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Forthcoming risk of invasive species *Arundo donax*: global invasion driven by climate change

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Arundo donax ranks among the world's 100 most invasive weed species, posing significant threats to native biodiversity, agriculture, and natural ecosystems. Global climate change, characterized by increasing temperatures and increased human activities, is projected to amplify the risk of *A. donax* invasion worldwide. In this study, species distribution modeling via the maximum entropy algorithm was employed to predict the potential distributions of species under current and future climate scenarios on the basis of the following shared socioeconomic pathways (SSPs): SSP2-4.5 and SSP5-8.5. Our study revealed that the human influence index (HII), annual mean temperature (Bio1), and ultraviolet radiation (UV-B) were the top contributors to the model output, with contribution rates of 59%, 23.6%, and 7.3%, respectively. Currently, approximately 10.15% of the total land mass is invaded by *A. donax*, with 21 countries, including France, Croatia, Italy, and Spain, identified as exhibiting more than 75% of their territories at high risk of invasion. However, the future projections for 2041–2060 and 2081–2100 indicated substantial expansion in suitable habitats, covering land mass proportions of 18.40% and 24.26%, respectively, under SSP2-4.5 and 19.39% and 25.66%, respectively, under SSP5-8.5. Notably, 41 countries (SSP2-4.5) and 42 countries (SSP5-8.5) were projected to shift from low to high or very high invasion risk categories from 2081–2100. Moreover, invasion risk was projected to increase across all continents, with Africa demonstrating the most significant increase (312.08%). These findings highlight the escalating threat of *A. donax* under global climate change and human activities, emphasizing the urgent need for proactive management strategies, including enhanced quarantine measures and effective control programs, to limit its spread and mitigate associated risks.

KEYWORDS

countries, maximum entropy, risk assessment, species distribution models, shared socioeconomic pathways

1 Introduction

The global spread of invasive alien plants (IAPs) is intricately linked with human activities and climate change, posing significant threats to biodiversity and ecosystem stability (Catford et al., 2009; Bellard et al., 2012). The IAPs are introduced through human-mediated pathways such as agricultural practices, global trade and tourism, and the development of transportation corridors. These activities facilitate the spread of these species into various ecosystems (Dukes and Mooney, 1999; Pejchar and Mooney, 2009; Adhikari et al., 2021). Changing climatic conditions, coupled with human-induced habitat disturbances, accelerate the spread of invasive plant species by altering ecosystem dynamics and resource availability (Walther et al., 2009; Bellard et al., 2013). Furthermore, human intervention not only shapes societal progress but also significantly impacts ecosystem stability and biodiversity (González-Moreno et al., 2014).

In addition to human activities, rapid climate warming and globalization have accelerated the invasion and dispersal of IAPs worldwide. With global temperatures projected to increase by approximately 2.7 °C by the end of the century (Walther et al., 2009; Bellard et al., 2013; Ripple et al., 2024), the changing climate can alter ecological conditions, thereby shifting suitable habitats and enhancing the establishment and spread of IAPs (Bellard et al., 2013; Petitpierre et al., 2016). Human-induced environmental changes, combined with increasing temperatures, exacerbate the spread of IAPs, which highlights the need for proactive strategies to mitigate their impact on global ecosystems (Zimmermann et al., 2014; Liu et al., 2024).

Arundo donax, also known as giant reed, is a highly invasive, fast-growing perennial grass native to East Asia (Perdue, 1958; Pilu et al., 2012). It has been cultivated for thousands of years across Asia and Europe for various traditional applications, including the provision of construction materials, fencing, basket weaving, and reeds in woodwind instruments (Perdue, 1958; Bell, 1998; Guthrie, 2007; Jiménez-Ruiz et al., 2021). Over time, the species has been introduced into tropical, subtropical, and warm temperate regions worldwide, where it has naturalized and subsequently become invasive (Jiménez-Ruiz et al., 2021; Goolsby et al., 2023). Historical records indicate its introduction into North America during the early 1800s, South Africa during the late 1700s, and Australia during the mid-1800s, primarily for ornamental purposes and erosion control (Guthrie, 2007; Virtue et al., 2010; CABI, 2022). In recent decades, *A. donax* has been widely planted for additional purposes, including the production of walking sticks, fishing poles and musical instruments and as a potential biofuel source (CABI, 2022).

The species exhibits rapid growth, with an observed height increase of up to 10 cm per day, reaching a maximum height of approximately 7.62 m within a year and yielding nearly 25 tons of biomass per acre per harvest (Bell, 1998; Sidella, 2013; CABI, 2022; CISR, 2022). The primary mode of reproduction is vegetative propagation through rhizomes and plant fragments, enabling rapid colonization and regrowth following disturbance (Ozudogru et al., 2023). Dispersal occurs through both natural and anthropogenic mechanisms; notably, hydrological events such as flooding facilitate the downstream transport of rhizome fragments, whereas human-mediated activities, including soil displacement and intentional planting, significantly contribute to its widespread establishment (Bell, 1998; Guthrie, 2007; Goolsby et al., 2023).

Arundo donax is a highly adaptable species capable of thriving under a wide range of climatic and soil conditions, making it one of the most invasive plants globally. It can grow in regions with annual precipitation amounts ranging from 300 to 4000 mm and temperatures between 9 °C and 29 °C (Perdue, 1958; Weber, 2017; Haworth et al., 2019). Its remarkable drought resistance is due to its extensive underground system of rhizomes and deep roots that can penetrate up to 5 m into the soil, enabling it to access water and nutrients even under arid conditions (Sánchez et al., 2021). *A. donax* also demonstrates remarkable ecological plasticity, thriving across a wide range of soil types, including loose sandy soils, gravelly substrates, heavy clay, and riverine sediments (Jiménez-Ruiz et al., 2021; Goolsby et al., 2023). Its physiological adaptations, including a base growth temperature threshold of 9 °C and a high carbon dioxide exchange capacity, enable it to persist under diverse climatic conditions, ranging from warm to cold environments and humid to arid environments (Perdue, 1958; Spencer and Ksander, 2006). This extensive adaptability has led to its classification as one of the world's 100 most invasive alien species (ISSG, 2011; CABI, 2022).

As a highly invasive species, *A. donax* exhibits profound ecological and economic impacts, particularly in riparian ecosystems, where it aggressively displaces native vegetation, alters soil nutrient dynamics, and increases fire hazards due to its high flammability (Ambrose and Rundel, 2007; Bruno et al., 2019). This highly invasive grass forms dense monospecific stands along waterways, thereby consuming nearly three times more water than native plants do, which is a major concern in areas with large-scale invasions, such as Australia, New Zealand, South Africa, the United States, and Mexico (Lambert et al., 2010; Virtue et al., 2010; Haddadchi et al., 2013; Nkuna et al., 2018; Jiménez-Ruiz et al., 2021). In South Africa, *A. donax* is the most abundant and widespread invasive alien grass species, and compulsory inclusion is legally required in invasive species control programs. Its dense growth disrupts the hydrological system, further reducing water availability in already water-scarce regions, making it a nationally recognized problematic invasive weed (Nkuna et al., 2018; Tshapa et al., 2021). Similarly, in California, *A. donax* exacerbates flood risks and fire hazards in riparian zones, with its dense, dormant biomass serving as a vertical fuel source that promotes the occurrence of wildfires and increases fire severity (Dudley, 2000; Quinn et al., 2007). Given its significant ecological and economic impacts, *A. donax* has become a priority for control and management efforts to mitigate further environmental and economic losses.

In recent years, species distribution models (SDMs) have emerged as critical tools for predicting the potential geographical distributions of species under changing climatic conditions (Araújo and Guisan, 2006; Franklin, 2013). Among the various SDMs, such as the maximum entropy (MaxEnt) algorithm, CLIMEX model,

random forest (RF) models, generalized linear models (GLMs), and artificial neural networks (ANNs), the MaxEnt algorithm has gained widespread recognition for its effectiveness in modeling species distributions, particularly for IAPs (Booth et al., 2014; Byeon et al., 2018; Adhikari et al., 2022, 2025). The MaxEnt model is especially advantageous for analyzing presence-only data and provides notable performance even with limited sample sizes (Phillips et al., 2006; Yi et al., 2016). Despite its limitations, including the risk of overfitting, the MaxEnt model remains an effective tool for assessing invasion risk and guiding IAP management (Phillips et al., 2017). Its ability to integrate bioclimatic variables and simulate species distributions under current and future climate scenarios makes it invaluable for understanding and mitigating the ecological impacts of invasive species (Phillips et al., 2006; Wang et al., 2023).

Considering the highly invasive nature and global impact of *A. donax* on agriculture, nature, and the economy, further studies are needed to support the control and management of invasive weeds. In this study, global species occurrence records of *A. donax* are employed to estimate its invasion risk in various countries and predict invasion risk on the basis of bioclimatic variables under current and potential future shared socioeconomic pathway (SSP) climate change scenarios (SSP2-4.5 and SSP5-8.5). This research is designed to achieve three primary aims: (1) identify the key environmental variables influencing the distribution of *A. donax*, (2) predict the potential geographical distribution of *A. donax* under current and future climate change scenarios, and (3) classify the invasion risk levels of *A. donax* in different countries. By elucidating the invasion dynamics of this highly invasive species, this study aims to contribute to the development of early warning systems, prevention strategies, and targeted management plans. Ultimately, the findings of the study could support global efforts to mitigate the ecological and socioeconomic disruptions caused by *A. donax* invasions.

2 Materials and methods

2.1 Occurrence records

In this study, 51,430 occurrence records for *A. donax* were obtained from the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org; accessed on 3 December 2024). To minimize duplicate coordinates and reduce sampling biases, we applied the spatially rarefy occurrence tool within the ArcGIS SDM toolbox v.2.4, thereby retaining a single observation within each 2.5-minute resolution grid cell (Brown et al., 2017). Ultimately, the number of occurrence record points was reduced to 7,975 (Figure 1), which is sufficient for MaxEnt modeling (Supplementary Table S1).

2.2 Environmental factor variables

The distribution of species is influenced by various factors, including climatic conditions, habitat, human activities, and radiation effects (Yang et al., 2022; Adhikari et al., 2023b, 2024; Mansinhos et al., 2024). In this study, we analyzed the global distribution of *A. donax* on the basis of 19 bioclimatic variables, the human influence index (HII), and ultraviolet radiation (UV-B) via the MaxEnt model (Supplementary Table S2). Current climatic data (1979–2013) were obtained from the PaleoClim v1.2 dataset (http://www.paleoclim.org/; accessed on 10 March 2024) at a 2.5-minute resolution (Brown et al., 2018). Future climate projections for 2041–2060 and 2081–2100, under the SSP2-4.5 and SSP5-8.5 scenarios, respectively, were sourced from World Climate (http://worldclim.org/; accessed on 15 January 2024) (Hijmans et al., 2005), with datasets representing the Beijing Climate Center Climate System Model (BCC-CSM2-MR) under the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Wu et al., 2019).

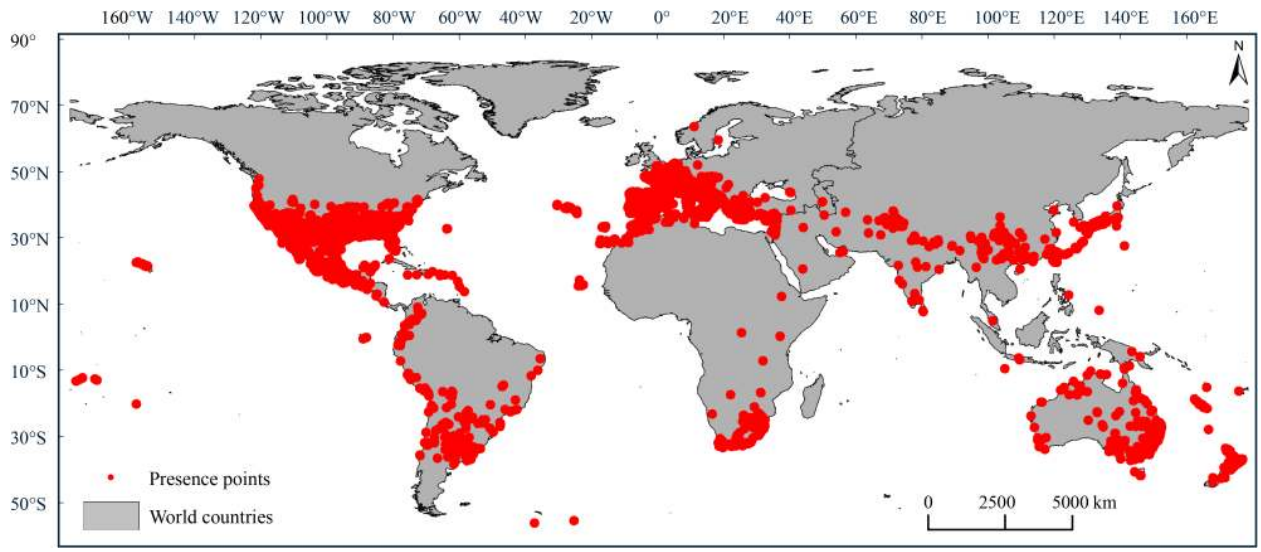


FIGURE 1
Global distribution points of *A. donax* (n=7,975). The red points indicate recorded global occurrence locations worldwide, illustrating its widespread distribution and invasive potential.

Human activities, such as global trade, transportation, and habitat alteration, play a significant role in controlling the invasion and spread of invasive species by facilitating their unintentional or intentional movement to new areas, often disrupting local ecosystems (Early et al., 2016; Chen et al., 2021). Therefore, we considered human factors when selecting environmental variables for modeling the distribution of *A. donax*. We downloaded data for the human influence index, with a resolution of 30 arc seconds (~1 km²) (http://sedac.ciesin.columbina.edu/; accessed on 4 April 2024), and resampled the data to a 2.5-minute resolution for our analysis. This variable, representing human impacts from 1995–2004, was used in modeling and includes data on the population density, land development, infrastructure, artificial lighting, and transportation networks sourced from the Wildlife Conservation Society (WCS, 2005). Additionally, UV-B radiation data were obtained from the gIUV database (http://www.ufz.de/gluv; accessed on 5 May 2024), highlighting plant physiology, growth, and ecosystem dynamics under climate change (Mansinhos et al., 2024). Similarly, we employed the global biome as a key variable, sourced from the Earth Engine data catalog (Dinerstein et al., 2017), to refine the species distribution modeling process and better understand invasive plant dynamics. Biomes, characterized by unique climatic conditions, vegetation patterns, and ecological processes, serve as fundamental drivers of species distributions and play a critical role in shaping the spread of invasive species (Olson et al., 2001; Conradi et al., 2020). As integrative environmental determinants, biomes encapsulate the interplay among climate and habitat factors, offering a holistic framework for predicting species invasions (Early et al., 2016). Combining environmental data with biome variables can enhance our ability to map ecological niches, assess invasion risks, and inform effective conservation strategies, providing greater insights into the mechanisms driving invasive species success.

Pearson's correlation analysis was conducted to reduce multicollinearity and increase the accuracy of the estimates and predictions. We used band collection statistics obtained with the spatial analyst tool in ArcGIS 10.8 (Esri, Redlands, CA, USA) to perform Pearson's correlation analysis. We analyzed 19 bioclimatic variables along with three additional variables: HII, UV-B, and Biome. Variables with low contribution rates and high correlations ($r > 0.75$, $P = 0.05$) were excluded (Supplementary Table S3). On the basis of the analysis, six climatic variables, namely, annual mean temperature (Bio1), mean diurnal temperature range (Bio2), isothermality (Bio3), annual precipitation (Bio12), precipitation in the wettest month (Bio13), and precipitation in the driest month (Bio14), along with three additional variables, i.e., HII, UV-B, and Biome, were selected (Table 1).

TABLE 1 List of the selected bioclimatic variables used in this study.

Category	Variable	Description	Unit
Bioclimatic variables	Bio1	Annual mean temperature	°C
	Bio2	Mean diurnal temperature range	°C
	Bio3	Isothermality (BIO2/BIO7) (* 100)	%
	Bio12	Annual precipitation	mm
	Bio13	Precipitation in the wettest month	mm
	Bio14	Precipitation in the driest month	mm
Human influence variable	HII	Human influence index	–
Radiation variable	UV-B	Annual mean UV-B radiation	kJ/m²
Biome variable	Biome	Biome	–

The key variables in our study, which were selected on the basis of their importance and minimal multicollinearity, were determined by Pearson's correlation analysis (r> 0.75).

2.3 Model development

We modeled the global distribution patterns of *A. donax* under current and future climate scenarios using the MaxEnt model version 3.4.4, a robust machine learning algorithm for species distribution modeling with presence-only datasets, which is particularly useful for mapping invasive species ranges (Phillips et al., 2006). Background points were determined to establish a standard protocol in ArcGIS 10.8 (ESRI, Redlands, CA, USA) (Barbet-Massin et al., 2012). The occurrence data were split into datasets for model training (75%) and validation (25%) (Araújo and Guisan, 2006). We replicated the model 100 times using optimized parameters via a cross-validation method to obtain an average outcome similar to that in the literature (Adhikari et al., 2023b, 2024; Poudel et al., 2024).

2.4 Model result evaluation and validation

The effectiveness of the MaxEnt model was evaluated, with a focus on the area under the curve (AUC) derived from receiver operating characteristic (ROC) curve analysis (Liu et al., 2011). The AUC, with values ranging from 0 to 1, provides a threshold-independent measure of the model performance, classified as failing (0.5–0.6), poor (0.6–0.7), fair (0.7–0.8), good (0.8–0.9), or excellent (0.9–1) (Swets, 1988; Fielding and Bell, 1997; Elith et al., 2006). By representing the area under the ROC curve, the AUC reflects the ability of the model to distinguish suitable from unsuitable habitats.

Additionally, the jackknife test was employed to evaluate the relative contributions of individual environmental variables to the species distribution modeling results. In this method, each variable is systematically excluded to measure its impact on the model performance, identifying the most influential predictors shaping the potential distribution of the species (Phillips et al., 2006; Merow et al., 2013).

2.5 Assessing the current and future potential distribution of *A. donax* worldwide

Binary habitat distribution maps for *A. donax* were developed by converting the MaxEnt probability outputs into suitable and unsuitable habitat classes via the maximum training sensitivity plus specificity cloglog threshold (Liu et al., 2016). These distribution maps were generated for three temporal scenarios, i.e., current (1979–2013), mid-century (2041–2060), and end-century scenarios (2081–2100), under two climate pathways, namely, SSP2-4.5 and SSP5-8.5.

Via the use of the Zonal Statistics tool in ArcGIS Desktop 10.8, the number of grid cells representing suitable habitats was calculated for each continent across the different scenarios. Each grid cell, covering approximately 4.5 km at the equator, was used to estimate the total area of suitable habitats. Changes in the suitable habitat area in each country were then estimated under the SSP2-4.5 and SSP5-8.5 scenarios for the 2041–2060 and 2081–2100 periods.

To evaluate the global invasion risk of *A. donax*, the invasion risk in each country was estimated on the basis of the average habitat suitability and classified into five categories: no invasion risk (0), low invasion risk (0.001–0.25), moderate invasion risk (0.26–0.50), high invasion risk (0.51–0.75), and very high invasion risk (0.76–1). These categories provide a framework for analyzing global invasion risks and identifying areas of vulnerability. Comparative analyses across periods revealed varying degrees of invasion risk under the current and projected climate conditions, highlighting regions requiring targeted management and intervention strategies. The overall research methodology explained in this section is summarized in a flowchart (Figure 2).

3 Results

3.1 Model contribution, evaluation, and validation

Among the selected variables, HII, Bio1, and UV-B were the top contributors, with contribution rates of 59%, 23.6%, and 7.3%, respectively, accounting for a cumulative contribution of 89.9% (Figure 3A). The remaining variables exerted a minimal influence on the model performance. Bio1, HII, and UV-B exhibited relatively high contributions to the model and were confirmed as the most influential predictors based on their impact on species distribution modelling (Figure 4).

The permutation importance analysis results also highlighted Bio1, HII, and Bio3 as key variables, with importance values of

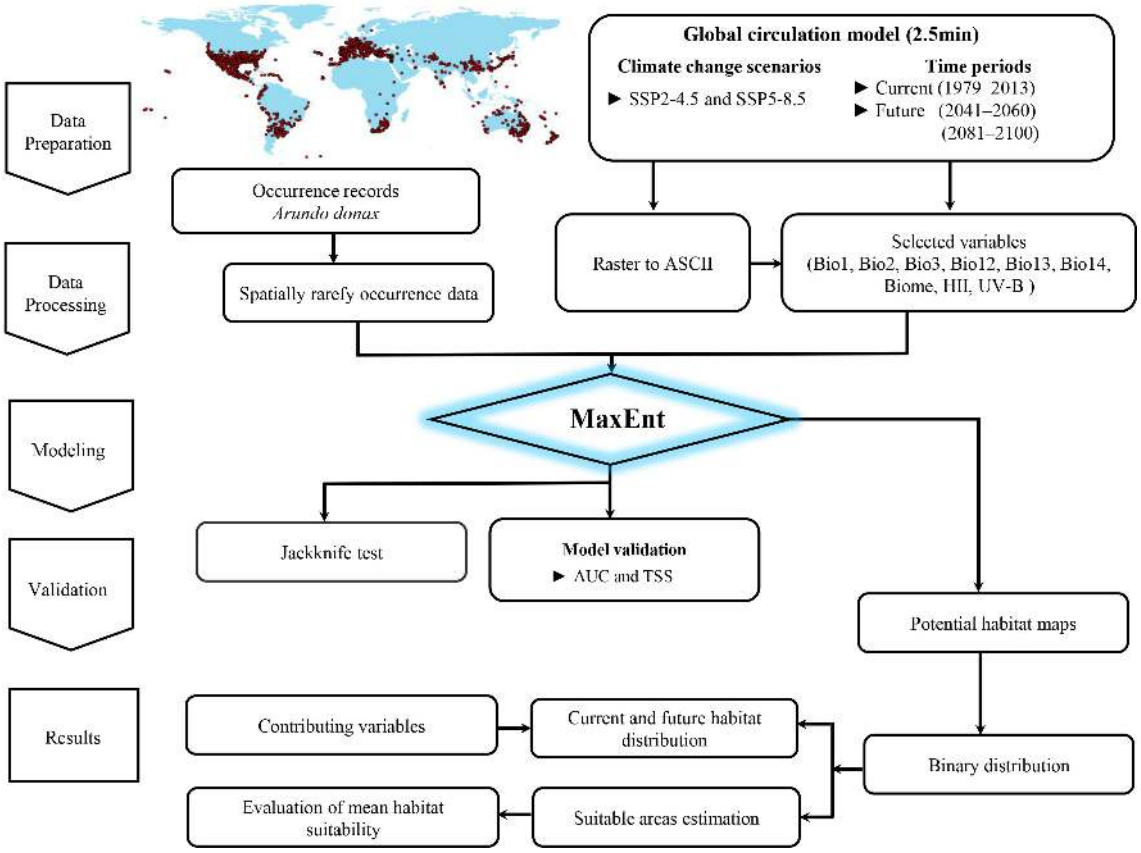


FIGURE 2
Flowchart showing the overall process of data preparation, modeling, and analysis.

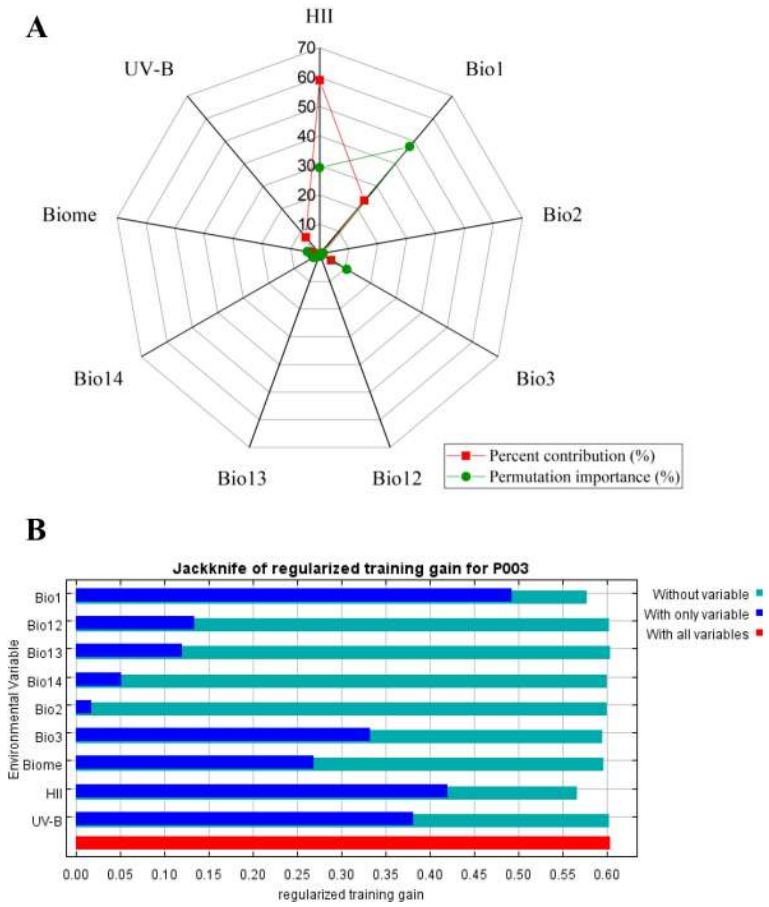


FIGURE 3
Estimating the contribution of bioclimatic variables in species distribution modeling of *A. donax*. **(A)** Radar chart showing the average percent contribution and permutation importance of the selected environmental variables in the MaxEnt model for *A. donax* under current and future climatic scenarios (SSP2-4.5 and SSP5-8.5, respectively) across the 2041–2060 and 2081–2100 periods. **(B)** Jackknife test results showing the relative significance of the bioclimatic variables used in the MaxEnt model.

47.54%, 29.26%, and 10.65%, respectively, underscoring their critical role in determining the model performance. The jackknife test outcomes supported these findings, identifying Bio1, HII, and UV-B as the most significant contributors (Figure 3B), demonstrating the relative contribution of each variable to the potential distribution of *A. donax*. The model performance was evaluated using AUC values. The predictions based on rarefied species occurrence points achieved a higher AUC score (0.901) than those based on all occurrence points (0.755), indicating that the use of rarefied data increases the prediction accuracy and reduces the risk of over- or underestimation.

3.2 Potential distribution of *A. donax* under current and future climate change scenarios

The MaxEnt model was used to predict the current and future distributions of *A. donax* (Figure 5). Currently, *A. donax* occupies a substantial global range, spanning 884,899 grid cells, equivalent to 10.15% of the world's total land area (Figure 6). The geographical reach of this species extends across 145 countries, with notable high-coverage regions, including South Africa, Belgium, Italy, France, Portugal, Israel, and Uruguay, where *A. donax* potentially occupies 50–100% of the land area (Supplementary Table S4).

Under the future climate change scenarios, the potential distribution of *A. donax* is projected to increase significantly. By 2041–2060, under SSP2-4.5, the species is projected to occupy 1,603,606 grid cells, accounting for 18.40% of the global land area. This expansion is projected to increase to 2,113,752 grid cells (24.26%) by 2081–2100. Similarly, under SSP5-8.5, the potential distribution increases to 1,690,048 cells (19.39%) from 2041–2060 and increases to 2,235,916 cells (25.66%) from 2081–2100 (Figure 6). These projections highlight the extensive potential spread of *A. donax* under global climate change.

Potential habitat expansion was also evaluated across continents for the two future periods under SSP2-4.5 and SSP5-8.5 (Table 2). Under SSP2-4.5, Africa and Asia exhibited the most significant increases in habitat suitability, with increases of 133.97% and 132.54%, respectively, from 2041–2060, increasing to 273.22% and 225.85%, respectively, from 2081–2100. South America also exhibited a notable upward trend, whereas Europe, Australia, North

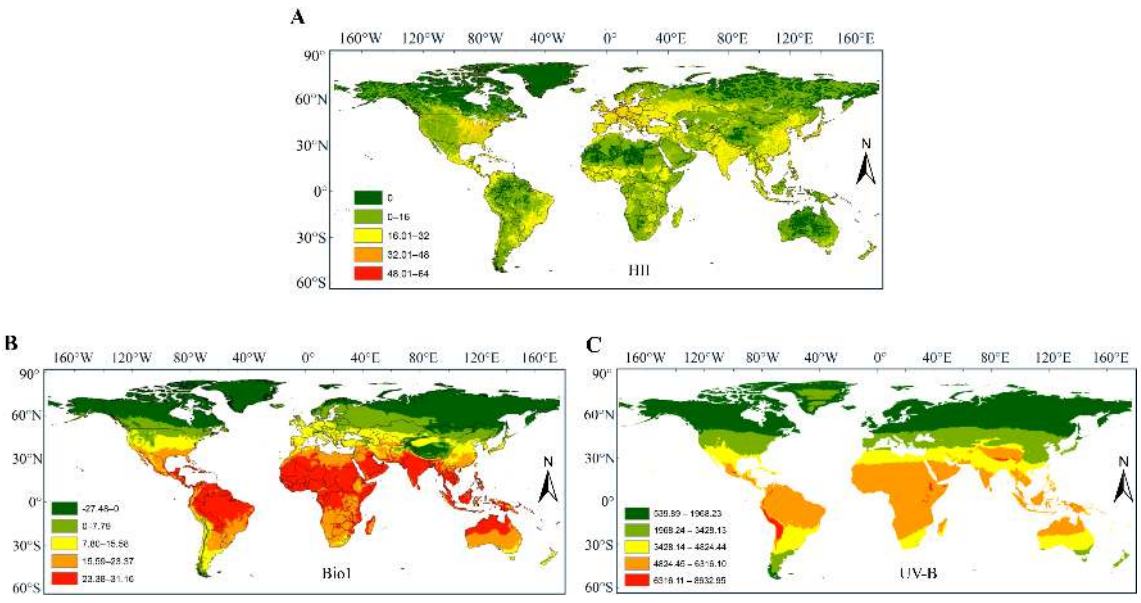


FIGURE 4
Highly contributing variables in the MaxEnt model for the global distribution of *A. donax*. **(A)** Human influence index (HII), **(B)** annual mean temperature (Bio1), and **(C)** annual ultraviolet radiation (UV-B). The colors corresponding to the legend indicate the varying levels of HII, Bio1 and UV-B across different parts of the world.

America, and Oceania exhibited moderate increases ranging from 38.41% to 85.82%.

Under SSP5-8.5, even greater expansions in the habitat distribution of *A. donax* were observed. Africa exhibited the largest increase, with habitat suitability increasing to 152.03% from 2041–2060 and 312.08% from 2081–2100. Asia demonstrated a similar pattern, increasing from 152.60% to 233.12%, whereas South America revealed an increase from 81.67% to 123.76% over the same periods. Europe, Australia, North America, and Oceania continued to exhibit moderate but consistent increases. Antarctica showed an absence of habitat suitability under the current or future scenarios and was therefore excluded from the analysis.

3.3 Classification of global invasion risk of *A. donax* in different countries

The mean habitat suitability of *A. donax* was assessed across all countries under the current and future climate scenarios (SSP2-4.5 and SSP5-8.5, respectively), categorizing countries into five risk levels: no invasion risk, low invasion risk, moderate invasion risk, high invasion risk, and very high invasion risk (Figure 7). Under the current climatic conditions, 39 countries exhibited no invasion risk, 84 countries exhibited low invasion risks, 24 countries exhibited moderate invasion risks, 16 countries exhibited high invasion risks, and 21 countries exhibited very high invasion risks. However, the future climate change scenarios revealed a decrease in the no- and low-invasion risk areas and a progressive increase in high- and very high-invasion risk countries (Table 3, Supplementary Table S5). Under SSP2-4.5, the number of very high-invasion risk countries increased to 44 from 2041–2060 and increased to 71 from 2081–2100. Under the more extreme SSP5-8.5 scenario, the trend increased, with 47 countries projected to exhibit very high invasion risks from 2041–2060, with the number of countries reaching 72 from 2081–2100.

Under the current climatic conditions, 21% of the global land area occurs within the no invasion risk category, whereas the areas with a low invasion risk, moderate invasion risk, high invasion risk, and very high invasion risk account for 46%, 14%, 8%, and 11%, respectively, of the total land area (Figure 8). The proportion of the global land area with a very high risk of invasion from *A. donax* is projected to increase substantially under the future climate scenarios. Compared with the value of 11% under the current conditions (1979–2013), this category increased to 23% (2041–2060) and 38% (2081–2100) under SSP2-4.5, which is similar to values of 26% and 38%, respectively, under SSP5-8.5. Areas at high invasion risk also increased slightly, reaching 17–18% during the future periods compared with the value of 8% currently. In contrast, the proportion of land in the no-risk and low-risk categories is projected to decrease under the future climate change scenarios. These results emphasize the increasing global exposure to severe invasion risk under changing climate conditions.

The model projected a significant expansion of *A. donax* habitats and a shift in invasion risk patterns, affecting multiple countries worldwide. Under the SSP2-4.5 scenario, of the 39 countries currently at no invasion risk, 25 countries, including Norway, Senegal, Brunei, and Poland, will shift to the low or moderate risk category. Similarly, under the SSP5-8.5 scenario, 20 countries, such as Sweden, Gabon, Guinea, and Denmark, will exhibit similar changes in risk level, affecting up to 50% of their land area (Tables 3, S6). Additionally, 41 countries may transition

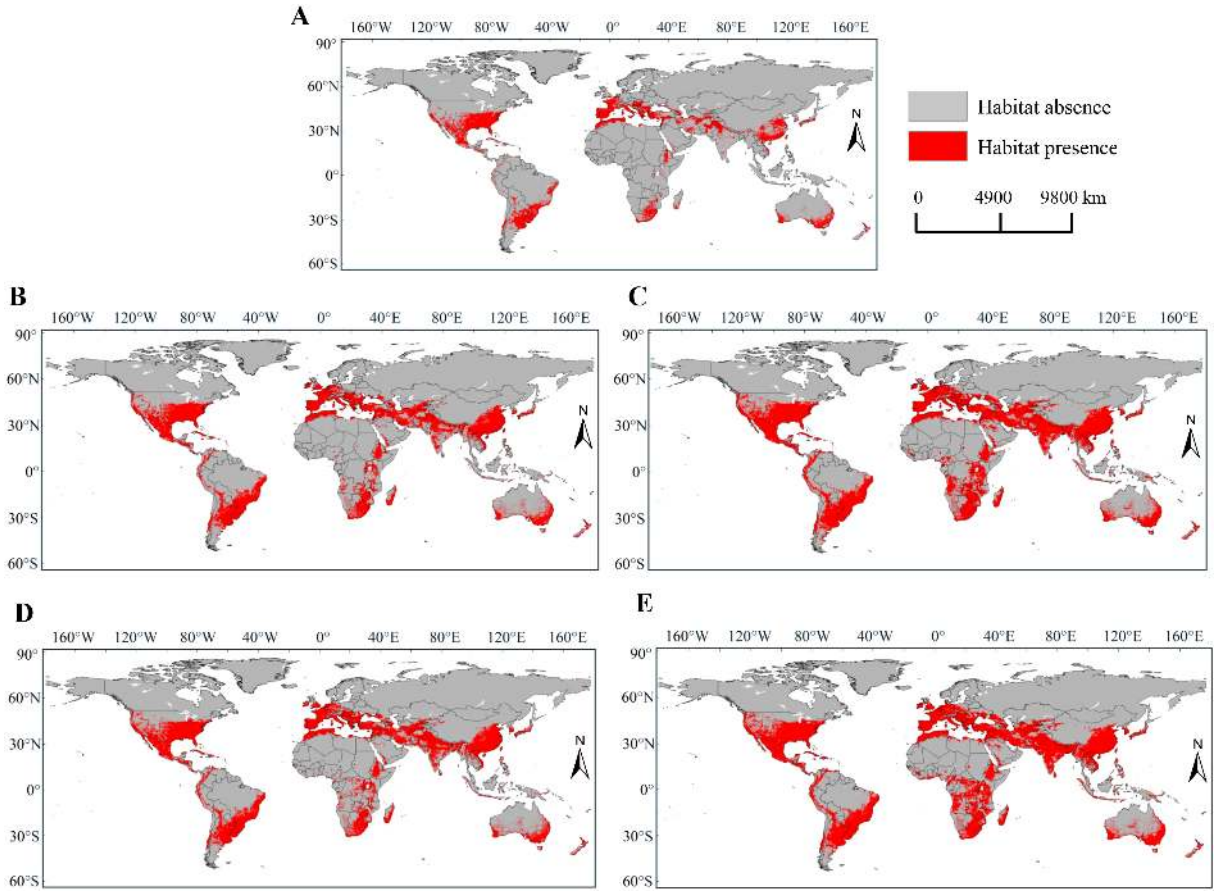


FIGURE 5
Potential geographical distribution of *A. donax* under current and future climate change scenarios (SSP2-4.5 and SSP5-8.5, respectively) for the 2041–2060 and 2081–2100 periods. **(A)** Current (1979–2013), **(B)** SSP-4.5 (2041–2060), **(C)** SSP2-4.5 (2081–2100), **(D)** SSP5-8.5 (2041–2060), and **(E)** SSP2-4.5 (2081–2100). Red and gray in the legend indicate the presence and absence, respectively, of *A. donax*.

from the low risk category to the high or very high invasion risk category under SSP2-4.5, including Austria, India, and Bangladesh, whereas 42 countries, such as Sri Lanka, Germany, and the Netherlands, could experience a similar shift under SSP5-8.5, covering between 50% and 100% of their total land area. These findings suggest that climate change may cause a shift in the risk level of *A. donax* invasion, placing multiple countries at greater threat and highlighting its potential for global expansion.

4 Discussion

This study provides critical insights into the global invasion dynamics of *A. donax*, with significant implications for biodiversity conservation and invasive species management under the global environment change. The identification of HII as the most significant predictor of species distribution underscores the growing role of anthropogenic activities in facilitating biological invasions (Chen et al., 2021). Environmental factors such as temperature, soil quality, and resource availability govern habitat. Human activities such as urbanization, transportation network establishment, land use changes, and intentional species introductions, catalyze the establishment and spread of invasive species (Kueffer, 2017; Chen et al., 2021). These anthropogenic activities not only disrupt the ecological balance but also create pathways for colonization, particularly through coastal waterways, highways, and navigable rivers, which serve as conduits for invasive propagules (With, 2002; Catford et al., 2012). Furthermore, ecosystem modifications such as infrastructure expansion, nocturnal lighting, and hydrological changes increase invasion risk through the generation of disturbed habitats that favor nonnative species over native species (Okorondu et al., 2022).

Arundo donax exemplifies the profound influence of humans on invasion dynamics. Historically dispersed through intentional introductions for erosion control, biofuel production, and ornamental use, its global spread has been intensified by accidental transport via agricultural machinery and the nursery trade (Perdue, 1958; Bell, 1998; Haddadchi et al., 2013; Jiménez-Ruiz et al., 2021). Human-induced disturbances, including land development, agricultural runoff, and water management practices, create ideal conditions for *A. donax* dominance. Nutrient enrichment resulting from wastewater discharge and irrigation promotes soil fertility, enabling *A. donax* to outcompete native species, whereas mechanical disturbances, including bulldozing and

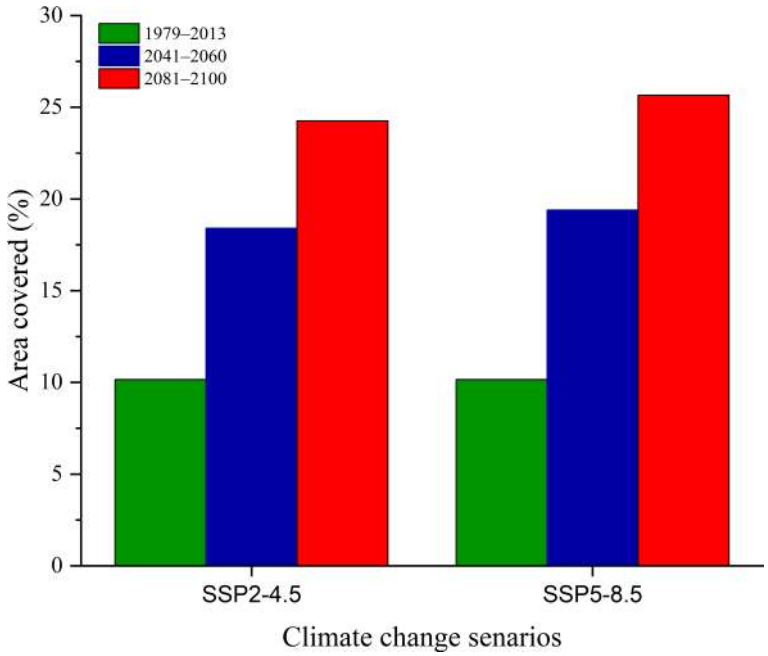


FIGURE 6
Bar graph showing the proportion of the global area occupied by *A. donax* under current and future climate change scenarios (SSP2-4.5 and SSP5-8.5, respectively) from 2041–2060 and 2081–2100. The analysis is based on a grid with a resolution of 2.5 minutes, equivalent to approximately 4.5 km at the equator.

tilling, can fragment *A. donax* rhizomes and stems, facilitating their vegetative reproduction and spread (Bell, 1998; Wijte et al., 2005). In fire-prone regions, human-induced burns enhance the competitive edge of *A. donax*, allowing rapid postfire recolonization while suppressing native vegetation recovery (Quinn et al., 2007; Goolsby et al., 2023). Given the notable influence of human activities on biological invasion, incorporating human factors, such as the HII, into invasion risk models increases the prediction accuracy, especially in regions with high levels of human activity (Bucklin et al., 2015; Zhu et al., 2017; Hong et al., 2021). In our study, the HII was the most critical environmental variable, with a significant contribution of 59% to the *A. donax* distribution modeling results (Figure 3A), underscoring the centrality of anthropogenic drivers in shaping its spread. Understanding these human-driven mechanisms is crucial for developing effective strategies to mitigate the spread and impact of IAPs and to preserve biodiversity and ecological balance.

Similarly, the annual mean temperature has second highest contribution in model prediction. Increasing temperature facilitates to expand the habitat of *A. donax* into the higher altitude and higher latitudes. The optimal temperature for *A. donax* germination varies between 20 °C and 30 °C (Bell, 1998), although it can tolerate a broader range of temperatures. However, temperatures below 0 °C

TABLE 2 Continental changes in the habitat distribution (%) of *A. donax* compared with that under the current climatic conditions (1979–2013).

Continents	Current[a] (1979–2013) Total no. of cells	Change in habitat categories (%)			
		SSP2-4.5		SSP5-8.5	
		2041–2060	2081–2100	2041–2060	2081–2100
Africa	101,665.69	133.97	273.22	152.03	312.08
Asia	199,530.62	132.54	225.85	152.60	233.12
Australia	63,043.26	45.67	85.54	44.78	80.32
Europe	148,964.67	49.60	85.82	55.12	91.15
North America	232,255.05	38.41	69.19	46.98	73.93
Oceania	7,736.33	46.87	68.31	43.30	62.31
South America	140,919.31	81.08	129.30	81.67	123.76

[a]The numbers in the column denote the current total number of cells covered by *A. donax* on different continents.

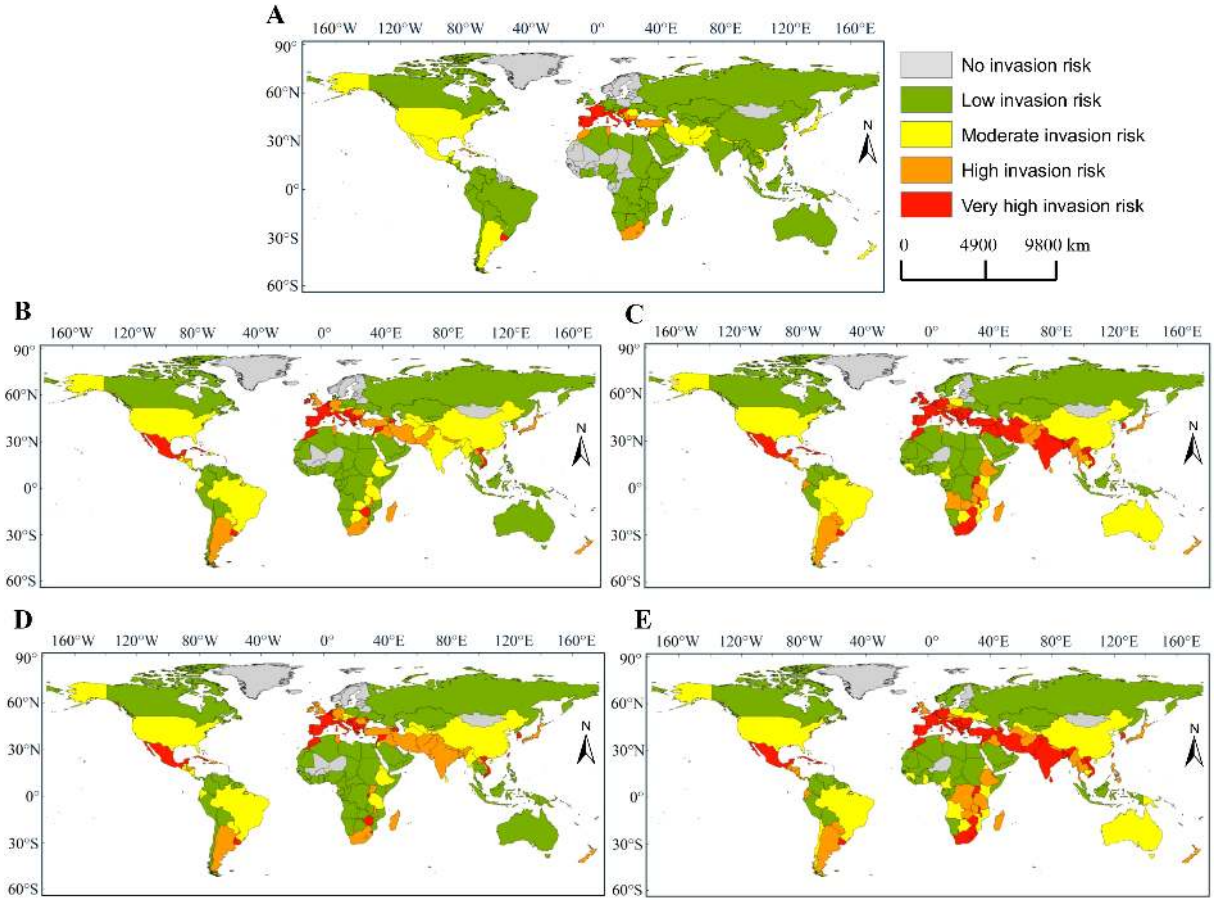


FIGURE 7
Mean habitat suitability of *A. donax* estimated for different countries worldwide under current and future climate change scenarios (SSP2-4.5 and SSP5-8.5, respectively) for the 2041–2060 and 2081–2100 periods. **(A)** Current (1979–2013), **(B)** SSP-4.5 (2041–2060), **(C)** SSP2-4.5 (2081–2100), **(D)** SSP5-8.5 (2041–2060), and **(E)** SSP2-4.5 (2081–2100). The risk levels are categorized as follows: no invasion risk (0), low invasion risk (0.001–0.25), moderate invasion risk (0.26–0.50), high invasion risk (0.51–0.75), and very high invasion risk (0.76–1).

can be detrimental to its growth (Bell, 1998; CABI, 2022). Given its preference for warm climates, *A. donax* has thrived in tropical, subtropical, and warm temperate regions, where it has adapted well to diverse soil types, including sandy gravel, heavy clay, and river sediments (CABI, 2022). Species resilience is highlighted by its ability to withstand increasing global temperatures, which have increased by approximately 1.1 °C since the late 19th century (Legg, 2021). This adaptability has facilitated an increase in the range of *A. donax* even under shifting climatic conditions. In support of this process, Bio 1 contributed significantly (23.60%) to the potential distribution of *A. donax* (Figure 3A), highlighting the dominant role of temperature in shaping its geographical spread.

TABLE 3 Number of countries invaded by *A. donax* globally under current and future climate change scenarios on the basis of the different risk categories.

Risk category	Current	SSP2-4.5		SSP5-8.5	
		2041–2060	2081–2100	2041–2060	2081–2100
No invasion risk	39	20	11	18	10
Low invasion risk	84	60	49	61	44
Moderate invasion risk	24	30	22	25	28
High invasion risk	16	30	31	33	30
Very high invasion risk	21	44	71	47	72

Invasion risk categories of *A. donax* under the current and future climate change scenarios (SSP2-4.5 and SSP5-8.5, respectively) for the 2041–2060 and 2081–2100 periods. The risk levels are categorized as follows: no invasion risk (0), low invasion risk (0.001–0.25), moderate invasion risk (0.26–0.50), high invasion risk (0.51–0.75), and very high invasion risk (0.76–1); SSP, shared socioeconomic pathway.

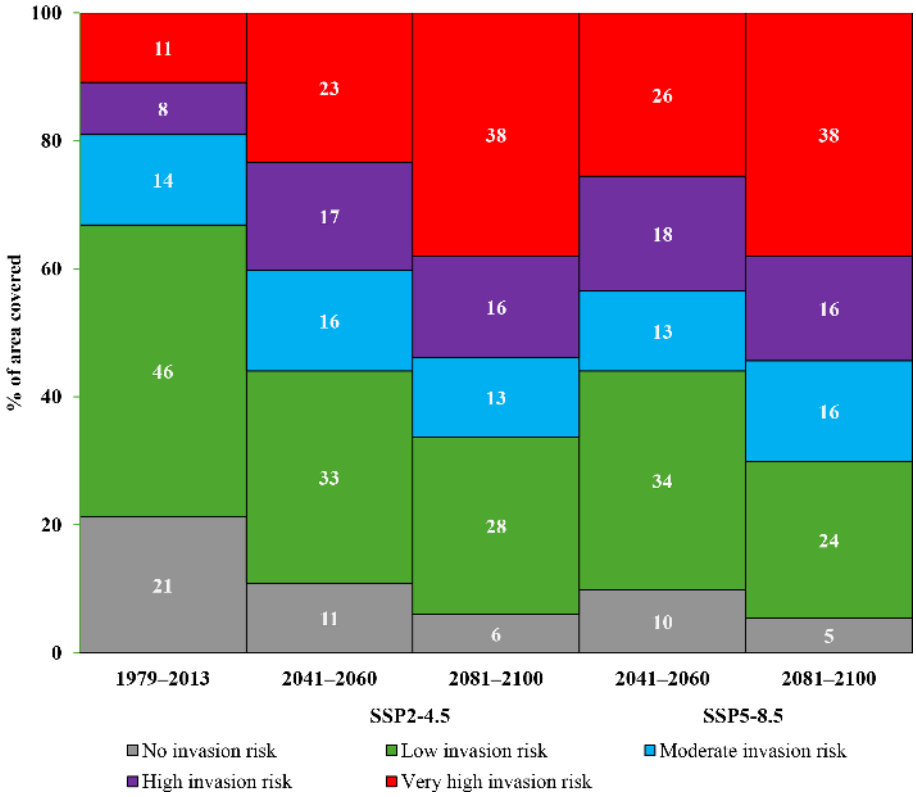


FIGURE 8
Percentage of the global area categorized by invasion risk level for *A. donax* under current and future climate scenarios (SSP2-4.5 and SSP5-8.5, respectively) for the 2041–2060 and 2081–2100 periods. Gray indicates no invasion risk, green indicates low invasion risk, blue indicates moderate invasion risk, purple indicates high invasion risk, and red indicates very high invasion risk.

Similarly, UV-B radiation plays a crucial role in determining the distribution of IAPs by influencing their competitive ability and survival (Hock et al., 2020; Mansinhos et al., 2024). While UV-B exposure can cause damage to DNA and cellular structures, leading to reduced growth rates and impaired reproduction, certain invasive species, such as *A. donax*, have developed adaptive mechanisms to thrive under high-UV and high-drought conditions (Liakoura et al., 1997; Mann et al., 2013). These adaptations include the production of UV-absorbing flavonoids and antioxidants, allowing them to exploit UV-driven changes in plant structure, nutrient cycling, and microbial interactions. In our study, UV-B radiation contributed 7.30% to the potential distribution of *A. donax* (Figure 3A). Although UV-B radiation can suppress invasive species by impairing their reproductive success, resilient species can withstand its effects, rendering UV-B radiation a key factor in predicting and managing plant invasions (Hock et al., 2020; Mansinhos et al., 2024).

With respect to bioclimatic factors, *A. donax* exhibits rapid growth, extensive roots, clonal reproduction via rhizomes, and notable tolerance to temperature and drought, increasing its invasiveness (Perdue, 1958; Guthrie, 2007; CABI, 2022). Initially, introduced for erosion control, bioenergy production, and ornamental landscaping, *A. donax* has become invasive because of its high germination rate, ability to regenerate roots, and adaptability to diverse climates (Virtue et al., 2010; CABI, 2022). By outcompeting native species, it reduces biodiversity and disrupts ecosystem functions such as hydrology, soil chemistry, and fire regimes. *A. donax* monopolizes sunlight, water, and nutrients, altering ecosystem dynamics and posing a threat to native flora and fauna (Waterworth, 2015). Our model revealed its presence in 145 countries under current climate conditions, covering approximately 10.15% of the global land surface. This study supports global risk assessments identifying *A. donax* as one of the most pervasive and damaging invasive species (Early et al., 2016), highlighting the urgent need for coordinated management strategies to curb its spread and mitigate its ecological impacts. Our findings indicated that areas in Africa, Asia, and South America are likely to exhibit a significant increase in suitable habitats for *A. donax*, with its spatial distribution projected to increase by up to 312.08% from 2081–2100 (Table 2). Increasing anthropogenic activities and temperatures could result in habitat loss for native species while facilitating a shift from unsuitable areas to those that are highly suitable for *A. donax*. This expansion of suitable conditions, combined with its rapid growth, will likely increase the invasion range of *A. donax*, as similar to other IAPs, such as *Lantana camara, Oxalis latifolia*, *Parthenium hysterophorus* and *Acacia mearnsii* (Ahmad et al., 2019; Tiwari et al., 2022; Poudel et al., 2023; Adhikari et al., 2024; Poudel et al., 2024).

The SSP5-8.5 scenario produced a greater invasion risk for *A. donax* from 2081–2100 than the SSP2-4.5 scenario did, with notable

increases in South Korea, Mexico, Vietnam, and Turkey and new risks emerging in Bangladesh, India, the Netherlands, Sri Lanka, Japan, and Bhutan, where the invasion risk may exceed 50% (Supplementary Table S4). Extreme climate changes under SSP5-8.5 cause expansion in suitable habitats, especially at relatively high latitudes and elevations, while adversely affecting native plant communities, increasing their vulnerability to invasion (Chen et al., 2022). The synergistic effects of climate change and human-driven factors, such as land use changes, exacerbate the invasion risk under SSP5-8.5 (Adhikari et al., 2019; Yang et al., 2023), resulting in a greater threat of global invasion than that under SSP2-4.5.

Countries were classified into five categories on the basis of their risk of invasion by *A. donax*. Currently, 39 countries, including Denmark, Guinea, Kuwait, and Norway, have no recorded presence of *A. donax* (Table 3). However, climate change and human-driven activities, such as research, exploration, exploitation, and tourism activities, have significantly increased over the past 200 years, increasing the likelihood of invasion in several of these countries (Weir, 2017; Adhikari et al., 2023a, 2024). Projections for 2081–2100 indicated a substantial shift in invasion risk patterns, with the proportion of global land classified as no-risk areas expected to decrease to just 5%. Conversely, areas categorized as high-invasion risk areas and very high-invasion risk areas are projected to expand, encompassing 38% of the global land area under both the SSP2-4.5 and SSP5-8.5 scenarios (Figure 8). These findings highlight countries at potential risk of invasion, emphasizing the need for the implementation of quarantine measures to prevent the introduction and spread of *A. donax*.

The limited northward distribution of *A. donax* is due primarily to climatic and environmental constraints that restrict its growth and survival at relatively high latitudes. As a warm-season C4 grass, *A. donax* is highly sensitive to low temperatures and cannot tolerate freezing conditions, which are common in northern regions such as Canada, northern Europe, and Siberia (Quinn et al., 2007; Mack, 2008). These areas experience harsh winters, shorter growing seasons, and reduced solar radiation, all of which limit the ability of plants to establish and thrive (Perdue, 1958; Bell, 1998). Additionally, water availability is often restricted in frozen soils, and repeated freeze–thaw cycles can cause plant rhizome damage, impeding plant spread (Dudley, 2000).

Human-mediated pathways, such as urbanization, agriculture, and transportation networks, typically facilitate the introduction and proliferation of invasive species such as *A. donax*. However, such activities are less prevalent in colder, sparsely populated northern regions, significantly reducing opportunities for anthropogenic dispersal and colonization (Dudley, 2000; Hulme, 2009; Early et al., 2016). Additionally, the competitive advantage of *A. donax* in warmer, disturbed ecosystems decreases in areas with colder climates, where native flora are better adapted to local environmental stressors (Bell, 1998; Goolsby et al., 2023).

The key limiting factors for *A. donax* at northern latitudes include low average annual temperatures, extreme cold during the winter months, and minimal human activity (Franco et al., 2006; CABI, 2022; Goolsby et al., 2023). These conditions collectively reduce habitat suitability and restrict species range expansion. The interplay of climatic stressors, physiological limitations, and reduced anthropogenic influence underscores the challenges facing *A. donax* in colonizing higher-latitude areas (Goolsby et al., 2023).

Despite its negative impacts, *A. donax* has significant economic value. It is utilized for biomass energy production, edible and medicinal fungus cultivation, windbreak construction, soil conservation, and soil remediation (Speck, 2003; Liu et al., 2009; Fagnano et al., 2015; Vasmara et al., 2023). Various methods have been employed to control the spread of *A. donax* (for example, mechanical control, such as repeated mowing, may be relatively effective, but even small root fragments can regenerate new growth) (Bell, 1998). Systemic herbicides are often applied after flowering, either as a cut-stump treatment or a foliar spray, with late summer or fall as the most effective period for application (Hoshovsky, 1986; Bell, 1998). Since *A. donax* rarely produces viable seeds, it spreads primarily through vegetative fragments, with rhizome clumps and culm nodes serving as key colonization sources (Bell, 1998). Control efforts are labor intensive, requiring multiple sessions to eliminate root fragments and prevent regrowth, often making it a costly, long-term process that can last up to 20 years (Hoshovsky, 1986; CABI, 2022). To prevent ecological disruption caused by *A. donax*, comprehensive border control measures are essential. The implementation of rigorous biosecurity protocols can restrict its spread, protect native plant biodiversity, and create opportunities for ecosystem restoration.

Although our study provides valuable insights into the invasion risk of *A. donax*, several limitations should be noted. First, we used a single GCM model, and incorporating multiple models in future analyses could improve the robustness of projections. Second, our global-scale analysis employed a 2.5-minute resolution, which may not accurately capture invasion dynamics in small or geographically isolated areas such as islands. Third, our study relied on model-based projections, and while the identified risk areas are informative, field validation is currently lacking. Finally, we applied only the Maxent model, which does not account for dispersal barriers and may therefore lead to under- or overestimation of potential distributions.

Future research should address the limitations identified in this study by incorporating multiple GCMs to enhance the robustness of climate projections, applying higher spatial resolutions for regional and island-scale analyses, and integrating dispersal mechanisms to more realistically capture invasion dynamics. Beyond the MaxEnt framework, employing ensemble modeling approaches that combine multiple species distribution models could help reduce biases and provide more reliable predictions. Moreover, field-based validation of the predicted high-risk areas is essential to ground-truth model outputs and refine management strategies. Together, these efforts will improve the accuracy of invasion risk assessments for *A. donax* and provide stronger scientific guidance for prevention, monitoring, and control under current and future climate change scenarios.

Our study highlights the urgent need for coordinated international strategies to manage the invasion risk of *A. donax*, particularly in regions highly vulnerable to its spread. We recommend implementing early detection, rapid response, and biosecurity measures, supported by strict regulations on its trade and cultivation. The species could be introduced through commercial grass seeds used in pasturelands; therefore, quarantine systems should be properly managed. Our study provides a list of countries potentially at risk of future invasion, which could serve as a reference for policymakers. As the study is based on model predictions, the results may differ from real-world scenarios and should therefore be applied with caution, especially in areas lacking field evidence. Furthermore, collaborative research on sustainable management approaches, along with awareness programs for stakeholders and the public, will be essential to minimize the ecological and economic impacts of *A. donax* under changing climate conditions.

5 Conclusion

Arundo donax poses a significant threat to biodiversity, ecosystems, and local economies. The risk of invasion is heightened by global climate change and human activities. In this study, species distribution modeling was applied to assess the invasion potential of *A. donax* globally under various climate change scenarios. Among the nine environmental variables considered, the HII contributed the most to the model output, emphasizing the role of human activities in facilitating its spread. Currently, *A. donax* occupies approximately 10.15% of the world's land area, but projections suggest that this value will increase to 25.66% from 2081–2100. The rate of invasion is particularly high in Africa, where it is expected to increase by up to 312.08%. Several countries, including South Africa, Morocco, Belgium, and Israel, are at high risk of invasion. The study identified regions with varying levels of invasion risk—low, moderate, high, and very high—along with emerging risks and expansion areas between 2041–2060 and 2081–2100. The future risk assessment results indicated that at least 20 countries will transition from no risk to low risk categories, and 42 countries will move from low to high and very high invasion risk categories. The results highlight the urgent need for the formulation of stringent quarantine measures and proactive management strategies to prevent the spread of these IAPs and mitigate their environmental and economic impacts.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

AP: Conceptualization, Data curation, Formal analysis, Writing – original draft. YL: Conceptualization, Methodology, Validation, Writing – review & editing. PrabA: Writing – review & editing, Data curation, Formal analysis. PradA: Conceptualization, Investigation, Supervision, Writing – review & editing. SH: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2025.1631747/full#supplementary-material

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