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ECOLOGY

Climate change may favor the expansion of *Adenium obesum* in arid and semi-arid regions?

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ABSTRACT. Future climate change may affect in the environmental suitability, which refers to the set of conditions necessary for a species to establish itself in a given ecosystem. The species *Adenium obesum* has a native distribution in desert regions, suggesting its adaptation to hot and arid climates. Thus, this study aimed to model the species environmental suitability for hot and dry climates, considering the premise of global temperature increase and the consequent possibility of expanding its distribution area. Occurrence data for *Adenium obesum* were obtained from the Global Biodiversity Information Facility (GBIF), while climate variables were sourced from the WorldClim database (version 2.1), with a spatial resolution of 5 arc-minutes. The modeling process employed the following algorithms: BRT, GAM, GLMPoly, MARS, MaxEnt, RF, and RPart. The models were evaluated using statistical metrics, considering those with AUC > 0.9 as potentially useful. For the True Skill Statistic (TSS) method, values above 0.7 were classified as good. To quantify, in km², the difference between the species' current potential distribution and the environmentally suitable areas projected for the future, the results were binarized, allowing the calculation of expansion, contraction, stability, and absence percentages. The future projections indicate an expansion of *Adenium obesum*, confirming the hypothesis that, due to its ecological and environmental characteristics, the species may achieve greater success in colonizing new areas under future climatic conditions characterized by higher temperatures and lower precipitation.

Keywords: Apocynaceae; invasive species; ecological niche modeling; desert rose.

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Introduction

Global Climate Change stands is one of the most pressing contemporary challenges, with potentially catastrophic consequences for the planet (Intergovernmental Panel on Climate Change [IPCC], 2022). The Intergovernmental Panel on Climate Change [IPCC] of the United Nations, in its latest report (IPCC, 2022), emphasized that rising global temperatures, shifts in precipitation patterns, and other climate-related changes are continuously and significantly affecting multiple aspects of the natural world (Smith et al., 2015). Unsustainable anthropogenic expansion processes have intensified, often resulting in a wide range of negative environmental impacts. Climate is among the most influential factors shaping the global distribution of species (Anselmetto et al., 2024).

In addition to these climate-related pressures, the commercial value of *Adenium obesum* as an ornamental plant increases the risk of its intentional or accidental introduction beyond native areas. Climate change may further enhance this process by providing favorable conditions for establishment in new habitats, which underscores the relevance of investigating its potential as an invasive alien species. Anticipating these dynamics through ecological niche modeling allows for a better understanding of the species' future distribution and supports the development of strategies aimed at minimizing biodiversity loss in vulnerable ecosystems (Li et al., 2024).

The intensification of anthropogenic activities has triggered substantial changes in the geographical distribution of species and in their physiological processes, leading to profound alterations in the structure and functioning of ecosystems. These transformations undermine ecological balance and directly contribute to the accelerated loss of biodiversity at multiple scales. Scientific evidence shows that human pressures alter community composition, reduce local diversity, and compromise essential ecosystem functions (Díaz et al., 2019). Consequently, the impacts of climate change can have an impact on the environmental suitability of species, which corresponds to the set of conditions and resources necessary for a species to establish itself and persist in a given ecosystem (Kufa et al., 2022).

The species *Adenium obesum* (Forssk.) Roem. & Schult. is native to the African continent, also found in Oman, Saudi Arabia and Yemen as a wild plant. This is a herbaceous species of the Apocynaceae family, which has been widely used as an ornamental plant cultivated throughout the world. Its center of origin is located in the Sahel region of Africa, which comprises the African deserts of the territorial strip from Senegal to Ethiopia and from Somalia to Tanzania (Oyen, 2006).

However, in some tropical African countries the genus *Adenium* faces threats of extinction due to the destruction of their natural habitats and excessive exploitation for commercial and ornamental purposes (Santos, 2015). Thus, environmental changes resulting from anthropogenic factors have direct impacts on the distribution of species (Giannini et al., 2012).

This scenario highlights the need to assess how species are distributed in the environment in order to understand the effects of these changes and support conservation strategies. A widely used procedure to assess species distribution is Ecological Niche Modeling (ENM) (Javeed et al., 2024). These approaches make it possible to estimate and understand the influence of climate change on species distribution (Wani et al., 2022).

Ecological Niche Modeling (ENM), also referred to as Species Distribution Modeling (SDM), has become a fundamental approach for understanding the geographical patterns of biodiversity and anticipating their responses to environmental change. These models are widely applied to support conservation planning, predict the impacts of climate change on species ranges, and identify areas vulnerable to biological invasions. Different modeling approaches, such as correlative and mechanistic methods, enable the estimation of climatically suitable areas and provide valuable insights for ecological management (Pshegusov et al., 2022). In the context of *Adenium obesum*, integrating SDM is particularly relevant, as the species' ecological plasticity and commercial importance increase the risk of expansion into non-native regions, reinforcing the need to evaluate its environmental suitability under future climate scenarios.

Given the facts presented, this project focuses on modeling the distribution of the species *Adenium obesum*, which presents environmental suitability for dry and hot climates, as a factor of native occurrence. Thus, this study aims to evaluate whether the increase in temperature, as indicated in the IPPC report, will affect the distribution of the species in the face of climate change. The central hypothesis is that *Adenium obesum* will tend to expand its distribution area in a warmer climate scenario.

Finally, assessing the potential impact of climate change on biodiversity patterns and species distribution is essential to determine the most vulnerable species and areas, which would allow prioritizing conservation efforts. The research questions addressed include: (i) assess the effects of global warming on the distribution of the species *Adenium obesum*; (ii) identify the climatically suitable areas for the species in the periods 2040-2060 and 2080-2100 for the most optimistic and pessimistic scenarios; (iii) quantify, in km², the areas of expansion or reduction of climatic suitability for the species.

Material and methods

Study area

The study area encompasses the entire globe, excluding Antarctica (Figure 1). The native distribution of the species *Adenium obesum* is concentrated mainly in the tropical region, specifically in the area known as the Sahel. This region includes the African deserts and areas in the Arabian Peninsula, where the species occurs naturally.

Species *Adenium obesum* (Forssk.) Roem. & Schult.

The species *Adenium obesum* is an herbaceous plant belonging to the Apocynaceae family, popularly known as desert rose. Several authors have divided the species *Adenium obesum* into subspecies or botanical varieties (Colombo et al., 2018).

In its natural habitat, cold and dry winters induce a period of dormancy, often accompanied by leaf loss. The leaves of this species are tubular and the color of the flower's ranges from intense red-purple to shades of pink and white. However, the species has been undergoing significant changes in its floral pigmentation, as well as in the size and shape of the flowers, which are mainly associated with ornamental cultivation and artificial selection for aesthetic traits. Nonetheless, these morphological modifications may also interact with environmental factors, potentially influencing adaptive responses in scenarios of expansion into new habitats (Figure 2) (Abreu et al., 2023).

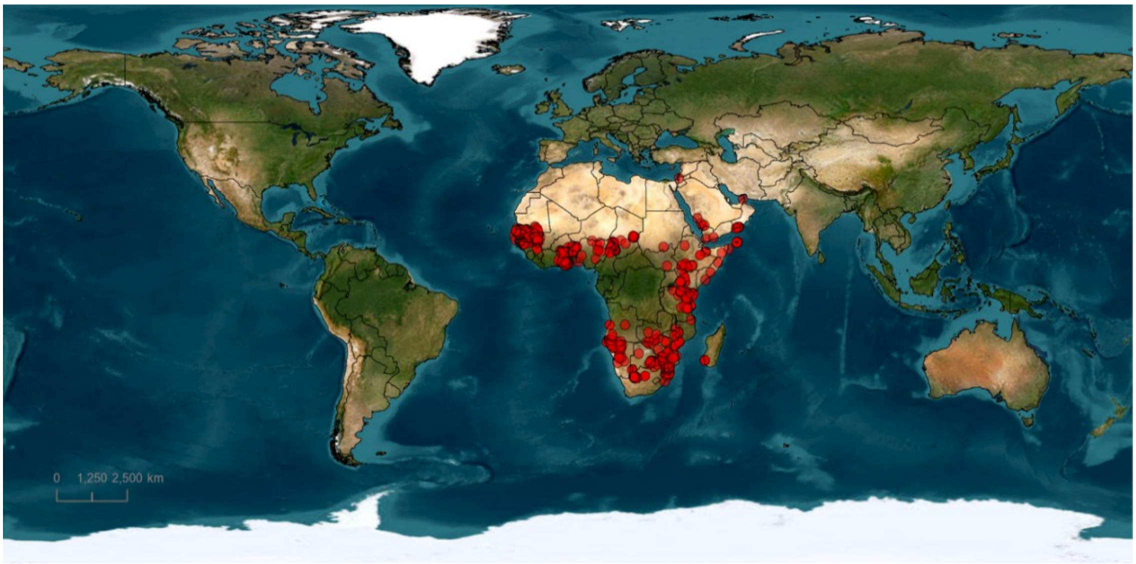

Figure 1. Distribution of the native occurrence of the species *Adenium obesum* in red dots.

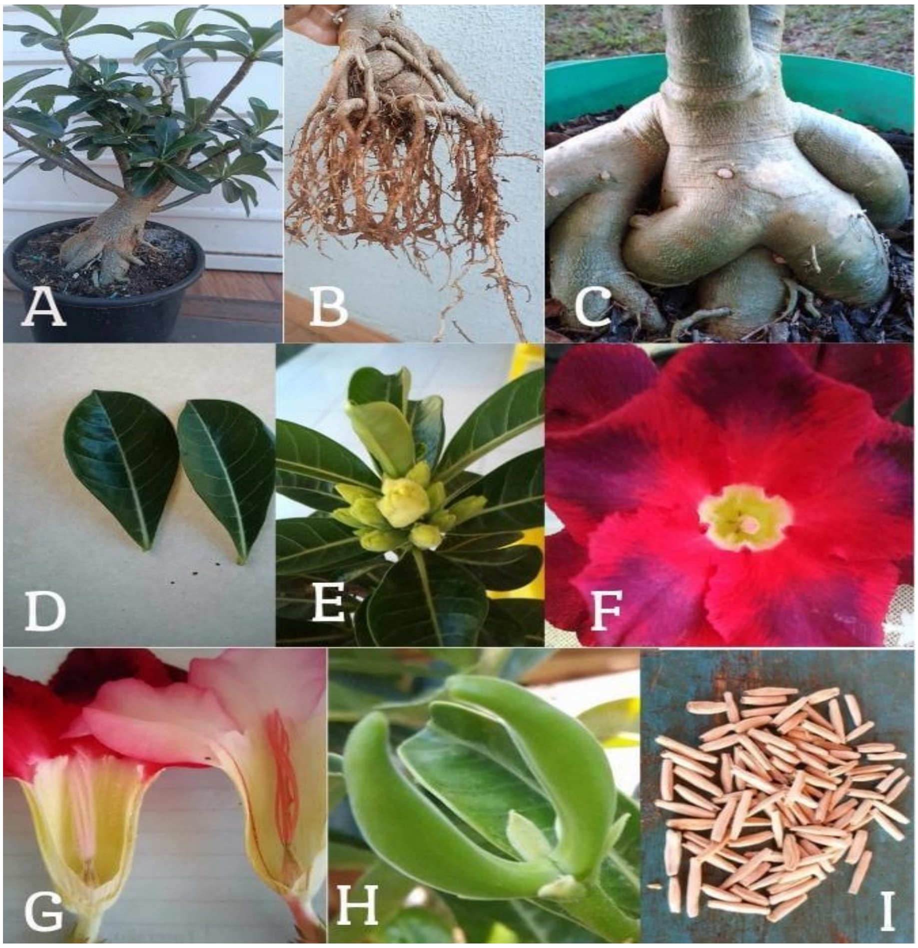

Figure 2. Morphology of *Adenium obesum*. (A) General view, in the basal part, the thickening of the caudex can be noted, in the apical part, the concentration of leaves can be noted. (B) Base of the stem and roots. (C) Thickened caudex and beginning of the stem. (D) Adaxial part of the leaves. (E) Flower buds at the apex of the branch. (F) Front view of the flower. (G) Flower in longitudinal section showing the arrangement of the calyx, corolla, androecium and gynoecium parts. Note the position of the ovary and five filiform staminal appendages. (H) Immature fruit, showing the two follicles joined by the basal region. (I) Seeds of *Adenium obesum*, showing their elongated morphology. Source: Own authorship.

The choice of *Adenium obesum* as the focal species for modeling was based on multiple factors, including the greater availability of occurrence records in relation to other congeners, its wide commercial use as an ornamental plant, and its ecological plasticity, which suggests a potential for expansion into non-native environments. In addition, some species of the same genus have been classified as threatened in parts of their native distribution, while *A. obesum* is increasingly cultivated worldwide, raising concerns about its invasive potential. These criteria reinforce the relevance of using *A. obesum* as a model to investigate distributional changes under future climate scenarios.

Occurrence data and environmental variables

In total, 135 records of the species *Adenium obesum* were identified through the online database Global Biodiversity Information Facility (https://www.gbif.org). To model the potential distribution of *Adenium obesum*, a multicollinearity analysis was performed using Variance Inflation Factors (VIF), removing highly autocorrelated variables (Marco Júnior & Nóbrega, 2018). The VIF calculation was performed using the 'vifcor' function with a cut-off limit of 0.3. A set of 19 bioclimatic variables and one topographic variable (altitude) available in the Worldclim database version 2.1 were used, with a spatial resolution of approximately 5 minutes (Fick & Hijmans, 2017). The analysis was conducted in R 3.6.3 Statistical Environment (R Core Team 2020; available at http://www.r-project.org/), using the 'USDM' package (Naimi et al. 2023).

In the context, a multicollinearity analysis was performed using Variance Inflation Factors (VIF), and variables with high correlation were excluded. From the initial 19 bioclimatic and one topographic variable, five were retained as the most independent and ecologically meaningful for the species: BIO5 (maximum temperature of the warmest month), BIO10 (mean temperature of the warmest quarter), BIO11 (mean temperature of the coldest quarter), BIO12 (annual precipitation), and BIO13 (precipitation of the wettest month), in addition to altitude. These predictors were considered to provide the strongest explanatory power for the potential distribution of *Adenium obesum*.

For future projections, two climate change scenarios were considered (2041-2060 and 2081-2100), one considered optimistic (Shared Socio-economic Pathways - SSPs 245) and the other pessimistic (SSPs 585). These scenarios were based on three global circulation models (IPSL-CM6 A-LR, MRI-ESM2-0 and MIROC6). The optimistic scenario predicts an annual increase of 0.5% in atmospheric CO_2 concentration and an average temperature variation of up to 2°C. The pessimistic scenario projects an increase of up to 1% in CO_2 indices and an average temperature variation of over 4°C (Fick & Hijmans, 2017).

Data analysis – Ecological Niche Modeling (ENM)

To model the ecological niche of the species *Adenium obesum*, the following species distribution modeling algorithms were used: Boosted Regression Tree (brt); Generalized Additive Models (gam); Generalized Linear Model with Polynomial Regression (glmpoly); Multivariate Adaptive Regression Splines (mars); Maximum Entropy Modelling (maxent); Randon Forest (rf); Recursive Partitioning and Regression Trees (rpart).

These algorithms individually consider different types of data and, together, encompass a variety of statistical techniques (Sillero et al., 2023). This diversity of approaches is used to assess the predictive uncertainty of the MNE (Parreira et al., 2019). For the final models, a consensus (ensemble) of the models was achieved for each scenario analyzed.

The quality of the generated models was evaluated using an independent data set, divided into two subsets: one for training the models (75% of the data) and another for testing (the remaining 25%). The models were validated using Receiver Operating Characteristic (ROC) analysis (Sunny et al., 2025), which evaluates the predictive performance of the model for all possible thresholds, calculating the Area Under Curve (AUC) (Konowalik & Nosol, 2021).

The AUC values range from 0.5 to 1.0, where values above 0.75 indicate that the models are potentially useful (Bedair et al., 2023). Furthermore, to verify the accuracy of the models, the True Skill Statistic (TSS) statistical method was applied (Yoon & Lee, 2023). The TSS values range between -1 and +1, where results > 0.6 are considered good, between 0.2-0.6 are moderate and < 0.2 are poor (Lee et al., 2022).

To calculate the model omission rate, a threshold or cut-off limit was used, the choice of which maximizes the agreement between the observed and predicted distributions of the species, meeting the research purposes. From a threshold, the continuous probability maps were converted into binary maps, indicating presence (1) or absence (0) of the species. The selected threshold was maxSSS (Maximizing the sum of sensitivity and specificity) recommended for presence and absence data (Yu et al., 2024).

To quantify the difference in km^2 between the current potential distribution and the areas of suitability projected for future scenarios, the percentages of expansion and reduction of the areas suitable for *Adenium obesum* were calculated. The maps were prepared with the help of the ArcGis Pro program version 3.4.

Results

Five environmental variables were selected that reflect aspects of temperature, precipitation and seasonality, factors considered essential for determining species distribution, in addition to an altitude variable (Table 1).

Table 1. Environmental variables selected for modeling the distribution of *Adenium obesum*. VIF – Inflation Value (VIF < 0.3). BIO5 – Maximum temperature of the hottest month; BIO10 – Average temperature of the hottest quarter; BIO11 - Average temperature of the coldest quarter; BIO12 - Annual precipitation; BIO13 – Precipitation of the wettest month.

Selected Variables	VIF
BIO5	1.341861
BIO10	1.074739
BIO11	1.445458
BIO12	1.326399
BIO13	1.397854
Altitude	1.145293

The variable BIO13 (Precipitation in the wettest month) proved to be the most relevant for building the models (Figure 3). Its importance is related to the direct impact that water availability during the period of greatest precipitation has on the ecological dynamics of ecosystems, being fundamental to understanding the water availability critical for the survival of *Adenium obesum*.

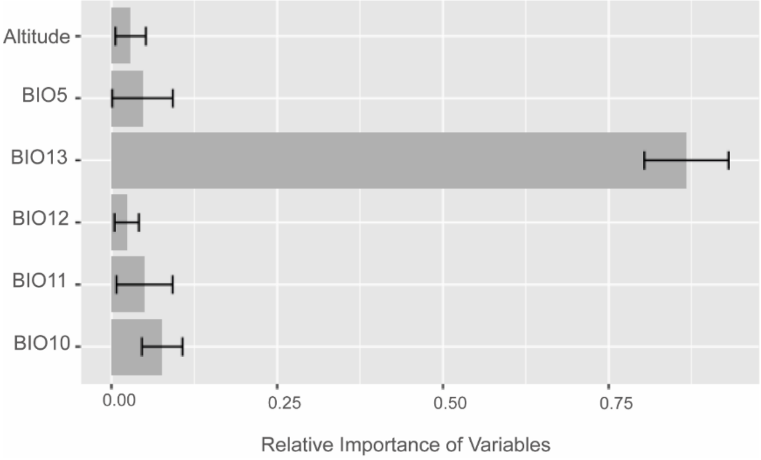

Figure 3. Selected environmental variables and relative importance for the *Adenium obesum* species models.

The models showed robust performance, with significant values for the AUC, TSS and COR metrics, demonstrating the effectiveness of the calibration and predictive capacity of the analyses (Table 2). The modeling results were consistent with the ecological processes of the species in the current model, indicating a distribution associated with environments climatically similar to its native range (Figure 4 A, B).

Table 2. Performance of the models created for the species *Adenium obesum*. AUC – curve over area, COR – correlation and TSS – true skill statistic. Boosted Regression Tree (brt); Generalized Additive Models (gam); Generalised Linear Model with Polynomial Regression (glmpoly); Multivariate Adaptive Regression Splines (mars); Maximum Entropy Modelling (maxent); Random Forest (rf); Recursive Partitioning and Regression Trees (rpart).

Algorithms	Methods			
	AUC	COR	TSS	Deviation
brt	0.97	0.86	0.85	0.69
gam	0.97	0.86	0.85	0.45
glmpoly	0.95	0.84	0.82	1.42
mars	0.96	0.85	0.83	0.48
maxent	0.97	0.86	0.85	0.78
rf	0.99	0.94	0.93	0.23
rpart	0.95	0.85	0.84	0.50

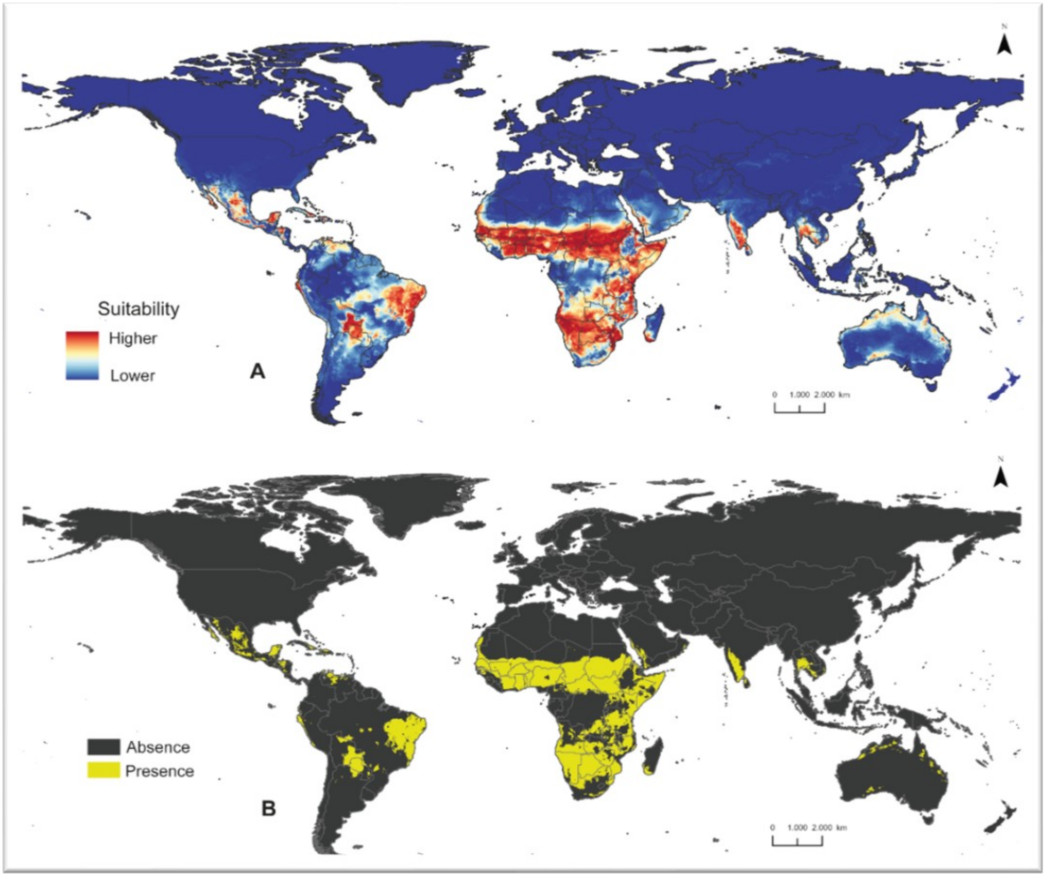

Figure 4. (A) Predictive modeling of the distribution of suitable areas for the species *Adenium obesum* in the current climate scenario. (B) Map of potential distribution of the species *Adenium obesum* in the current scenario.

The results indicate a growing trend of expansion areas in all future scenarios analyzed (Figure 5 and Table 3). According to the proposed models, the greatest expansion occurs in the most pessimistic scenario (SSP585), with a 27.44% increase in environmentally suitable areas. Although there is stability in some native areas, a significant reduction in potential areas of occurrence is observed in these regions.

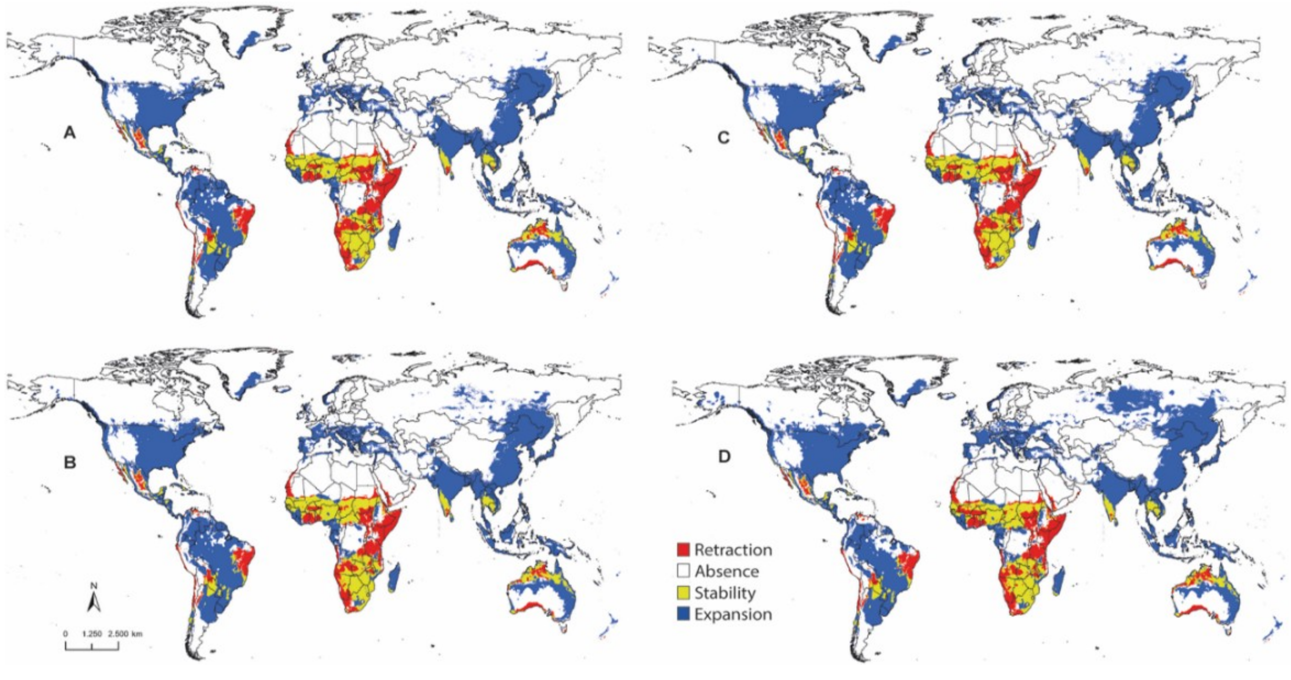

Figure 5. Maps of the potential distribution of the species *Adenium obesum* in different future climate scenarios. A) SSP245 for the period 2041–2060; (B) SSP245 for the period 2081–2100; (C) SSP585 for the period 2041–2060; and (D) SSP585 for the period 2081–2100.

Table 3. Values in km^2 and in% of contraction, absence, stable, and expansion areas for future models analyzed for the species *Adenium obesum*.

Scenarios			Contraction	Absence	Stable	Expansion
2041/2060	SSP245	Km^2	10610283.63	70510804.52	11148600.78	41310539.21
		%	25,78	26,06	24,29	23,36
	SSP585	Km^2	10484864.96	69434258.89	11274019.45	42387084.84
		%	25,47	25,66	24,57	23,97
2081/2100	SSP245	Km^2	9644927.97	67263539.62	12113956.44	44557804.11
		%	23,43	24,86	26,40	25,20
	SSP585	Km^2	10412423.56	63301887.49	11346460.85	48519456.24
		%	25,30	23,40	24,72	27,44

Discussion

The models indicate that the predicted increase in the area of environmental suitability for *Adenium obesum* reflects the influence of rising global temperatures, since the species is native to hot and dry environments, which represents a positive climatic bias for its expansion. The results obtained align with those of Osland et al. (2023), who showed that warming winters reduce freezing constraints and facilitate the northward expansion of tropical invasive species. This is consistent with the idea that species adapted to hot climates may gain additional advantages under scenarios of increasing temperature. Similarly, Soheili et al. (2023) demonstrated that *Quercus brantii* exhibits morphological and anatomical plasticity across different climatic zones, with traits such as leaf area, stomatal density, and trichome development adjusting to environmental conditions. These findings suggest that structural and functional adjustments of plant traits represent adaptive strategies that can improve tolerance to climatic stressors, indirectly supporting the notion that species with higher phenotypic plasticity may cope better with climate change.

Calcerrada et al., (2022) highlight that increasing temperatures and changes in rainfall regimes affect the physiological performance of plants, reducing their ability to perform gas exchange. This evidence reinforces the importance of considering climate variability as a key driver of distributional shifts, and it helps contextualize the expansion potential observed for *Adenium obesum* in the models.

The reliability of the models in the present study is reinforced by the performance metrics obtained (AUC > 0.9 and TSS > 0.7), which indicate strong predictive capacity. These values are consistent with the thresholds proposed by Henderson et al., (2023), who highlight that models meeting such criteria can be considered both robust and useful for ecological forecasting. In the present study, the retained predictors (maximum temperature of the warmest month (BIO5), mean temperature of the warmest and coldest quarters (BIO10 and BIO11), and precipitation of the wettest month (BIO13)) were found to exert strong influence on the potential distribution of *Adenium obesum*, corroborating the species' high sensitivity to climatic seasonality.

Similar studies, such as that by Menezes (2021), about *Eschweilera tetrapetala*, demonstrate that there was an expansion of the potential area during the Mid-Holocene, followed by a retraction in the present and projections of future scenarios with a higher rate of retraction. Thus, the present results extend previous evidence by explicitly demonstrating how climatic variables drive the species' distribution and by reinforcing the broader applicability of the modeling approach.

Global climate changes have caused accelerated shifts in the geographic boundaries of occurrence of various plant species, which directly affects the connectivity among previously separated populations and alters ecological and genetic dynamics. This redistribution can favor lineage exchange and contribute to ecosystem diversification. Furthermore, the increase in average temperatures tends to expand ecologically suitable areas for certain species, as observed in tropical aquatic plants, whose habitat expansion enhances their capacity for dispersal, invasion, and genetic exchange between previously isolated populations (Shay et al., 2021; Yang et al., 2023).

According to Tiwari & Talreja (2023), *Adenium obesum* is adapted to survive and develop in arid and semi-arid environments, exhibiting specialized traits such as water-storing caudex and succulent leaves that confer drought tolerance. This ecological versatility reinforces the importance of precipitation-related variables in modeling its distribution. In particular, Almeida et al. (2021) demonstrate that climatic factors, such as annual precipitation and precipitation seasonality (e.g., BIO13), play a determining role in shaping the richness, composition, and distribution of invasive plant species, influencing both biodiversity patterns and ecosystem resilience.

Another factor that may accelerate the expansion of *Adenium obesum* in future scenarios is the global trade of the species. The widespread commercialization of *Adenium obesum* as an ornamental plant may contribute to its dispersion, enhanced by climate change, which creates ideal conditions for its cultivation (Van Kleunen et al., 2015; Wan & Wang, 2018). Therefore, this study is justifiable to understand the impacts of the introduction of invasive alien species in different biomes, aiding in the conservation of wildlife and ecosystems (Li et al., 2024).

The attractiveness of the species is associated with the presence of the caudex, a thickening of the base of the stem and its roots that accumulates water reserves, providing resistance to drought and a peculiar shape (Colombo et al., 2018).

Furthermore, it is important to emphasize that, although adapted to hot environments, *Adenium obesum* is not restricted to these ecosystems and can tolerate colder environments. In regions with hot and dry climates, the species exhibits adaptations such as epidermal desquamation and water storage in vegetative organs (Brown, 2012). In colder areas, it is induced into dormancy and presents leaf drop (Oyen, 2006), which explains its presence in models that predict expansion to regions such as Canada and Russia. In addition, the species demonstrates some tolerance to low temperatures (Oliveira & Cassemiro, 2013).

Despite the uncertainties about the impacts of climate change on biodiversity, it is well established that invasive species have a high potential for expansion. Species distribution modeling enables the projection of future invasion scenarios, providing relevant data for environmental managers to formulate strategies aimed at protecting native species against invasive taxa that may be favored by climate change (Cavalcante et al., 2020). Lemos et al., (2019) report that *Schinus molle* has a high expansion capacity due to its efficient dispersal and survival and is considered a pest in orange plantations in California.

According to Zanin et al. (2017), climate change may reduce dense forest areas in Brazil, particularly in the north and center of the country, favoring the expansion of open vegetation. This process, intensified by rising carbon emissions, tends to create more arid and less forested landscapes. Cartereau et al. (2023) reinforce that climate change affects species from both cold and tropical climates, increasing the risk of biodiversity loss on a global scale. In this context, the projections indicate that the expected reduction of dense forests and the advance of open and arid areas may facilitate the expansion of *Adenium obesum* in Brazil. As this species tolerates high temperatures and seasonal climates, the new environmental conditions projected for future scenarios could transform the country into a suitable region for its establishment and potential invasive expansion.

Conclusion

Based on the findings of this study, we can conclude that the species *Adenium obesum* tends to expand its distribution to moderate and pessimistic future scenarios, in the face of climate change. Thus, the impact of future climate change tends to be positive for *Adenium obesum*, confirming our hypothesis that, due to its environmental and ecological characteristics, the species is better adapted to warmer environments, similar to its native areas. Thus, *Adenium obesum* may be more successful in expanding into environmentally suitable areas in a future characterized by higher temperatures and lower precipitation.

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