



Research Letters

Climate-driven potential distribution of the invasive tree tobacco and its overlap with biodiversity conservation areas worldwide

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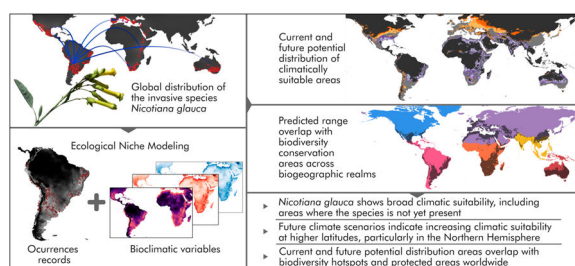
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HIGHLIGHTS

- Ecological niche models reveal that *Nicotiana glauca* has a broad climatic suitability that includes regions where it is not yet present.
- Future climate scenarios indicate increased suitability at higher latitudes, especially in the Northern Hemisphere.
- Current and future potential distribution areas overlap with biodiversity hotspots and protected areas worldwide.
- Protected areas and hotspots in the Palearctic realm are projected to become increasingly suitable in the future.
- The results provide spatially explicit guidance to support targeted prevention, early detection, and control of this highly invasive species.

GRAPHICAL ABSTRACT



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ABSTRACT

Biological invasions threaten global biodiversity, especially in high-value conservation areas, making it essential to predict where invasive species may become established in order to guide regional-scale biosecurity efforts. We used ecological niche modelling to estimate the potential distribution of the highly invasive plant *Nicotiana glauca* under current and future climate scenarios, and we assessed its overlap with global biodiversity hotspots and protected areas. Our findings showed that the species' suitable environment has an extensive geographical distribution, encompassing regions of Asia and northern Africa where it is not currently present or invasive. Although projections under climate change scenarios show an overall reduction in the total suitable area, higher-latitude regions, particularly in the Northern Hemisphere (i.e. the Nearctic and Palearctic realms), would become suitable for the species. Notably, a significant proportion of biodiversity hotspots and protected areas worldwide are currently suitable for *N. glauca*, and those located in the Palearctic realm are projected to become increasingly suitable in the future. Our study provides crucial spatial insights for the targeted prevention and control of a highly invasive plant. More broadly, it highlights the importance of incorporating region-specific assessments into invasion risk analyses to improve conservation planning.

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Introduction

An alien plant is considered invasive once it establishes self-sustaining populations and spreads extensively through regions outside its natural range (IPBES, 2019). The various stages involved in a plant invasion may be affected by climate, which can greatly influence its success (Theoharides and Dukes, 2007). Biological invasions are recognized as one of the most pressing global threats to biodiversity (Bellard et al., 2016; IPBES, 2019). Conservation priorities, such as biodiversity hotspots and protected areas, are particularly vulnerable to the establishment of invasive plants (Bellard et al., 2014; Li et al., 2016; Liu et al., 2020; Montti et al., 2021). Because eradication of invasive species is notoriously difficult and resource-intensive, predicting their potential spread is crucial for effective prevention management (Thuiller et al., 2005; Epanchin-Niell and Hastings, 2010). Although predictive models are increasingly being used, our understanding of how climate-related shifts may influence the potential distribution of invasive plant species at fine spatial scales remains limited.

Increases in temperature and atmospheric CO₂, alongside changes in land use, are expected to facilitate the gradual process of ecological succession, enabling certain invasive plant species to become established and spread over time (Walther et al., 2009; Bellard et al., 2013). Consequently, climate change is expected to promote future invasions worldwide. Nevertheless, not all invasive species are predicted to expand their ranges under future climate conditions; some may instead undergo range contractions (Buckley and Csergő, 2017; Manzoor et al., 2021). Such divergent responses complicate the development of generalisable predictions and emphasize the importance of conducting species-specific assessments to guide prioritization of areas for invasion policy and management (Essl et al., 2011; Roy et al., 2014; McGeoch et al., 2016).

There is growing evidence that the effect of climate change on the potential distribution of invasive plant species varies greatly from region to region, resulting in different invasion outcomes, even when protected areas are considered (Bellard et al., 2013; Fulgêncio-Lima et al., 2021; Wan et al., 2021). Consequently, broad-scale global assessments may overlook critical local patterns of suitability for invasive plant species. Therefore, adopting a regional perspective when identifying the potential distribution of invasive plants is essential for designing geographically tailored prevention and management strategies. However, detailed spatial assessments of the current and future distributions of many high-impact invasive plants, especially in conservation-priority areas, are scarce (but see Montti et al., 2021).

South American tree tobacco (*Nicotiana glauca* R. Graham; Solanaceae) is considered one of the world's 100 worst invasive species (Vélez-Gavilán, 2023). Native to north-west Argentina and southern Bolivia, it has successfully invaded diverse semi-arid environments across South America, North America, Europe, Africa and Australia (Ollerton et al., 2012; Issaly et al., 2024). Its ability to colonise semi-natural and natural habitats, ranging from sea level to 3,500 metres and spanning multiple continents, makes *N. glauca* a valuable case study. Furthermore, extensive research into the invasion biology of this species provides a solid foundation for understanding how it colonizes new areas and adapts to novel biotic and abiotic environments (Ollerton et al., 2012; Issaly et al., 2020; García et al., 2020; Costa et al., 2023; Issaly et al., 2024; Ferreras et al., unpublished data). Despite there being strong evidence of the species' adaptive potential and ecological impact, its current and future climate-driven distribution remains uncertain.

In order to estimate the potential distribution of the invasive plant *N. glauca* under present and future climate scenarios, we employed ecological niche modelling (ENM), focusing particularly on biodiversity conservation areas within a spatial assessment of biogeographic realms. Specifically, we address the following questions: (a) What is the current potential global and regional range of *N. glauca*? (b) How might climate change alter its future distribution in different regions? and (c) To what extent does the species predicted range overlap with biodiversity

hotspots and protected areas under current and future environmental conditions across biogeographic realms?

Methods

Occurrence data

We assembled a global dataset, encompassing both native and non-native occurrences for *N. glauca* by combining records from Issaly et al. (2024) with additional presence data retrieved from the Global Biodiversity Information Facility (GBIF, 2021). We filtered the dataset by removing duplicate entries, marine records, observations before 1970, and those lacking geographic coordinates. The final cleaned dataset included 1,963 unique presence records (Fig. 1). The extent of model calibration was defined using a 200 km buffer around occurrence records in each region (Figure S1). The methodological details of the partition data and the calibration area are available in the Supplementary Information.

Environmental variables

We obtained bioclimatic variables for both current (1970–2000) and future (2041–2060) conditions from the WorldClim database v2.1 (<http://www.worldclim.org/>; Fick and Hijmans, 2017) at a spatial resolution of 2.5 arc minutes (~5 km at the Equator). To reduce multicollinearity among predictors, we assessed spatial correlations among the current variables using 10,000 randomly sampled points within the study area using the flexsdm R package (Velazco et al., 2022). From highly correlated pairs (Pearson's $r \geq 0.8$), we retained the variables that were most biologically relevant to *N. glauca*. This resulted in a final set of seven current bioclimatic variables being used for modelling purposes (see Table S1 for details), ensuring an ecologically meaningful selection based on Issaly et al. (2024).

To assess range dynamics under climate change, we projected models onto two future climate scenarios based on the Shared Socio-economic Pathways (SSPs), corresponding to moderate (SSP 2–4.5) and high (SSP 5–8.5) greenhouse gas emission pathways (Riahi et al., 2017). To account for variability among climate projections, we used three General Circulation Models (GCMs): BCC-CSM2-MR, IPSL-CM6A-LR, and MIROC6.

Ecological niche modeling

We performed ecological niche modeling (ENM) of *N. glauca* using a multi-algorithm ensemble framework, as combining algorithms with distinct statistical foundations helps account for model-specific biases and uncertainty in species–environment relationships (Araújo and New, 2007). Models were generated using four algorithms suitable for presence-background data: Maximum entropy (MaxEnt), Random Forest (RF), Support Vector Machine (SVM) and Generalized Boosted Regression Models (GBM). For MaxEnt, we evaluated different combinations of regularization multipliers (0.5–2, in increments of 0.5) and feature classes (linear, quadratic, and product) to balance model complexity and ecological interpretability. Model performance was assessed using the area under the curve (AUC), the Boyce Index and omission rates as complementary indicators of model discrimination and reliability. To generate a consensus prediction, we computed an ensemble model by averaging the suitability outputs across algorithms. To differentiate suitable from unsuitable conditions while accounting for potential inaccuracies in the occurrence dataset, we applied a threshold based on an allowable omission error rate (E) of 5 %.

We summarized projections by calculating the median suitability across replicates and GCMs for each scenario. These were then used to generate continuous suitability maps and thresholded binary maps of potential distribution. Because GCMs represent different but plausible future climates, integrating them captures their variability. The median

provides a robust central estimate that is not driven by extremes, facilitating comparison across scenarios. Additionally, we assessed climate-driven changes in suitability by comparing binary projections from future scenarios against the current distribution. Suitability layers were reclassified and summed to generate a final map depicting areas of climatic habitat gain, loss, or stability under each scenario (Cobos et al., 2019a). To evaluate environmental extrapolation and model transferability, we quantified environmental similarity using both the Multivariate Environmental Similarity Surface (MESS; Elith et al., 2010) and the Mobility-Oriented Parity (MOP; Owens et al., 2013). Both analyses help identify areas where projections should be interpreted with caution. The entire modeling workflow was conducted using the flexsdm R package (Velazco et al., 2022), and map visualizations were produced using the tmap R package (Tennekes, 2018). Figures were post-processed using Inkscape v.1.3.2 (Inkscape Project, 2023, available at <https://inkscape.org>).

Potential distribution within biodiversity conservation areas

We assessed the extent to which different biogeographic realms are

suitable for *N. glauca* in current and both future climatic scenarios. Biogeographic realms were defined following Dinerstein et al. (2017), with minor adjustments: Greenland was included in the Nearctic, the high Himalayas in the Palearctic, and southern Patagonian glaciers in the Neotropical realm. Antarctica, regions classified as “Rock and Ice” without clear ecological assignment, and oceanic realms were excluded. To assess the current and future potential distribution of *N. glauca* within biodiversity conservation areas, we examined the degree of overlap between suitable habitats and biodiversity hotspots, as well as protected areas, within each biogeographic realm. Boundaries for biodiversity hotspots were obtained from Myers et al. (2000) and Mittermeier et al. (2004), and protected areas from the World Database on Protected Areas (WDPA; UNEP-WCMC and IUCN, 2020), updated in April 2021. Both datasets were rasterized to match the resolution (2.5 arc-minutes) and extent of the species suitability layers. We calculated the area of suitable habitat using binary (thresholded) maps derived from the median ensemble suitability raster for each scenario (current, SSP 2–4.5, SSP 5–8.5). All spatial analyses were performed in R using the terra package (Hijmans, 2024) under the geographic coordinate system EPSG:4326.

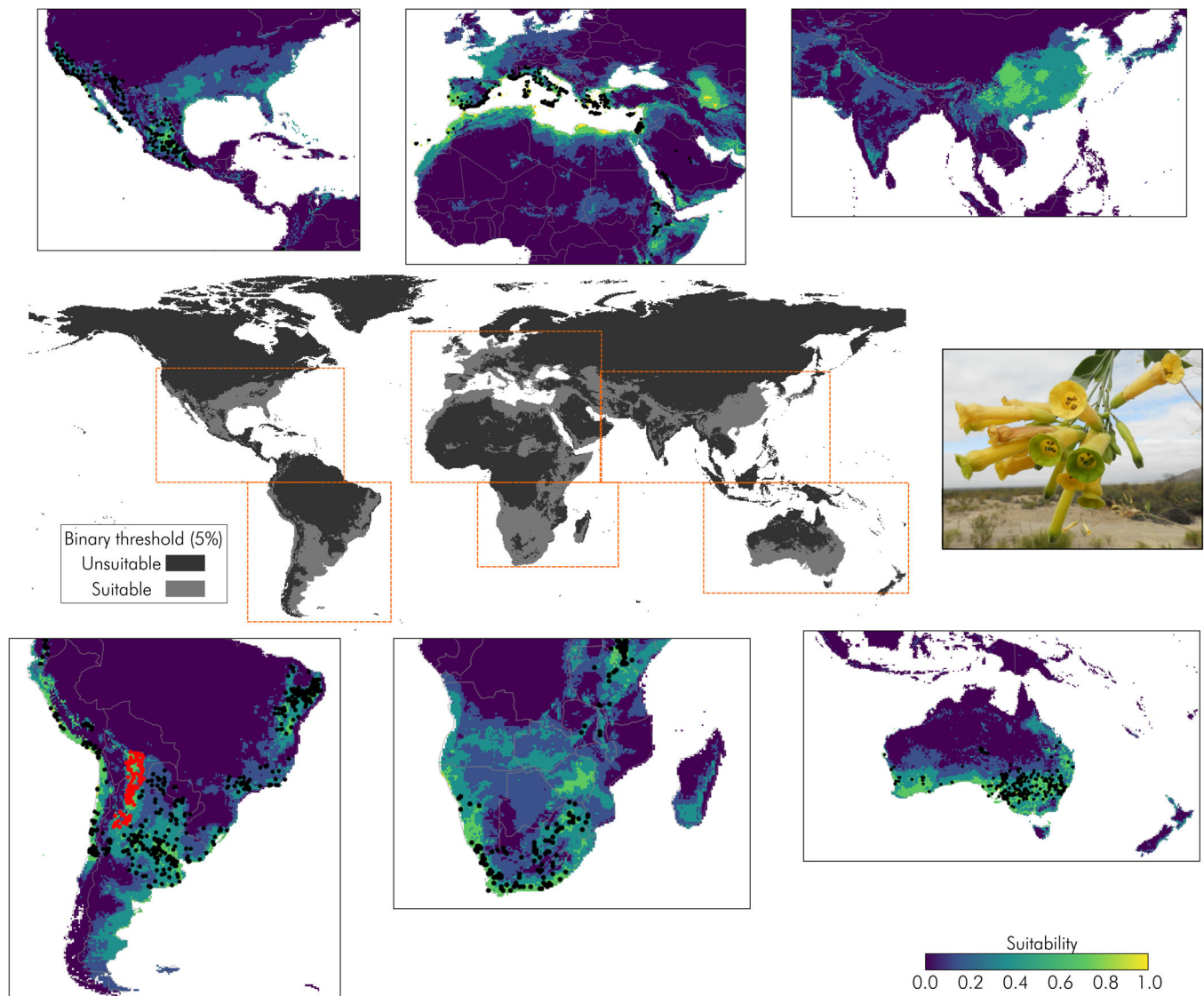


Fig. 1. The central image represents a map of the current potential distribution of *Nicotiana glauca* depicting presence and absence areas defined by the application of the 5% threshold. Surrounding panels show continuous habitat suitability values in selected regions, highlighting fine-scale variation in model predictions. Species occurrence points are overlaid: red dots indicate records within the native range, while black dots represent occurrences in the invaded range. Photography: E.A. Issaly. *N. glauca* inflorescence bearing ornithophilous tubular flowers, typically greenish-yellow to the human eye.

Results

Current potential distribution

Models across algorithms performed well according to the evaluation metrics used (Table S2). The ensemble model identifies extensive areas with high suitability both within the species' native range and beyond it, estimating a total of approximately 36.5 million km² across all continents. Most of these suitable regions coincide with existing occurrence records; however, some areas in northern Africa and the southern and eastern parts of Asia show high predicted suitability despite the absence of documented occurrences (Fig. 1).

Future potential range dynamics

Based on both the SSP 2–4.5 and SSP 5–8.5 climate change scenarios, our future projections for the period 2041–2060 indicate a reduction in the total area with suitable climatic conditions for *N. glauca*, as well as a significant geographic shift in the potential range of the species (Fig. 2). The total reduction is projected to reach 11.22% under the SSP 2–4.5 scenario and 12.55% under SSP 5–8.5, relative to the current distribution. Beyond this contraction, the projections reveal a clear shift towards higher latitudes of areas with suitable conditions, particularly under the SSP 5–8.5 scenario (Fig. 2, violin plot). In the Northern Hemisphere, suitable habitats are predicted to expand northwards across Europe, Asia, and North America. In the Southern Hemisphere, the increase in suitable areas at higher latitudes is smaller in magnitude than that observed in the Northern Hemisphere, and is accompanied by a pronounced loss of suitability at lower latitudes. The new suitable areas are projected to be found in western South America. In contrast, the projections for Africa and Oceania indicate consistent losses of suitable areas, with no compensatory gains at higher latitudes (Fig. 2). Furthermore, the MESS and MOP analyses indicated no non-analogous

climates in the regions identified as suitable, with the exception of northern Asia and central Africa indicating cautions in the interpretation in these areas (Figure S2 and S3).

Potential distribution within biodiversity conservation areas

Our models indicate that *N. glauca* might currently be present in areas with suitable climatic conditions across all the assessed biogeographic realms, biodiversity hotspots, and protected areas. However, the extent and distribution of these suitable areas vary markedly among regions (Fig. 3). Under present conditions, an average of 28% of biogeographic realm surfaces is climatically suitable for *N. glauca*, with the Australasian realm showing the highest proportion (44.31%) and the Nearctic, the lowest (15.65%). Suitability within biodiversity hotspots averages 46%, peaking in the Nearctic (83.95%), Afrotropical (58.51%), and Australasian (55.63%) realms, while the Indomalayan shows the lowest proportion (28%). Protected areas show a similar pattern, with 23% of their total surface overlapping suitable zones, especially in the Afrotropical (47%) and Australasian (37.86%) realms, and only 7.58% in the Nearctic. Under future scenarios, suitable areas are projected to contract by an average of 14.2%. Losses reach 45% in the Indomalayan and 46.5% in the Afrotropical realms, a trend mirrored in hotspots and protected areas. The Palearctic and Nearctic realms are the only exceptions, with projected increases of 28.4% and 20%, respectively, under SSP 5–8.5. In the Palearctic realm, this increase in potential suitable areas under future climate scenarios would also occur in hotspots and protected areas (PAs).

Discussion

Our findings shed light on the potential distribution of *N. glauca* under current and future climatic conditions, and on the suitability of biodiversity conservation areas for this highly invasive species. This

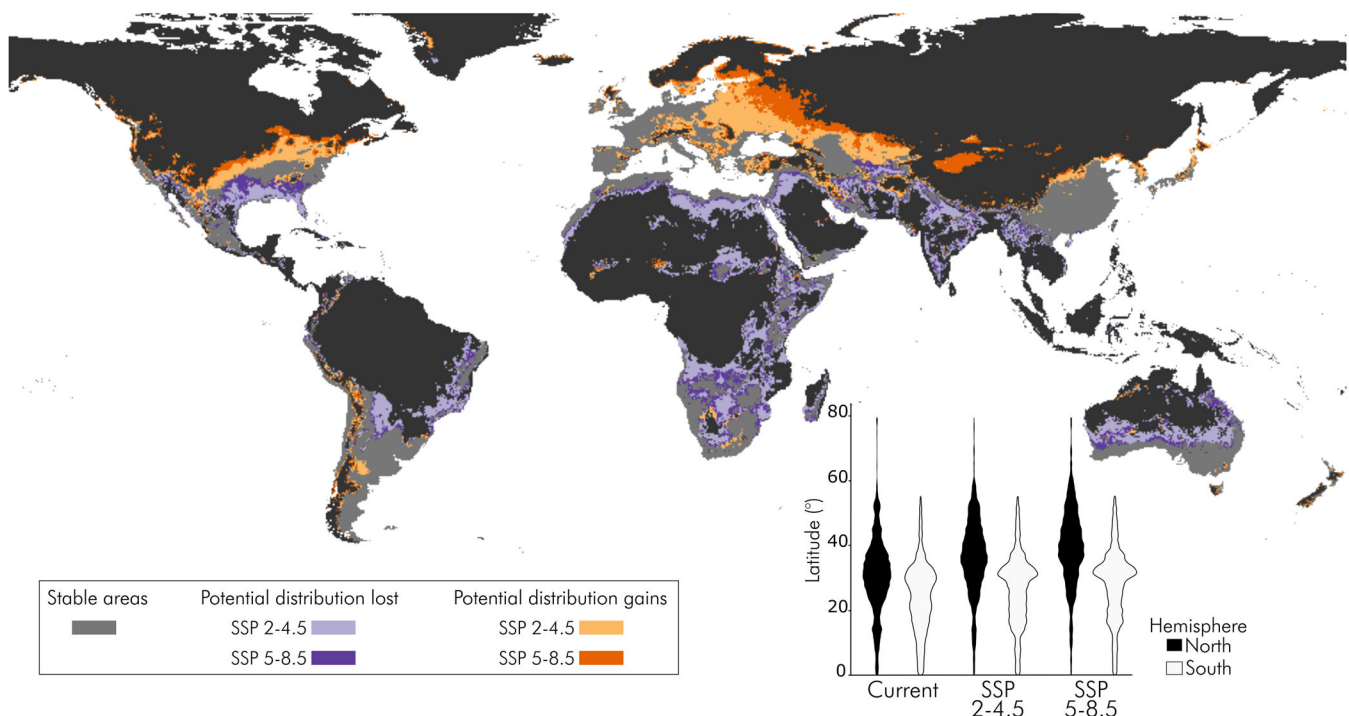


Fig. 2. Changes in climatically suitable areas for *Nicotiana glauca* under future (2041–2060) scenarios (SSP 2-4.5 and SSP 5-8.5), based on binarized maps using a 5% threshold. Grey indicates areas that remain suitable across all scenarios (“stable”). Light orange and orange represent new suitable areas gained under SSP 2-4.5 and SSP 5-8.5, respectively. Light violet and violet show areas that were suitable under current conditions but become unsuitable under SSP 2-4.5 and SSP 5-8.5, respectively. Violin plots show the distribution of suitable pixels across absolute latitude for each scenario, revealing a potential poleward shift in the species' range under climate change.

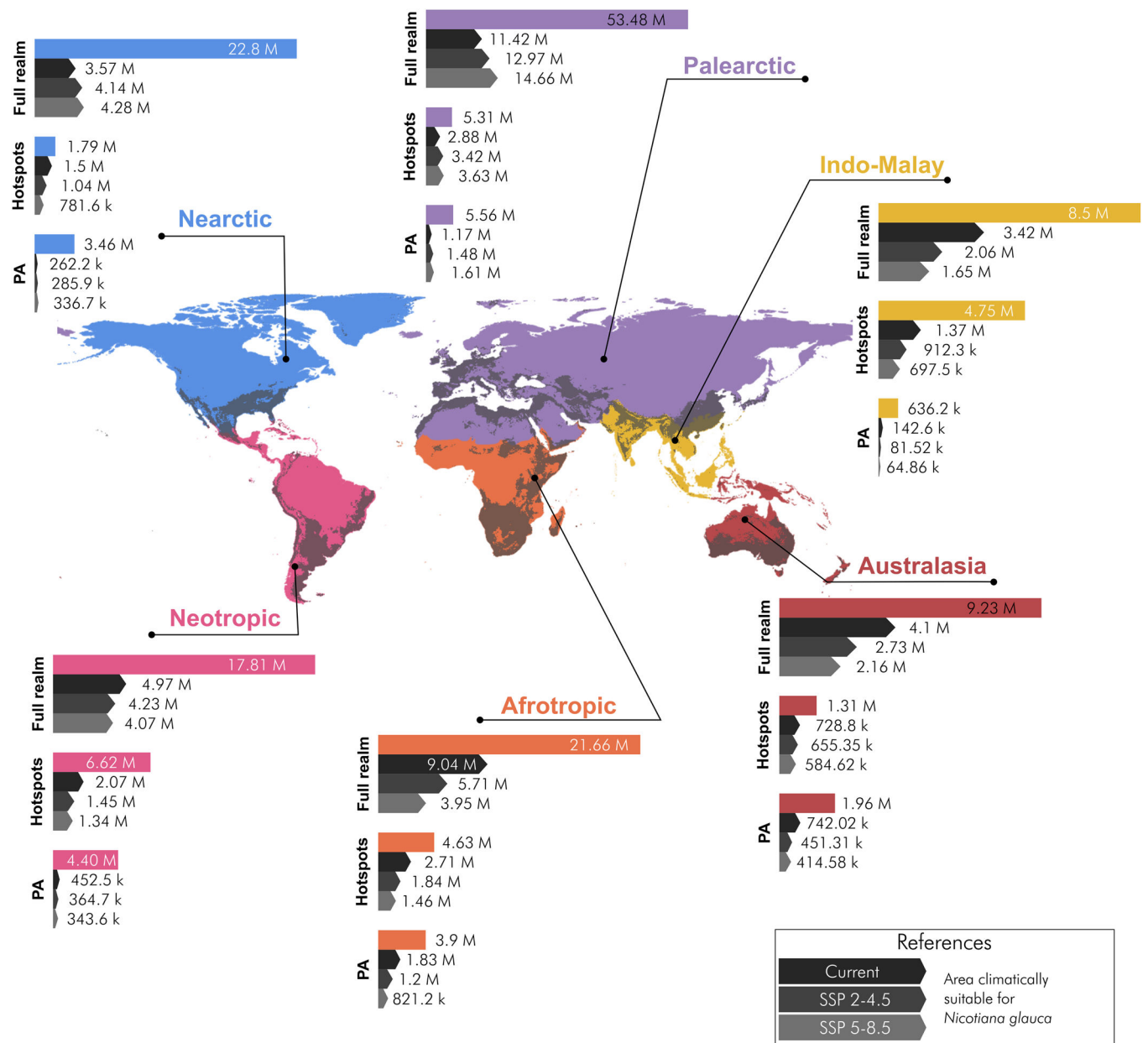


Fig. 3. Potential distribution map divided into biogeographic realms (Dinerstein et al., 2017), each of which is shown in a different colour. The climatically suitable area for *Nicotiana glauca* at present is shown in grey. The bar charts show, in colour, the total area of each realm, the extent of biodiversity hotspots, and protected areas within it; and, in shades of grey, the extent of climatically suitable habitats for *N. glauca* under different scenarios within these total areas. All areas are expressed in km².

information is essential for guiding conservation priorities and strengthening biosecurity efforts (Essl et al., 2011; Roy et al., 2014).

Ecological niche models that use biologically relevant predictors can provide a more accurate estimation of species’ potential distributions by capturing how climate shapes their environmental limits. For *N. glauca*, which inhabits warm, arid environments, temperature variables reflect growth limits and tolerance of thermal extremes, while precipitation variables capture water availability and drought exposure. Its germination responses are known to be influenced by local temperature and water availability in both its native and invaded ranges (Ferrerás et al., unpublished data). Using these biologically informed variables, our projections under current climatic conditions indicate that *N. glauca* could potentially occupy a wide range of suitable areas worldwide. These include its native range and the regions it has already invaded in North and South America, southern Africa, Australia, and

Mediterranean Europe. We also identify climatically suitable areas in East Asia and North Africa where the species is not currently reported as present or invasive. Notably, this potential distribution closely resembles that of the invasive woody plant *Ligustrum lucidum*, native to East Asia (Montti et al., 2021). The absence of *N. glauca* from certain climatically suitable regions may be due to dispersal limitations, biotic resistance, invasion lags, or under-reporting associated with socio-economic and political factors (Gurevitch et al., 2011; Shackleton et al., 2019). Nevertheless, our findings suggest that *N. glauca* could colonize new areas that are potentially suitable but where it is not yet established. Its capacity for rapid adaptation to novel biotic and abiotic conditions (Issaly et al., 2020; García et al., 2020; Costa et al., 2023; Ferreras et al., unpublished data) could facilitate further invasions in the future. Consequently, preventive measures and trade regulations should be prioritized in these regions (Roy et al., 2024).

As reported for other invasive plant species (Hellmann et al., 2008), future climatic changes are expected to alter the potential distribution of *N. glauca*. Our predictions of reduced overall habitat suitability under global warming scenarios suggest that favourable climatic conditions for the establishment of this species may become increasingly limited in the long term. This pattern may be linked to a shift toward colder, drier, and less seasonal climates, which has been hypothesized to occur in parallel with its invasion history (Issaly et al., 2024). Although a potential contraction of *N. glauca*'s range could be interpreted as positive, the species may still expand by shifting its climatic niche within invaded regions (Issaly et al., 2024) and by rapidly adapting to novel biotic and abiotic conditions (Issaly et al., 2020; García et al., 2020; Costa et al., 2023; Ferreras et al., unpublished data). Moreover, several regions are projected to remain climatically stable, allowing the species to persist where it is already established. A notable poleward shift in suitable areas is anticipated, particularly in the Northern Hemisphere, where warming and subsequent drying are expected to meet the species' climatic requirements. The projected expansion of suitable habitats in the Palearctic and Nearctic realms aligns with patterns reported for other invasive plants (Wan et al., 2021; Nair et al., 2024). In the Southern Hemisphere, South America is the only continent expected to experience a marked increase in suitability, especially in central and southern regions east of the Andes. Our findings indicate that conservation planning should prioritize regions in northern Europe, central Asia, central North America, and southwestern South America, where climatic conditions are projected to become increasingly favourable for the species. Nonetheless, projections for Asia should be interpreted cautiously, as these areas include non-analogous climates that may increase model uncertainty.

Although biodiversity hotspots and protected areas are essential for conservation, they are increasingly threatened by plant invasions, even in remote or relatively undisturbed environments (Foxcroft et al., 2017; Montti et al., 2021). Our research revealed that a significant proportion of these areas, particularly in the Nearctic, Afrotropical and Australasian regions, currently provide suitable habitats for *N. glauca*. Furthermore, habitat suitability within biodiversity conservation areas in the Palearctic realm is projected to increase under future climate scenarios. This is of particular concern given the rapid growth of this invasive plant and its capacity to form dense stands that displace native vegetation (Vélez-Gavilán, 2023). To safeguard the ecological integrity of these priority areas, integrated management strategies, including early detection, habitat restoration, biosecurity measures, and community engagement, are urgently needed (Kumschick et al., 2015). Integrating our global and regional findings enables us to identify the specific regions where biodiversity hotspots and protected areas should be prioritized for early detection and control of *N. glauca*, both currently (i.e. southern and eastern Africa, southern Australia, and southern North America) and in the future (i.e. northern Europe).

In conclusion, our study suggests that *N. glauca* has the potential to spread beyond its current range into unoccupied areas where climatic conditions are suitable. Although this invasive species is not expected to expand globally under future climate scenarios, our projections indicate that climatically suitable conditions will increase at higher latitudes, particularly in the Northern Hemisphere across the Palearctic and Nearctic realms. Notably, a substantial proportion of biodiversity hotspots and protected areas worldwide are already suitable for *N. glauca*, and those located in the Palearctic realm are projected to become increasingly favourable in the future. Our study provides crucial spatial information that can be used to prevent and control this highly invasive plant more effectively. Furthermore, it highlights the importance of incorporating regional assessments into invasion risk analyses to enhance conservation planning.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and DeepL for language editing to improve the readability of some paragraphs. After using these tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.pecon.2026.02.002>.

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