Weed Research

ORIGINAL ARTICLE

Observed Distribution and Predicted Further Spread of *Araujia sericifera* From Europe to the Southern Caspian Sea Coast

Mostafa Oveisi[1] | Sima Sohrabi[2] | Ramin Piri[1] | Heinz Müller-Schärer[1,3,4]

[1]Department of Agronomy and Plant Breeding, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran | [2]Rice Research Institute of Iran (RRII), Rasht, Iran | [3]Department of Biology, University of Fribourg, Fribourg, Switzerland | [4]College of Resources & Environment, Huazhong Agricultural University, Wuhan, China

Correspondence: Mostafa Oveisi (moveisi@ut.ac.ir)

Received: 29 June 2025 | **Revised:** 21 October 2025 | **Accepted:** 7 November 2025

Subject Editor: Erik Lehnhoff New Mexico State University, Las Cruces, USA

Funding: The corresponding author gratefully acknowledges the support and facilities provided by Agroscope in Cadenazzo, Switzerland, during his research visit, funded by the Swiss National Science Foundation (SNSF) grant IZSEZ0_229771. The authors are also grateful to Dr. Ramona Maggini for her valuable consultation.

Keywords: bioclimatic niche | climate change | habitat suitability | invasive alien species | land use category | species distribution modelling

ABSTRACT

Araujia sericifera, an alien species in Europe and Western Asia, is a perennial climbing vine that aggressively overgrows and shades native vegetation, causing substantial biodiversity loss. Its global distribution reveals five invasion hotspots, with a major hotspot extending from Western Europe to northern Iran. Historical records indicate a gradual eastward expansion along the Mediterranean corridor through Western Asia. Habitat suitability modelling, based on climate and land cover variables, identifies a continuous belt of high suitability from Portugal through southern Europe into Western Asia, particularly in coastal and lowland regions. In Iran, the southern Caspian Sea coast, including Gilan, Mazandaran, and Golestan provinces, represents a major area of invasion risk, with high suitability closely matching recent occurrence records. The species' climatic niche is characterised by winter temperatures above −10°C, summer temperatures below 35C, and precipitation exceeding 20mm during the driest month. It avoids extremely arid regions and areas with monsoonal rainfall exceeding 800mm in the wettest month, showing a strong association with urban environments. Although historical dispersal followed a primarily longitudinal pattern, climate change projections indicate high potential for northward expansion. Given its rapid spread, high ecological suitability in the vulnerable Hyrcanian Forests along the southern Caspian Sea, and strong association with anthropogenic landscapes, intensified monitoring and targeted management are recommended to prevent further negative impacts.

1 | Introduction

In recent decades, biological invasions have emerged as one of the most significant threats to biodiversity, ecosystem functioning, and human well-being (Pyšek et al. 2020; Sá 2025). Anthropogenic activities, particularly globalisation, international trade, and landscape transformation, have drastically increased the rate of species introductions, especially alien plant species, into new biogeographic regions (Van Kleunen et al. 2018). While many introduced species fail to establish, some become invasive, proliferating rapidly and causing ecological displacement, biodiversity loss, and considerable economic costs (Vilà et al. 2011). Among these, *A. sericifera* Brot., commonly known as moth plant or cruel vine, has gained increasing attention as an aggressive and ecologically disruptive invader (Bellache et al. 2022).

Araujia sericifera is native to South America, with its range spanning northeastern Argentina, southern and southeastern Brazil, Paraguay, and Uruguay (Powo 2025), and was introduced to Europe in the early 19th century primarily for ornamental purposes (Smith and Panetta 2005). It soon escaped cultivation through horticultural trade and botanical exchanges, subsequently becoming naturalised in Mediterranean Europe. By 1976, it was reported as established in the wild in Spain, and it is now classified as invasive in several southern European countries, including France, Spain, and Italy (Brunel et al. 2010; Lazzaro et al. 2018). In contrast, its spread into central and northern Europe has been limited, likely constrained by colder climates that offer less favourable growing conditions. Today, *A. sericifera* is widely established across temperate, Mediterranean, and subtropical regions, including parts of North and South America, Australia, southern Africa, and the Middle East (Bellache et al. 2022). Its invasion success is attributed to a suite of traits, including rapid growth, high seed production, environmental stress tolerance, effective resource allocation, and opportunistic use of native insect pollinators (Bernich et al. 2024). The species thrives in disturbed environments ranging from roadsides and canals to agricultural plantations, urban green spaces, vineyards, and orchards (Al-Sheikh and Gedeon 2025).

Ecologically, *A. sericifera* poses serious threats to native biodiversity. In Mediterranean ecosystems, it overtops and shades native vegetation such as *Quercus ilex*, leading to shifts in vegetation structure and composition. Agriculturally, it can smother crops like citrus and grapes, with reported yield reductions of up to 20% in affected areas (Gómez de Barreda-Ferraz et al. 2020). Its climbing habit and dense foliage not only inhibit light penetration but also exert physical pressure on host plants, contributing to ecosystem degradation. Recent records confirm its eastward expansion into southeastern Europe and the Middle East, with established populations in Greece, Türkiye, and Georgia marking the easternmost limits of its current European range (Maharaj et al. 2024; Altinözlü and Dönmez 2003). Beyond this, the species has colonised northern parts of Palestine and Syria (POWO). In Iran, it was first recorded in 2014 in the northern provinces of Mazandaran and Gilan (Sajedi and Amini Rad 2014), where it threatens ecologically sensitive areas such as the Hyrcanian forests along the southern coast of the Caspian Sea, a UNESCO World Heritage site and global biodiversity hotspot. The establishment of *A. sericifera* in these forests raises serious concerns about its potential to disrupt native species dynamics and forest structure.

Despite its expanding range and growing ecological footprint, significant knowledge gaps remain. Specifically, little is known about the climatic and land use factors driving its spread or about the regions that may be at risk under future climate scenarios. Addressing these gaps is critical to anticipate invasion risks and guide management interventions, especially in ecologically sensitive areas such as northern Iran's Hyrcanian forests.

Species distribution models (SDMs) that integrate climate and land-use variables at both global and regional scales were employed. The study focuses on Europe and the Middle East, with particular emphasis on northern Iran, which represents the current frontier of the species' eastward spread. Specifically, the following questions were posed: (1) What are the key climatic and land-use drivers promoting the current expansion of *A. sericifera* from Europe to northern Iran? (2) Which areas are currently suitable for the species, and which of these have already been invaded? (3) How might the species' distribution shift under future climate scenarios, and which regions are most at risk?

Based on its known ecology, it is hypothesised that: (1) temperature-related variables are the primary determinants of *A. sericifera*'s distribution, reflecting its preference for warm, semi-arid to subtropical climates; (2) human-modified environments, particularly disturbed lands and certain agricultural systems, enhance habitat suitability; and (3) while past expansion has been mainly longitudinal, future climate change will drive a stronger latitudinal (northward) shift in the species' range.

Ultimately, the results aim to anticipate future invasion risks and inform urgent management strategies, particularly for vulnerable ecosystems of high conservation value.

2 | Materials and Methods

Occurrence records of *A. sericifera* were obtained from the Global Biodiversity Information Facility (GBIF: accessed on 27 March 2025, https://www.gbif.org/) and the Centre for Agriculture and Bioscience International (CABI 2025, www.cabi.org/isc). Duplicate entries identified based on matching species name, geographic coordinates, and collection date were removed. Records from 1950 to 2023 were retained, excluding those with georeferencing uncertainty greater than 1 km (based on metadata fields such as coordinateUncertaintyInMeters). Spatial autocorrelation was minimised and sampling bias from well-surveyed regions (e.g., urban western Europe) was reduced by applying spatial thinning using the spThin package in R with a 1-km thinning radius. This filtering resulted in 9233 spatially unique occurrence records.

Environmental availability was represented by generating 9233 geographically random background points across the study area using the randomPoints function from the dismo package. These points were uniformly sampled to match the number and geographic extent of the occurrence data.

Nineteen bioclimatic variables at 1-km resolution were obtained from the CHELSA v2.1 global climate database, describing long-term patterns in temperature and precipitation (Karger et al. 2017). Variables with pairwise Spearman's correlation coefficients >0.7 or variance inflation factors $(\mathrm{VIF}) > 5$ were excluded to reduce multicollinearity. From the remaining predictors, summary statistics (mean, standard deviation, and 5th and 95th percentiles) were calculated to characterise the species' realised climatic niche.

The Random Forest (RF) algorithm was selected due to its strong performance in ecological niche modelling and invasion risk assessments, particularly for capturing complex nonlinear interactions among predictor variables (Cui et al. 2025). Unlike regression-based approaches, RF makes no rigid assumptions about data distribution and is less sensitive to collinearity among predictors (Hengl et al. 2018). Compared to linear regression and extreme gradient boosting, the Random Forest Regressor demonstrated superior predictive performance, achieving the lowest error metrics (Adewale et al. 2023). These characteristics make RF particularly suitable for modelling the global climatic suitability of *A. sericifera* across diverse and heterogeneous environments.

For the global model, occurrence and background datasets were split into training (70%) and testing (30%) subsets. Hyperparameters were tuned using the caret package in R, and performance was evaluated via repeated 10-fold cross-validation, utilising accuracy, Cohen's Kappa, and AUC (pROC package) (McHugh 2012; Bexiga et al. 2017).

Predictions at finer scales, particularly from western Europe to northern Iran, were enhanced using a hierarchical modelling framework. In this framework, outputs from the global RF model were used as an input covariate in a regional RF model that also incorporated high-resolution land cover data (2019 Copernicus Global Land Cover, 100-m resolution). Local habitat variability such as forests, croplands, grasslands, and urban areas not captured by climate alone, was accounted for by including land cover. This combination of global climatic suitability and regional habitat data improved the accuracy for identifying areas at high invasion risk. The regional model was validated using the same cross-validation and performance metrics as the global model.

The impacts of climate change on *A. sericifera* habitat suitability were assessed using downscaled bioclimatic projections from the CHELSA v2.1 dataset (Karger et al. 2023), which provides high-resolution (~1 km) climate layers based on multiple global climate models (GCMs) and alternative socioeconomic pathways (SSPs). We focused on the mid-century period (2041–2070) under two emission scenarios: SSP370 (intermediate) and SSP585 (high). Habitat suitability was modelled for each GCM–scenario combination with a Random Forest algorithm trained on species occurrence records and current climatic predictors. To address inter-model variability, ensemble predictions were generated by combining results across five GCMs within each SSP (Porfirio et al. 2014). This ensemble approach reduces biases associated with individual models and yields more robust estimates of potential climate-driven shifts in habitat suitability.

Habitat preferences were analysed by overlaying occurrence records onto the Copernicus land cover raster to extract dominant land cover classes at invaded sites. These classes were cross-referenced with habitat annotations in GBIF and CABI records to verify consistency and accuracy. Ecologically distinct clusters among invaded sites were examined using hierarchical cluster analysis based on land cover composition. Clustering was performed using Ward's minimum variance method and Euclidean distance. Cluster validity was evaluated using silhouette widths to assess the distinctiveness and cohesion of the resulting groups.

Finally, an independent dataset from Gilan Province, Iran (Bidarlord and Tokasi 2024) was used as an external validation set to test model performance in a recently invaded region not included in model training.

3 | Results

3.1 | Global Occurrence of *A. sericifera*

The global distribution of *A. sericifera* is concentrated in five major regions (Figure A1). Its native range is in South America, which has the highest density of occurrence records. Populations in Central America are sparser. Outside its native range, *A. sericifera* is established in South Africa, Australia, and a broad area spanning Europe and western Asia, the latter being its most extensive invaded range. Cluster analysis based on climate and land cover revealed four ecologically distinct clusters: South and Central America formed one cluster, while South Africa, Australia, and Europe–West Asia each represented separate clusters, indicating region-specific environmental associations.

Figure A1 illustrates the dominant land cover type at each occurrence point using region-specific colours. In Australia, *A. sericifera* is primarily associated with bare soils and sparse vegetation. In contrast, in South America, South Africa, and Europe–West Asia, the species is more frequently found in urban and peri-urban areas. Overall, open forest was the most common land cover type associated with the species, accounting for over 34% of global occurrence points, followed by woodland (13%). This pattern suggests either a true ecological preference or increased detectability of *A. sericifera* in semi-natural and anthropogenically altered environments. Notably, irrigated orchards, especially orange plantations, accounted for about 11% of records, highlighting the species' association with specific agricultural systems. Less frequent occurrences were recorded in open woodland, closed forest, *citrus* orchards, and the "data not transcribed" category, each contributing less than 10% to the total.

3.2 | Spatiotemporal Expansion of *A. sericifera* Across Europe and Western Asia

The distribution of *A. sericifera* in the Mediterranean Basin shows a pattern of eastward expansion from Western Europe over the past two centuries (Figure A2). The species was first introduced in France in 1818 as an ornamental plant, followed by Spain in 1915 and Italy by 1990 (EPPO 2014). Introductions in southeastern Europe and the Eastern Mediterranean are more recent and less extensive.

Occurrence records are concentrated in coastal and peri-coastal regions, particularly in Western Europe. This indicates a strong association of *A. sericifera* with Mediterranean climates and human-disturbed habitats, reflecting its invasive characteristics and history of ornamental use.

3.3 | Habitat Suitability Modelling

The habitat suitability model demonstrated strong predictive performance (Table A1). The test accuracy was 0.985, and the area under the ROC curve (AUC) was 0.995. The correlation coefficient

(COR) reached 0.983, while F1-score, precision, and recall were approximately 0.990. The True Skill Statistic (TSS) was 0.970. Cross-validation tuning of the mtry parameter (2–8) produced similar results, with accuracy ranging from 0.988 to 0.990 and Kappa from 0.976 to 0.980. The highest values were observed at mtry = 2 (Accuracy = 0.990, Kappa = 0.980), although differences among candidate values were within overlapping variability. Independent evaluation yielded comparable metrics, suggesting that model performance was stable across both training and testing data, with no conclusive evidence of overfitting.

Figure A3a illustrates the predicted habitat suitability for *A. sericifera* across a longitudinal gradient from Portugal to Iran, based on climate and land-use data. The suitability index, displayed on a light green–to–red gradient, highlights regional variation in environmental suitability for the species. Highest suitability values are concentrated in Western Europe, particularly in Portugal and southern France, with extensive optimal conditions. In Spain, high suitability is primarily along the northeastern border with France, with smaller patches elsewhere. Italy and the Mediterranean islands also show high suitability, corresponding closely with occurrence records. In contrast, suitability declines sharply towards northern latitudes, with countries like Switzerland and Germany exhibiting low suitability and lacking confirmed records.

A continuous belt of high habitat suitability is projected along the Mediterranean coastal regions of Southern Europe and Northern Africa. High-suitability hotspots are evident along the coasts of Algeria and Tunisia, while interior areas display lower suitability due to increasing aridity. Further east, high suitability is predicted along the coastal zones of Greece, Türkiye, Syria, Lebanon, and Palestine, with inland regions showing a gradual decline. The model identifies highly suitable zones along the southern Black Sea coast in Türkiye and the western Caspian Sea coast of Georgia. *Araujia sericifera* was first recorded in Georgia in 2010 (Kikodze et al. 2010) along the Black Sea coast, followed by its appearance along the Caspian Sea shore in Iran in 2014. Strong suitability is also projected along the Caspian coast of Azerbaijan, although no confirmed occurrences have been reported there. Therefore, *A. sericifera* is predicted to thrive mainly in coastal and lowland regions across Southern Europe, the Levant, and parts of North Africa and Western Asia, with constrained distribution in inland arid zones, high-altitude areas, and much of Eastern Europe and Central Asia.

The suitability index for Iran delineates a continuous zone of relatively high environmental suitability along the coastal plains of Gilan, Mazandaran, and Golestan provinces, spanning approximately 48° E to 55° E (Figure A4). Suitability decreases sharply inland, particularly beyond the Alborz Mountain range, where climatic gradients and land-use patterns appear less favourable for the establishment of *A. sericifera*.

Independent occurrence data from Gilan Province, which were excluded from model calibration, were used for validation. Their correspondence with areas predicted as suitable suggests that the model reliably reflects the environmental factors influencing the species' potential distribution. This validation reduces the likelihood of overfitting and indicates that the results may be more broadly applicable. The agreement between predictions and independent records further suggests that the Caspian Sea coastal zone, particularly Gilan Province, could represent a current area of localised expansion for *A. sericifera*.

3.4 | Climate Change Impact

Since its introduction in 1818, *Araujia sericifera* has primarily expanded eastward from Western Europe to Iran, with limited latitudinal spread. Climate change projections suggest a northward expansion of suitable habitat (Figure A3b,c). Currently, high suitability extends up to approximately 50° N, covering northern France, Belgium, Luxembourg, and southern England. Under the intermediate emissions scenario (SSP370, Figure A3b), suitability expands to include all of Belgium and the Netherlands, as well as most of the United Kingdom. Under a high-emissions scenario (SSP585, Figure A3c), suitable habitat extends into northern Germany, southern Denmark, and Ireland, indicating a significant poleward shift. In contrast, areas at lower latitudes, including the southern Mediterranean coast and northern Iran, are projected to decline in suitability due to increasing temperatures and reduced moisture availability.

3.5 | Climatic Niche Similarity

Cluster analysis of global occurrence points of *A. sericifera* revealed three distinct climatic groups (MANOVA: Pillai's trace = 0.756, $F = 4075$, $p < 2.2\text{e-}16$) (Figure A5a). Populations in France, Italy, Greece, Türkiye, Georgia, and Iran clustered cohesively, indicating negligible climatic differentiation among these regions. Environmental niche analysis (Figure A5b) shows the species occupies a narrow climatic space defined by moderate temperatures and seasonal aridity. It favours mean temperatures during the warmest quarter (BIO10) between 15°C and 30°C and coldest month temperatures (BIO6) above −10°C, avoiding cold extremes and hyper-arid heat. Precipitation during the driest and warmest quarters (BIO17 and BIO18) ranges from 50 to 200 mm and 100 to 400 mm, respectively, excluding desert and monsoonal climates. The isothermality range (BIO3: 0.28–0.51) indicates adaptation to regions with low diurnal-to-annual temperature variation. Visualisation highlights a tight clustering of presence points around this climatic centroid, reinforcing niche conservatism. The congruence between spatial model outputs and the species' environmental preferences supports its confinement to Mediterranean-type environments with warm summers, mild winters, and moderate dry-season rainfall.

3.6 | Land Cover Associations

Habitat suitability modelling shows that urban and built-up areas account for about 85% of the predicted high-suitability landscape for *A. sericifera* (Figure A6). This indicates that urban environments are particularly favourable for the species' establishment and spread. Other land cover types with moderate to high suitability include herbaceous wetlands, open forests, and various forest categories such as evergreen needleleaf and closed forests, each contributing around 20%–35% to the suitable range. In contrast, agricultural lands and natural habitats like shrublands, snow/ice, permanent water bodies, and bare or sparsely vegetated areas have limited suitability according to model predictions.

4 | Discussion

The global distribution of *A. sericifera* reflects considerable ecological tolerance, spanning five distinct biogeographic regions, with its widest spread in Europe and western Asia. This range illustrates significant plasticity, enabling the species to persist across diverse climates and land-use systems. Its presence in semi-natural woodlands and certain agricultural mosaics underscores broad environmental adaptability. Conversely, *A. sericifera* remains uncommon in closed-canopy forests and undisturbed habitats ($< 10\%$ of records), where low light and strong competition restrict colonisation. This distributional pattern is consistent with ruderal invaders that thrive in high-light, low-competition environments (Cohen et al. 2025). Collectively, the evidence indicates that *A. sericifera* combines broad ecological tolerance with particular success in human-altered habitats, providing the foundation for its rapid spread.

The eastward expansion of *A. sericifera* across the Mediterranean Basin during the past two centuries reflects a combination of historical, environmental, and anthropogenic drivers. Its initial establishment in France, Spain, and Italy was likely facilitated by horticultural trade and botanical exchanges during the 19th and early 20th centuries, when port infrastructure and plant trading networks promoted the introduction of ornamentals (EPPO 2014). Concentrations of early occurrences in coastal areas align with the species' affinity for Mediterranean-type climates, mild, wet winters and hot, dry summers that favour germination, growth, and reproduction (Santa Cruz and Cordero 2018). Such coastal hubs also offered abundant disturbed habitats, including transport corridors and peri-urban edges, which facilitated establishment by reducing competition from native vegetation (Carboni et al. 2010).

More recent records from southeastern Europe and western Asia indicate ongoing expansion beyond its historical stronghold. Long-distance dispersal is probably mediated by human activities, particularly transport along road networks and the movement of soil, plant material, and contaminated horticultural stock (Hulme 2009). Climate warming has also relaxed constraints in northern regions, allowing the species to spread beyond its earlier limits (Adhikari et al. 2022). Together, these processes demonstrate how a combination of horticultural introductions, disturbance, and climate change has shaped the invasion trajectory of *A. sericifera* in Europe and adjacent regions.

Urbanisation and land-use change are now the dominant forces driving contemporary spread. Urban areas represent more than 80% of predicted high-suitability zones, reflecting their mosaic of microhabitats, frequent disturbance, reduced competition, and multiple pathways for human-mediated dispersal (Santana Marques et al. 2020). The urban heat island effect may further align local microclimates with the species' thermal requirements, enhancing colonisation success (Maharaj et al. 2024). Transportation networks, horticultural trade, and intentional plantings compound this process by supplying continuous propagule pressure (Santa Cruz and Cordero 2018). As such, urban centers act both as primary invasion hubs and as stepping stones that facilitate spread into surrounding landscapes (Pianta et al. 2024).

Agricultural systems present a more nuanced picture. Intensively managed croplands often suppress establishment through competition and frequent disturbance, whereas irrigated orchards and peri-agricultural mosaics create favourable conditions. Citrus plantations, vineyards, and similar systems provide open structure, regular irrigation, and reduced canopy cover, which together sustain populations (Alston and Richardson 2006; Smith and Panetta 2005). This explains the mixed pattern of association with agriculture: not all systems are equally suitable, but those with moderate disturbance and resource availability can function as effective corridors between urban and natural habitats.

Despite its broad distribution, *A. sericifera* remains largely restricted to climates resembling its Mediterranean-type niche. It thrives where mean temperatures of the warmest quarter range from 15°C–30°C and where the coldest month does not fall below −10°C, conditions that prevent tissue damage and mortality (Fahad et al. 2017). Precipitation thresholds of 50–200 mm during the driest quarter and 100–400 mm during the warmest quarter support germination and growth while avoiding severe drought stress (Santa Cruz and Cordero 2018). These constraints explain its scarcity in hyper-arid zones, cold continental climates, and monsoonal regions, where physiological tolerance is exceeded (Adhikari et al. 2022). Affinity for isothermality values of 0.28–0.51 suggests a preference for relatively stable temperature regimes, buffering metabolic processes against rapid fluctuations (Smith and Panetta 2005). The species' observed niche conservatism indicates that thermal minima and seasonal water availability remain the key constraints shaping distribution.

Habitat suitability modelling highlights western Europe, particularly Portugal, southern France, and northeastern Spain, as current hotspots where climate and land-use conditions converge to favour establishment (Santa Cruz and Cordero 2018). Suitability is also high along Mediterranean and North African coasts and around the Caspian Sea, especially in Iran and Azerbaijan. In Iran, the Gilan, Mazandaran, and Golestan provinces emerge as hotspots, combining humid subtropical to Mediterranean climates, fertile soils, and intensive land use that create highly favourable environments (Bidarlord and Tokasi 2024; Noroozi et al. 2020). In contrast, habitat suitability declines sharply inland across the Alborz rain shadow, where increasing aridity imposes climatic barriers. The congruence of recent occurrence data with these predicted zones provides strong validation of model performance.

Future projections under SSP370 and SSP585 scenarios suggest a pronounced northward expansion, with suitable habitats extending beyond 50° N into northern Germany, Denmark, Ireland, and the UK. These shifts are driven primarily by milder winters, which reduce cold-related mortality and expand the thermal niche (Petitpierre et al. 2015; Alsos et al. 2015). This pattern contrasts with the predominantly longitudinal expansion observed historically. At the same time, declining suitability is projected in southern Mediterranean and northern Iranian regions, where increasing summer heat and drought exceed physiological limits. Such poleward expansion and equatorward contraction are consistent with broader trends among Mediterranean-adapted invaders under global warming (Adhikari et al. 2022).

While models capture broad-scale distribution patterns, several limitations remain. Occurrence data are unevenly distributed, with under-sampled regions potentially biassing habitat suitability estimates (Boyd et al. 2021). Habitat suitability models also assume climatic niche conservatism and do not incorporate biotic interactions such as competition, herbivory, or mutualisms, which may substantially influence realised distributions (Qazi et al. 2022). Similarly, dynamic drivers of invasion, such as urban expansion, land-use intensification, and trade pathways are only partially represented, though they are clearly central to spread (De Kort et al. 2020). Climate model uncertainty and variation between emission scenarios further add to predictive limitations. These caveats underscore the need for cautious interpretation of projections and for future integration of ecological, socio-economic, and evolutionary processes into invasion risk assessments.

Taken together, the results provide consistent support for the study hypotheses. Hypothesis 1 is supported by evidence of climatic niche conservatism: minimum temperature thresholds and seasonal precipitation regimes remain the primary constraints on distribution. Hypothesis 2 is confirmed by the strong association with human-modified landscapes, particularly urban centers and irrigated orchards, which provide disturbed, resource-rich habitats that promote establishment. Hypothesis 3 is validated by model projections, which indicate future northward expansion under climate warming, contrasting with the primarily east–west expansion observed historically. By integrating climatic constraints, anthropogenic disturbance, and future projections, the findings highlight both the mechanisms underpinning the current distribution and the processes likely to shape future spread.

5 | Conclusion

Araujia sericifera is a climate-tolerant and disturbance-adapted invader whose success is closely linked to human-modified landscapes. Its persistence in urban centers, transport corridors, and irrigated orchards underscores its strong pathway dependence and elevates its risk potential across Mediterranean and temperate regions.

Management should prioritise early detection and pathway control. Surveillance in invasion hotspots, particularly along the Caspian Sea coast and in urban–rural transition zones, is essential. Stricter monitoring of horticultural trade and transport corridors can reduce propagule pressure, while sanitation protocols and rapid eradication in irrigated orchards will limit agricultural establishment. Awareness campaigns aimed at growers, urban planners, and horticultural stakeholders can further disrupt inadvertent spread.

Climate change will expand invasion risks northward. Anticipated range shifts into central and northern Europe necessitate precautionary actions, including stronger quarantine measures, coordinated monitoring networks, and the integration of invasion risk into land-use and climate adaptation policies. Sustained, adaptive management that connects ecological dynamics with socio-economic drivers will be critical to curbing future spread.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

Adewale, M. D., D. U. Ebem, O. Awodele, et al. 2023. "Comparative Performance Evaluation of Random Forest, Extreme Gradient Boosting and Linear Regression Algorithms Using Nigeria's Gross Domestic Products." In *International Conference on Innovations and Interdisciplinary Solutions for Underserved Areas*, 131–150. Springer Nature Switzerland.

Adhikari, P., Y. H. Lee, P. Adhikari, S. H. Hong, and Y. S. Park. 2022. "Climate Change-Induced Invasion Risk of Ecosystem Disturbing Alien Plant Species: An Evaluation Using Species Distribution Modeling." *Frontiers in Ecology and Evolution* 10: 1–13.

Al-Sheikh, B., and J. Gedeon. 2025. "Newly Documented Invasive Alien Plant Species in the West Bank, Palestine." *Journal of Botanical Taxonomy and Geobotany* 16, no. 12: 26225–26233.

Alsos, I., C. Ware, and R. Elven. 2015. "Past Arctic Aliens Have Passed Away, Current Ones May Stay." *Biological Invasions* 17: 3113–3123.

Alston, K. P., and D. M. Richardson. 2006. "The Roles of Habitat Features, Disturbance, and Distance From Putative Source Populations in Structuring Alien Plant Invasions at the Urban/Wildland Interface on the Cape Peninsula, South Africa." *Biological Conservation* 132: 183–198.

Altinözlü, H., and A. A. Dönmez. 2003. "*Araujia* Brot.: A New Genus (Asclepiadaceae) Record for Turkey." *Turkish Journal of Botany* 27, no. 3: 231–234.

Bellache, M., N. Moltó, L. A. Benfekih, et al. 2022. "Physiological and Biochemical Responses to Water Stress and Salinity of the Invasive Moth Plant, *Araujia sericifera* Brot., During Seed Germination and Vegetative Growth." *Agronomy* 12, no. 2: 361.

Bernich, A., K. French, and M. Bedward. 2024. "Assessing the Invasion Potential of Five Common Exotic Vine Species in Temperate Australian Rainforests." *NeoBiota* 90: 79–96.

Bexiga, F., D. Rodrigues, R. Guerra, et al. 2017. "A TSS Classification Study of Rochapear (*Pyrus communis* L.) Based on Non-Invasive Visible/Near Infra-Red Reflectance Spectra." *Postharvest Biology and Technology* 132: 23–30.

Bidarlord, M., and S. Tokasi. 2024. "Distribution and Risk Assessment of *Araujia sericifera* Brot. In Gilan Province." *Iran Nature* 9, no. 4: 63–72.

Boyd, R. J., G. D. Powney, C. Carvell, and O. L. Pescott. 2021. "occAssess: An R Package for Assessing Potential Biases in Species Occurrence Data." *Ecology and Evolution* 11, no. 22: 16177–16187.

Brunel, S., G. Schrader, G. Brundu, and G. Fried. 2010. "Emerging Invasive Alien Plants for the Mediterranean Basin." *EPPO Bulletin* 40: 219–238.

CABI. 2025. *Invasive Species Compendium*. CAB International. https://www.cabi.org/isc.

Carboni, M., R. Santoro, and A. T. Acosta. 2010. "Are Some Communities of the Coastal Dune Zonation More Susceptible to Alien Plant Invasion?" *Journal of Plant Ecology* 3, no. 2: 139–147.

Cohen, O., E. Sheffer, N. Bar-Shmuel, et al. 2025. "Determinants of Naturalization and Invasion of *Tetraclinis articulata* in Eastern Mediterranean Drylands: Is It a Superinvader?" *Biological Invasions* 27, no. 3: 1–19.

Cui, Z., X. Qian, and M. Cai. 2025. "A Comprehensive Analysis of Plant Invasion Classification Using Random Forest Method." In *Artificial Intelligence and Human-Computer Interaction*, 62–71. IOS Press.

De Kort, H., M. Baguette, J. Lenoir, and V. M. Stevens. 2020. "Toward Reliable Habitat Suitability and Accessibility Models in an Era of Multiple Environmental Stressors." *Ecology and Evolution* 10, no. 20: 10937–10952.

EPPO. 2014. *PQR Database*. European and Mediterranean Plant Protection Organization.

Fahad, S., A. A. Bajwa, U. Nazir, et al. 2017. "Crop Production Under Drought and Heat Stress: Plant Responses and Management Options." *Frontiers in Plant Science* 8: 1–16.

Gómez de Barreda-Ferraz, D., V. De Luca, J. M. Osca, M. Verdeguer, and M. Muñoz. 2020. "Control químico de la mala hierba invasora *Araujia sericifera* Brot." *Información Técnica Económica Agraria* 116, no. 3: 212–226.

Hengl, T., M. Nussbaum, M. N. Wright, G. B. Heuvelink, and B. Gräler. 2018. "Random Forest as a Generic Framework for Predictive Modeling of Spatial and Spatio-Temporal Variables." *PeerJ* 6: 1–47.

Hulme, P. E. 2009. "Trade, Transport and Trouble: Managing Invasive Species Pathways in an Era of Globalization." *Journal of Applied Ecology* 46, no. 1: 10–18.

Karger, D. N., O. Conrad, J. Böhner, et al. 2017. "Climatologies at High Resolution for the Earth's Land Surface Areas." *Scientific Data* 4, no. 1: 1–20.

Karger, D. N., S. Lange, C. Hari, et al. 2023. "CHELSA-W5E5: Daily 1 Km Meteorological Forcing Data for Climate Impact Studies." *Earth System Science Data* 15, no. 6: 2445–2464.

Kikodze, D., N. Memiadze, D. Kharazishvili, Z. Manvelidze, and H. Mueller-Schaerer. 2010. *The Alien Flora of Georgia*. Joint SNSF SCOPES and FOEN Publication.

Lazzaro, L., R. Bolpagni, A. T. R. Acosta, et al. 2018. "An Assessment of the Impacts of Invasive Alien Plants on Habitats in Italy: First Results From the ISPRA-SISV Convention." In *NEOBIOTA 2018 10th International Conference on Biological Invasions. New Directions in Invasion Biology. Programme & Book of Abstracts*, 84. NEOBIOTA.

Maharaj, S., B. W. Cowie, M. J. Byrne, and N. Venter. 2024. "Insights Into the Invasion of the Moth Catcher Vine, *Araujia sericifera* (Apocynaceae), in South Africa." *South African Journal of Botany* 171: 517–528.

McHugh, M. L. 2012. "Interrater Reliability: The Kappa Statistic." *Biochemia Medica* 22, no. 3: 276–282.

Noroozi, J., A. Talebi, and M. Doostmohammadi. 2020. "The Alborz Mountain Range." In *Plant Biogeography and Vegetation of High Mountains of Central and South-West Asia, Plant and Vegetation*, 117–149. Springer.

Petitpierre, B., K. MacDougall, T. Seipel, O. Broennimann, A. Guisan, and C. Kueffer. 2015. "Will Climate Change Increase the Risk of Plant Invasions Into Mountains?" *Ecological Applications* 26, no. 2: 530–544.

Pianta, M., M. Calbi, D. Dagnino, C. Turcato, and E. Roccotiello. 2024. "Peri-Urban Mediterranean Plant Communities Are Shaped by Chronic Anthropogenic Disturbances." *Urban Forestry & Urban Greening* 95, no. 2: 128333.

Porfirio, L. L., R. M. Harris, E. C. Lefroy, et al. 2014. "Improving the Use of Species Distribution Models in Conservation Planning and Management Under Climate Change." *PLoS One* 9, no. 11: 113749.

POWO. 2025. *Plants of the World Online*. Facilitated by the Royal Botanic Gardens. https://powo.science.kew.org/.

Pyšek, P., P. E. Hulme, D. Simberloff, et al. 2020. "Scientists' Warning on Invasive Alien Species." *Biological Reviews* 95: 1511–1534.

Qazi, A. W., Z. Saqib, and M. Zaman-ul-Haq. 2022. "Trends in Species Distribution Modelling in Context of Rare and Endemic Plants: A Systematic Review." *Ecological Processes* 11, no. 1: 1–11.

Sá, R. M. 2025. "The IPBES Thematic Assessment on Invasive Alien Species and Their Control: Futurity and Policy Opportunities in a More Than Human-World." In *Global Public Goods Communication*, 135–156. Springer.

Sajedi, S., and M. Amini Rad. 2014. "First Report of the Invasive Plant *Araujia* From Iran." *Rostaniha* 15, no. 1: 71–74.

Santa Cruz, J., and S. Cordero. 2018. "First Record of *Araujia sericifera* (Apocynaceae: Asclepiadoideae) for Chile, a New Alien Climbing Species From South America." *Boletin de la Sociedad Argentina de Botanica* 53, no. 2: 1–10.

Santana Marques, P., L. Resende Manna, T. Clara Frauendorf, E. Zandonà, R. Mazzoni, and R. El-Sabaawi. 2020. "Urbanization Can Increase the Invasive Potential of Alien Species." *Journal of Animal Ecology* 89, no. 10: 2234–2245.

Smith, G. V., and F. D. Panetta. 2005. "Seedling Recruitment, Seed Persistence and Aspects of Dispersal Ecology of the Invasive Moth Vine, *Araujia sericifera* (Asclepiadaceae)." *Australian Journal of Botany* 53: 225–230.

Van Kleunen, M., F. Essl, J. Pergl, et al. 2018. "The Changing Role of Ornamental Horticulture in Alien Plant Invasions." *Biological Reviews* 93, no. 3: 1421–1437.

Vilà, M., J. L. Espinar, M. Hejda, et al. 2011. "Ecological Impacts of Invasive Alien Plants: A Meta-Analysis of Their Effects on Species, Communities and Ecosystems." *Ecology Letters* 14, no. 7: 702–708.

Appendix A

TABLE A1 | Evaluation metrics and random forest model parameters for the habitat suitability model of *A. sericifera*.

Metric/parameter	Value
Model performance metrics	
Accuracy	98.5%
AUC (Area Under Curve)	99.5%
True Skill Statistic (TSS)	97.0%
Sensitivity (Recall)	99.0%
Specificity	97.9%
F1-score	99.0% (F1 = 2 × (Precision × Recall)/(Precision + Recall))
Precision	99.0%
Correlation Coefficient (COR)	98.3%
Random forest model parameters	
mtry	2
ntree	100
RMSE	0.0136 (normalised units)

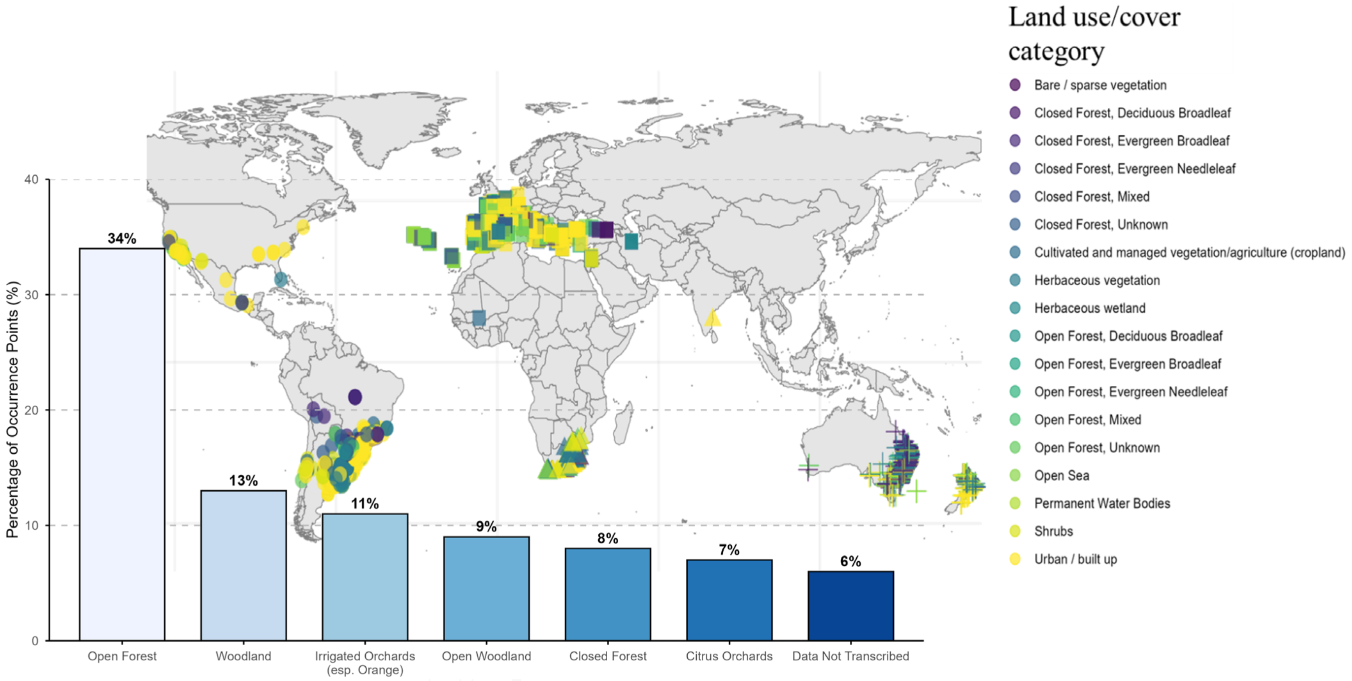

FIGURE A1 | Global occurrence of *A. sericifera* and classification of invaded regions. Five regions are identified based on a cluster analysis of land use and bioclimatic variables. Colour gradients represent dominant land use categories, while point shapes denote cluster memberships from hierarchical clustering.

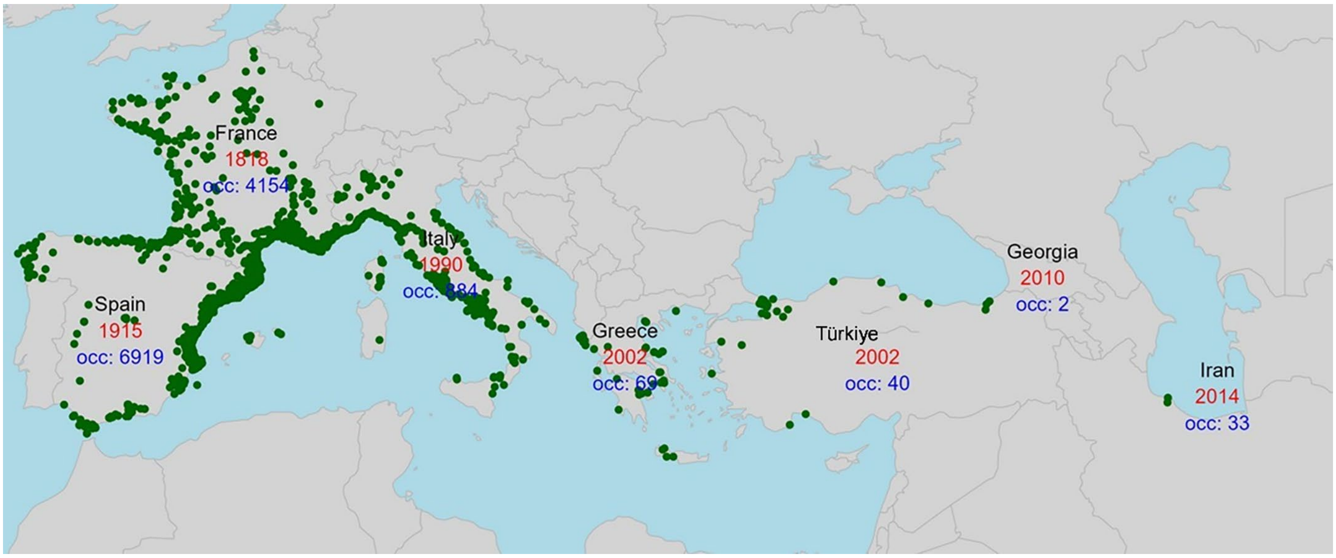

FIGURE A2 | Spatiotemporal distribution of *A. sericifera* in Europe and the Middle East. The map illustrates the year of first recorded occurrence and the number of total records per country, capturing temporal dynamics and spread intensity.

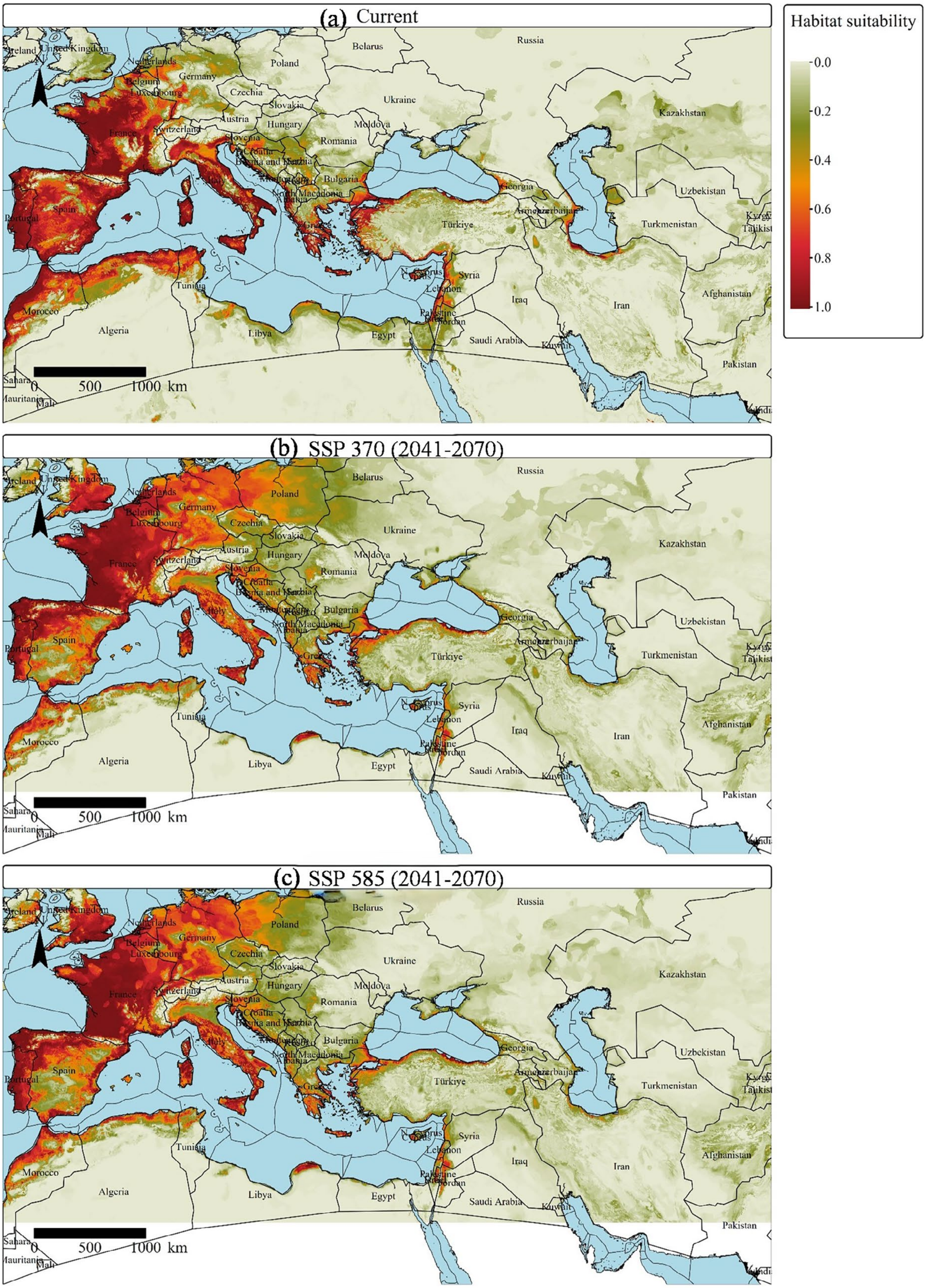

FIGURE A3 | Current and projected habitat suitability for *A. sericifera* from Western Europe to Iran. The map shows present (a) suitability based on climate and land cover predictors, along with mid-term projections (2041–2070) under SSP370 (b) and SSP585 (c) scenarios. Projections were generated using five global climate models (GCMs) and CHELSA v2.1 climate data.

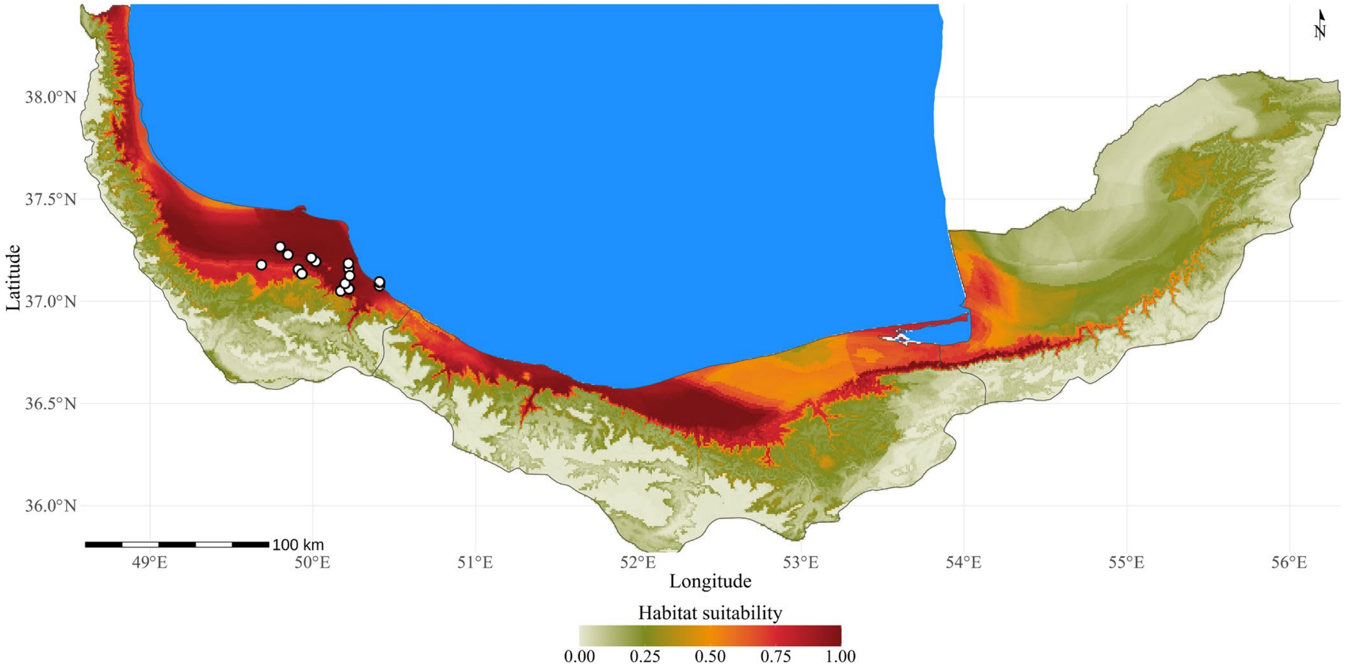

FIGURE A4 | Fine-scale prediction of habitat suitability for *A. sericifera* in northern Iran. White circles across the region indicate independent occurrence records used for validation.

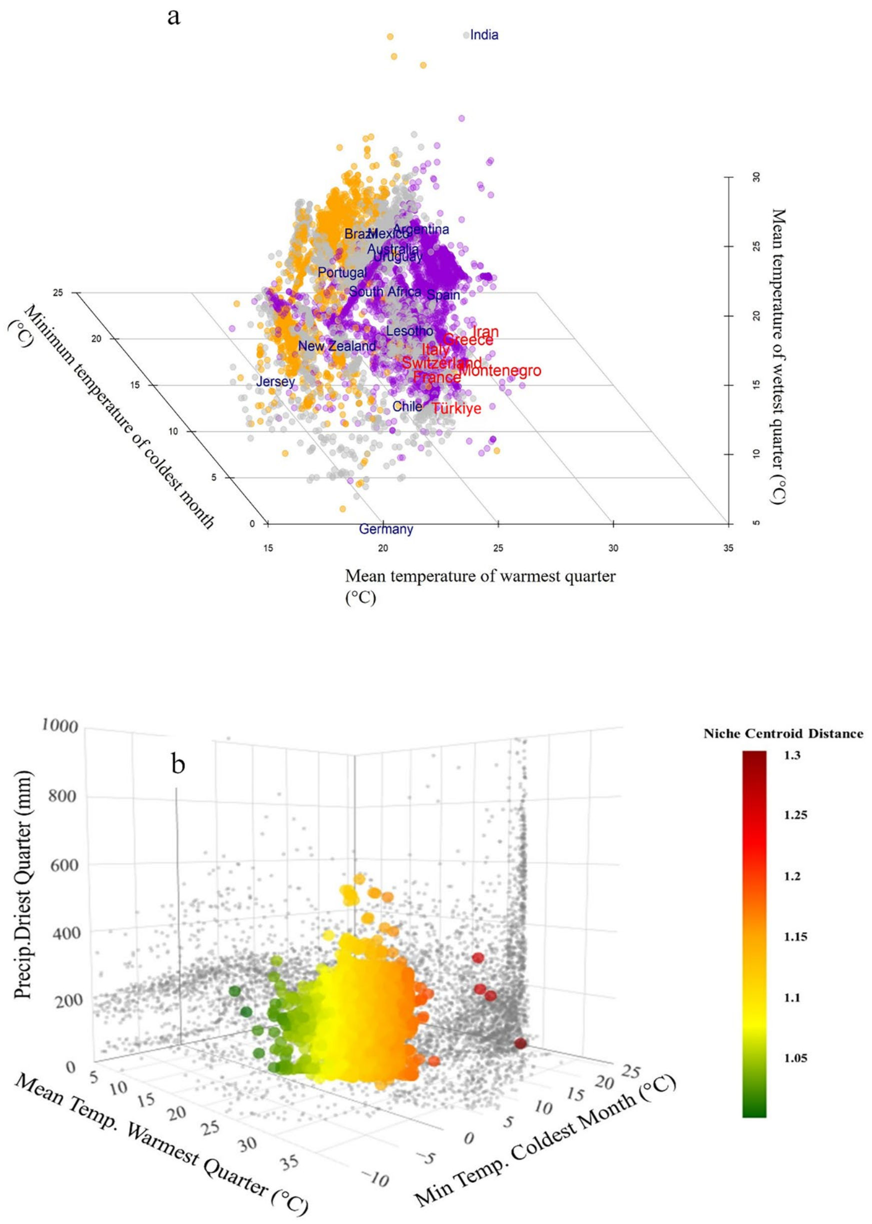

FIGURE A5 | Climatic niche structure of *A. sericifera* based on multivariate analysis. Panel (a) presents a three-dimensional cluster plot based on bioclimatic variables, with countries assigned to bioclimatic clusters. Panel (b) shows the species' suitability response to its most influential temperature and moisture variables.

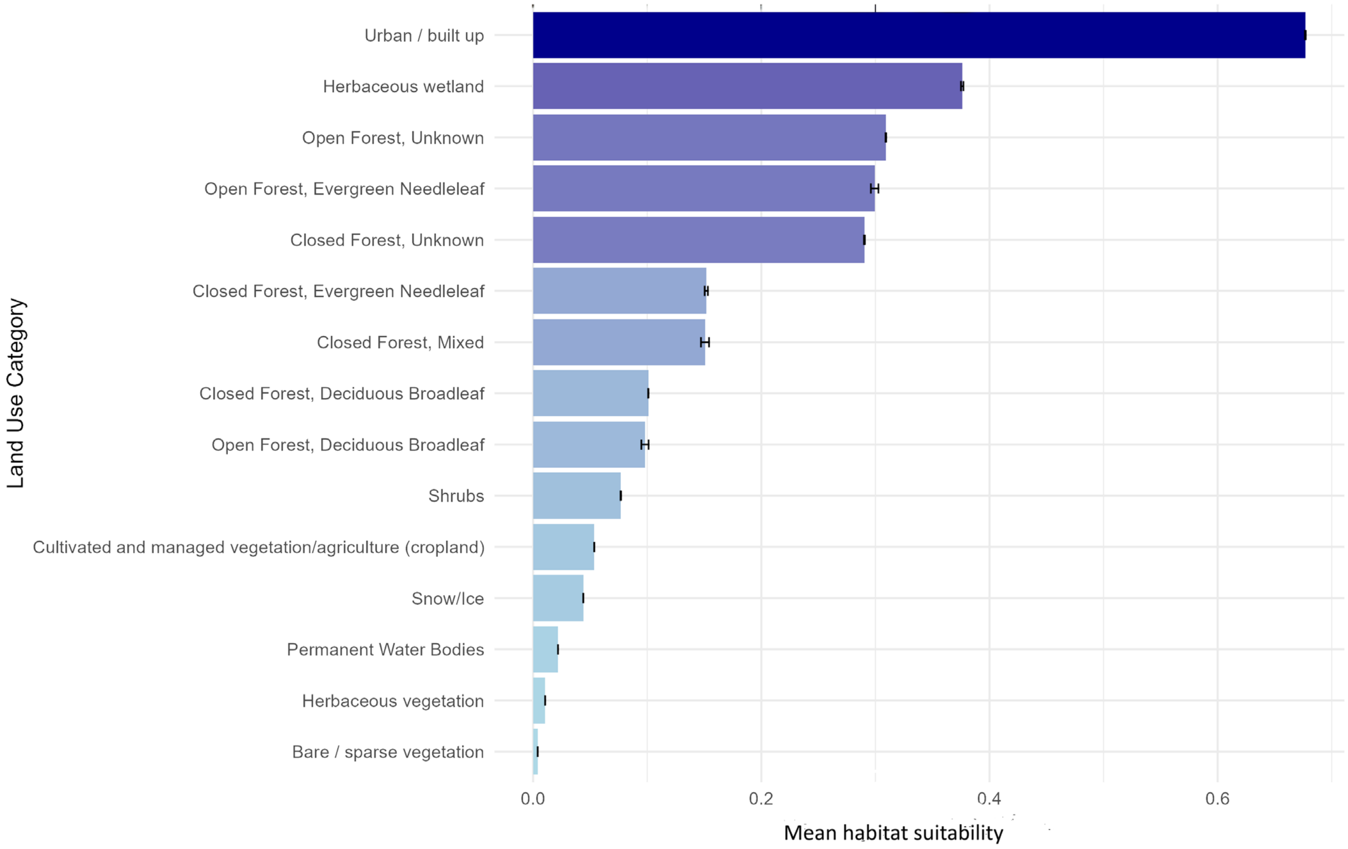

FIGURE A6 | Mean predicted habitat suitability (±SE) for *A. sericifera* across land use categories used in habitat suitability modelling.