakame (*U. pinnatifida*, but this is due to the fact that its score is calculated with only three Parks) (Table 3). Terrestrial plants dominate the Top 5 NNS with the highest risk for the Parks Network (Table 3). Species that may benefit the most from climate change include the American blackbass (*M. salmoides*), fountain grass (*P. setaceum*) and mustard tree (*N. glauca*). In contrast, NNS negatively affected by climate change include the American mink (*N. vison*), Pampa grass (*C. selloana*) and the Cape fig *(C. edulis*).

# Discussion

The Global Biodiversity Framework (GBF) aims to reduce the introduction of invasive alien species by 50% and minimize their impacts by 2050 (Target 6, GBF 2020). Achieving this goal requires prioritizing areas and NNS that pose the highest

**Table 3** Non-native species (NNS) of concern for the Spanish Network of National Parks

| Scientific name | Common name | Group | Num. Parks | EICAT | Accuracy SDM | Suitability SDM | Risk score | Change 2050 | Change 2070 |
|---|---|---|---|---|---|---|---|---|---|
| *Pennisetum setaceum* | Fountain grass | Terr. Plant | 3 | MO | 0.81 ± 0.04 | 552 | 74 | +3 | +3 |
| *Cortaderia selloana* | Pampas grass | Terr. Plant | 2 | MO | 0.92 ± 0.02 | 582 | 72 | −3 | −4 |
| *Paspalum paspaloides* | Eternity grass | Terr. Plant | 3 | MR | 0.94 ± 0.02 | 586 | 69 | −1 | −2 |
| *Opuntia ficus-indica* | Prickly pear cactus | Terr. Plant | 7 | MR | 0.85 ± 0.02 | 759 | 67 | −2 | −2 |
| *Eichhornia crassipes* | Water hyacinth | Aquatic Plant | 1 | MV | 0.79 ± 0.04 | 213 | 65 | +2 | +1 |
| *Neovison vison* | American mink | Mammal | 2 | MR | 0.84 ± 0.04 | 431 | 65 | −4 | −4 |
| *Nicotiana glauca* | Mustard tree | Terr. Plant | 5 | MN | 0.86 ± 0.03 | 713 | 62 | +3 | +3 |
| *Carpobrotus edulis* | Cape fig | Terr. Plant | 4 | MV | 0.94 ± 0.01 | 515 | 59 | −3 | −3 |
| *Tradescantia fluminensis* | Wandering creeper | Terr. Plant | 2 | MR | 0.94 ± 0.01 | 151 | 57 | −2 | −2 |
| *Micropterus salmoides* | American blackbass | Fish | 4 | MV | 0.83 ± 0.05 | 113 | 57 | +4 | +5 |
| *Ameiurus melas* | Black Bullhead | Fish | 3 | MR | 0.83 ± 0.07 | 316 | 56 | +2 | +2 |
| *Vespa velutina* | Asian hornet | Insect | 1 | MR | 0.92 ± 0.03 | 144 | 50 | −1 | −1 |
| *Myocastor coypus* | Coypu | Mammal | 0 | MO | 0.89 ± 0.03 | 367 | 49 | −3 | −3 |
| *Oxalis pes-caprae* | Buttercup oxalis | Terr. Plant | 6 | MR | 0.89 ± 0.03 | 340 | 49 | +1 | +2 |
| *Lepomis gibbosus* | Pumpkinseed | Fish | 4 | MR | 0.89 ± 0.03 | 97 | 49 | −3 | −3 |
| *Trachemys scripta* | Red-eared slider | Amphibian | 3 | MR | 0.86 ± 0.05 | 331 | 45 | +2 | +2 |
| *Procyon lotor* | Raccoon | Mammal | 0 | MR | 0.88 ± 0.04 | 616 | 43 | +1 | +1 |
| *Salvelinus fontinalis* | Brook trout | Fish | 2 | MR | 0.83 ± 0.04 | 133 | 41 | −2 | −2 |
| *Ammotragus lervia* | Barbary sheep | Mammal | 2 | MR | 0.86 ± 0.04 | 284 | 41 | +2 | +2 |
| *Psittacula krameri* | Rose-ringed Parrakeet | Bird | 1 | MO | 0.75 ± 0.07 | 281 | 28 | 0 | 0 |
| *Caulerpa cylindracea** | Caulerpa | Marine Weed | 1 | MV | 0.93 ± 0.03 | 969 | 75 | +6 | +6 |
| *Undaria pinnatifida** | Wakame | Marine Weed | 1 | MV | 0.78 ± 0.03 | 401 | 47 | 0 | −3 |

Num. Parks: number of parks already invaded. EICAT categories: MC-Minimal Concern, MN-Minor, MO-Moderate, MR-Major, MV-Massive. Accuracy SDM: Accuracy of models measured with the TSS of the model ± SD. Suitability SDM: Median value of suitability for the species within the Spanish Network of National Parks, under the current scenario. Risk score: total score reflecting the probability of introduction, establishment, impact and management in the Spanish Network of National Parks. Change 2050 and 2070: increase or decrease in the score of the species taking into account its climatic suitability in the corresponding scenario. *Marine species that can only affect 3 of the national parks. For these two species, future scenarios refer to the 2050 and 2090 timeframes. Species ordered by current risk score

risk. This study presents the most comprehensive inventory to date of NNS within the Spanish Network of National Parks, alongside a detailed risk-analysis of 22 priority NNS. It provides a baseline for tracking NNS changes in protected areas, and identifies priority NNS and national parks for focused action to advance towards meeting GBF objectives.

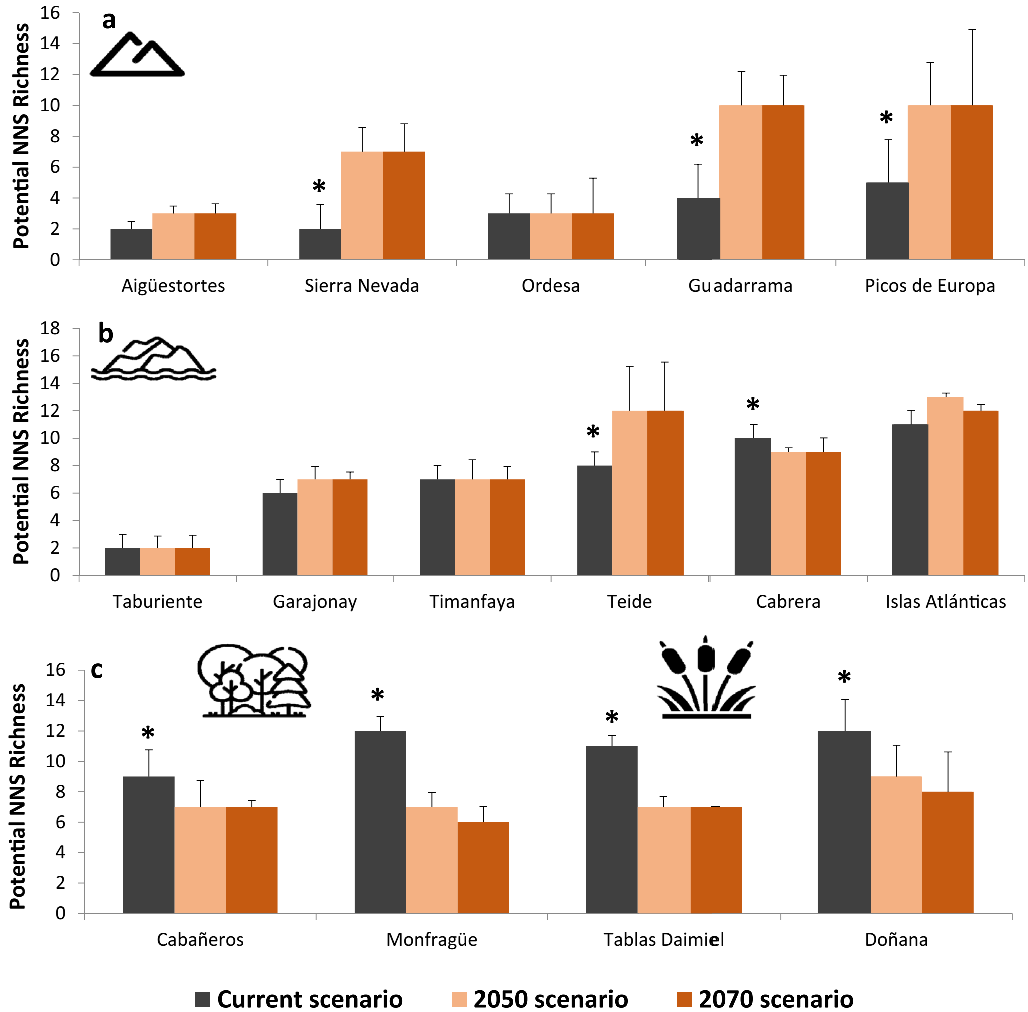


**Fig. 2** Potential richness of non-native species (NNS) in the Spanish Network of National Parks. The Y-axis indicate the total number of NNS with potential suitable condition within the limits of each park under current and two future scenarios. Parks are divided into three major groups depending on their dominating habitat: mountain (**a**), island (**b**), Mediterranean forests and wetlands (**c**). Error bars represent the standard deviation of the mean. * indicates significant differences at $P < 0.05$ between the potential NNS richness under the current and 2050 scenario

## NNS present in the Spanish Network of National Parks

We identified 200 NNS, with 39% included in the national catalogue of NNS due to their negative impacts on biodiversity (MITECO, 2024). While this means that their trade and introduction are illegal, many of the invasive ornamental plants in the national catalogue can still be easily found in the market (Bayón and Vilà 2019).

We didn't find a correlation between the number of NNS and characteristics of the park related with propagule pressure, such as visitor numbers, but this may be due to the limited sample size of analyses (N = 15 parks). However, other studies have demonstrated a direct correlation between the level of invasion and the year a protected area was declared (Gallardo et al.

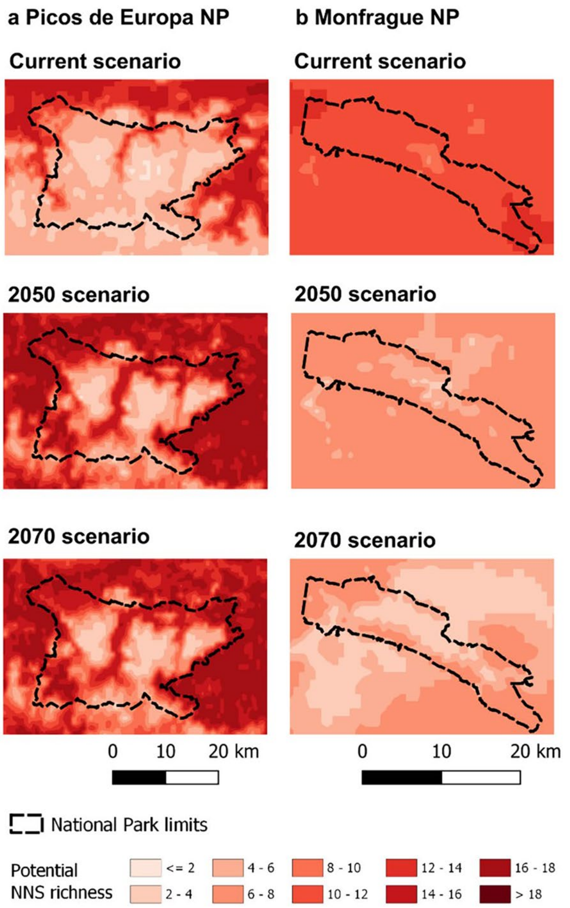


**Fig. 3** Potential richness of non-native species (NNS) in two national parks under current and future climate change scenarios. The two parks represent two contrasting trends: in Picos de Europa (**a**) the richness of NNS is expected to increase under future scenarios, whereas in Monfragüe (**b**) it is expected to decrease. Richness maps for the rest of the parks investigated can be consulted in Suppl. Info 3

2017), suggesting that the establishment of protected areas early on can prevent invasions by controlling human activities and ensuring robust conservation efforts. Additionally, factors like accessibility and the perimeter of protection have been identified as significant in explaining the extent of invasion (Foxcroft et al. 2011; Gallardo et al. 2017).

Our scoring protocol identified five plants as top invasive species: fountain grass (*P. setaceum*), Pampa grass (*C. selloana*), eternity grass (*P. paspalodes*), prickly pear cactus (*O. ficus-indica*) and water hyacinth (*E. crassipes*) (Table 3). Detailed descriptions of their characteristics and impacts can be consulted in Suppl. Info 2. Our results may nevertheless reflect a bias in the literature towards vascular plants that are easier to detect and study than animals or aquatic organisms (Pyšek et al. 2008).

We also found that parks located at low elevations, such as Islas Atlánticas, Doñana and Archipelago de Cabrera, are the most vulnerable to invasion by our 22 priority invaders. While high mountain parks currently have low risk scores, this is expected to increase substantially under future climate change scenarios, particularly in Sierra de Guadarrama, Picos de Europa and Sierra Nevada. In comparison with other mountains of the world, European mountains present a relatively low biodiversity intactness index, developed road networks, increasing minimum temperatures and proximity to ports and cities, which may explain their increasing vulnerability to biological invasions (García-Rodríguez et al., in press). It is important to note that our risk scores aggregate data from multiple species and various aspects of invasion (introduction, establishment, impact and management). This aggregation may obscure individual species trends, which are detailed in Suppl. Info 4.

## Potential distribution of NNS under present and future scenarios

National parks, often viewed as pristine sanctuaries immune to biological invasions, actually host an high number of NNS given their protection status, low propagule pressure and high conservation level (García-Rodríguez et al., in press). While protected areas may be better poised to resist initial invasions due to their limited accessibility and conservation status (Gallardo et al. 2017), they become vulnerable as invasions progress, simply because protected areas have more to lose. This is especially evident when compared to areas more influenced by human activities and with poorer conservation value, where invasive species are less likely to be a direct threat to biodiversity (Hiley et al. 2014; Liu et al. 2023).

Island and wetland parks displayed the current greatest suitability for NNS (e.g. Islas Atlánticas, Doñana and Cabrera Archipelago), yet the potential richness of NNS decreases under future scenarios due to the expected increase in aridity. In contrast, susceptibility towards biological invasions is predicted to rise with increasing minimum temperatures in high mountain parks such as Sierra Nevada, Picos de Europa and Sierra de Guadarrama. Our results align with other studies demostrating that cold environments, previously thought to be less invasion-prone due to harsh climatic conditions and limited accessibility, are now experiencing increased rates of invasion, driven by human activities such as road building, climate and land-use changes (Lembrechts et al. 2016; Pauchard et al. 2016).

The combined effects of climate change and biological invasions on the Spanish Network of National Parks could significantly alter ecosystem structures and functions, and endanger their ability to provide valuable ecosystem services such as pollination, water regulation or flood control (Vilà and Hulme 2017; Gallardo et al. 2024). A major concern is the feedback between the two threats. For instance, protected and especially endemic species, which often have restricted distributions and high sensitivity, are less likely to cope with on-going climate changes (Bradley et al. 2024); a loss that will in turn reduce the resistance of natural communities to colonisation by new NNS (Rahel et al. 2008). At the same time, ecosystem alterations caused by NNS could intensify the adverse effects of climate change. For example, rising temperatures due to climate change are expected to boost extreme events like fires, potentially aiding the spread of fire-adapted invasive species such as fountain grass (*P. setaceum*) (GISD 2024). Many invasive plants like the fountain grass contribute to the fuel load, thereby escalating the fire risk. Similarly, species like the water hyacinth (*E. crassipes*) exacerbate drought conditions linked to global warming through their substantial evapotranspiration rates, provoking anoxia events (Villamagna and Murphy 2010). In addition, there are established NNS that have not yet posed significant problems, but could become invasive as climate change increases their competitive edge or rate of spread (i.e. sleeper species, Bradley et al. 2018; O'Uhuru et al. 2024). Conversely, a few NNS might decline under climate change, unable to cope with shifts in temperature and precipitation patterns, or might retreat from current invaded zones, moving towards northern latitudes or higher elevations (Bradley et al. 2024). Distribution models suggest this may be the case of cold-adapted species like the American mink and the brook trout.

While distribution models are invaluable, recognizing the challenges in predicting invasive species dynamics under climate change is necessary. This includes the variability in species responses and the uncertainties of future climate scenarios. A recent review found that, in comparison with native species, NNS spread 1000 times faster and display broader climatic tolerance (Bradley et al. 2024). Accordingly, distribution models anticipate larger and faster range expansion of NNS than native species under climate changes scenarios (Bradley et al. 2024). However, it must be noted that predictive maps are simplified representations of reality that indicate probabilities based on a limited number of predictors, and not a real representation of what will happen, especially in future scenarios of high uncertainty. Nevertheless, this type of models has proven to be very useful in detecting trends in the expansion of invasive species and represents one of the few tools for assessing future risks that can support prevention actions.

## Towards meeting the GBF targets: weaknesses and opportunities of the Spanish Network

Our study provides essential resources to advance toward meeting the GBF targets within the Spanish National Parks network. Our NNS database serves as a baseline reference, enabling comparisons of invasion rates across parks and tracking changes over time. This tool supports the monitoring of invasion levels within the network and provides park managers with basic data to inform prevention and control strategies. We offer detailed ecological and impact assessments of 22 priority invaders identified by park managers. Anticipating the potential effects of climate change on invasion trends, we also introduce climate scenarios and a simple scoring method to identify the NNS posing the greatest threats and highlight the parks most vulnerable to biological invasions under current and future climate conditions. In doing so, we demonstrate how models and scenarios can inform policy and management decisions, promoting early response plans to limit their expansion before they establish extensively. User-friendly platforms such as Wallace 2 (Kass et al. 2023, https://wallaceecomod.github.io/), SDMtoolbox (http://www.sdmtoolbox.org/), and ZOON (Golding et al. 2018, https://zoonproject.wordpress.com/), allow calibrating species distribution models and could assist park managers identifying high-risk areas within parks for other species of concern.

To translate our findings into effective management actions, it is crucial to address key areas requiring improvement. First, enhancing coordination among national and regional administrations is essential for sharing information about new NNS and organizing rapid response teams. While most National Parks' management plans address the prevention of biological invasions, they show varying levels of awareness and response, and little coordination with other parks and relevant authorities. A unified management strategy across the Parks Network would allow for more efficient resource use and avoid duplicating efforts. Second, our research underscores the need for more robust and proactive investment in NNS management, particularly in controlling sources of propagules outside park boundaries. Finally, public awareness is vital, as many NNS are inadvertently spread through human activities and the number of visitors is increasing annually. Raising awareness among park visitors could significantly reduce accidental introductions. In addition to eradication efforts, the restoration of invaded ecosystems is essential to enhance biodiversity and ecosystem services. However, care must be taken to ensure that restoration activities do not inadvertently facilitate further invasions. By integrating our basic research findings with improved coordination, resource allocation, and public awareness, we can better align management practices within the Spanish network of National Parks with GBF goals, thereby strengthening the role of protected areas in safeguarding native biodiversity against biological invasions.

**Author contributions** All authors contributed to the study conception and design. Data collection and the risk evaluation for NNS were performed by L.C.. Statistical analyses and distribution models were performed by B.G. The first draft of the manuscript was written by B.G. and L.C. commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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**Data availability** Data collected in this study is available in four supplementary information files.

**Declarations**

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.



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