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Species Distribution Models in plant conservation science: a comprehensive review with a focus on Iran

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Abstract – This review article thoroughly examines the role of Species Distribution Models (SDMs) in plant conservation science, with a specific focus on applications within Iran. Commencing with an extensive methodological approach, involving an exhaustive search across reputable academic databases such as Scopus, Web of Science, and Google Scholar, the review synthesizes a comprehensive set of studies. It offers deep insights into SDM principles, challenges, and transformative applications. Addressing these challenges, the review explores contemporary data collection methods, including the use of remote sensing, drones, and citizen science, which enhance the precision and scope of SDMs. A detailed examination of various modeling algorithms and approaches, including MaxEnt, Random Forest, Bayesian models, and others, highlights their specific applications and contributions to plant conservation. The review also integrates climate change data and various scenarios into SDMs, showcasing case studies that illustrate SDMs' potential to predict shifts in plant distributions in response to changing climate conditions and overexploitation. Emphasizing the importance of spatial scale, the review discusses its critical impact on the accuracy of modeling and conservation planning. The article concludes by underlining the indispensable role of SDMs in advancing plant conservation efforts, offering tailored recommendations for researchers, policymakers, and conservation practitioners.

Key words: climate change impacts, modeling algorithms, overexploitation, plant conservation, spatial scale, Species Distribution Modeling.

Riassunto – Species Distribution Model nella conservazione della biodiversità vegetale: una rassegna completa con un focus sull'Iran.

Questo articolo di rassegna esamina a fondo il ruolo degli Species Distribution Model (SDM) nella conservazione della biodiversità vegetale, con un focus specifico sulle loro applicazioni in Iran. Partendo da un approccio metodologico approfondito, che ha comportato una ricerca esaustiva in rinomate banche dati accademiche come Scopus, Web of Science e Google Scholar, questa revisione sintetizza una serie completa di studi e offre una visione approfondita dei principi, delle sfide e delle applicazioni trasformative degli SDM. Per affrontare queste sfide, la rassegna esplora i metodi di raccolta dati contemporanei, tra cui l'uso del telerilevamento, dei droni e della citizen science, che migliorano la precisione e la portata degli SDM. Un esame dettagliato di vari algoritmi e approcci di modellazione, tra cui MaxEnt, Random Forest, modelli bayesiani e altri, evidenzia le loro applicazioni specifiche e i contributi alla conservazione delle piante. La rassegna integra anche i dati sul cambiamento climatico e vari scenari negli SDM, mostrando casi di studio che illustrano il potenziale degli SDM nel prevedere i cambiamenti nella distribuzione delle piante in risposta al cambiamento delle condizioni climatiche e al sovrasfruttamento. Sottolineando l'importanza della scala spaziale, la rassegna discute il suo impatto critico sull'accuratezza della modellazione e sulla pianificazione della conservazione. L'articolo si conclude sottolineando il ruolo indispensabile degli SDM nel far progredire gli sforzi di conservazione della biodiversità vegetale, offrendo raccomandazioni su misura per i ricercatori, i responsabili politici e gli operatori della conservazione.

Parole chiave: algoritmi di modellazione, conservazione delle piante, impatto dei cambiamenti climatici, scala spaziale, sovrasfruttamento, Species Distribution Modeling.

INTRODUCTION

Plants are the backbone of ecosystems, providing food, shelter, and oxygen to countless organisms, including humans (Pesce *et al.*, 2023). They contribute to nutrient cycling, soil formation, and climate regulation (Petsch *et al.,* 2023). The extinction or decline of plant species can have cascading effects on entire ecosystems, impacting wildlife, pollinators, and ecosystem services such as clean air and water (Plutino *et al.*, 2022). Recognizing this, plant conservation has gained increasing attention worldwide (Nyumba *et al.,* 2018; Palit *et al.,* 2022).

Plant conservation is a critical component of global biodiversity efforts, as plants form the foundation of terrestrial ecosystems and provide essential services to human societies (Mason *et al.,* 2022). However, the accelerating loss of plant species due to habitat destruction, climate change, invasive species, and other anthropogenic pressures has prompted an urgent need for effective conservation strategies. In this context, Species Distribution Modeling (SDM) has emerged as a powerful tool to inform and guide plant conservation efforts (Nicholson *et al.*, 2021).

Species Distribution Modeling, also known as "Habitat Suitability Modeling" or "Ecological Niche Modeling" (Fragniere *et al.*, 2022), is a computational approach that leverages environmental and species occurrence data to predict the spatial distribution of species across landscapes. Initially developed in the field of biogeography, SDMs have evolved significantly over the past few decades, catalysed by advancements in computational techniques, data availability, and ecological understanding (Lippi *et al.,* 2019). In terms of practical applications, SDMs have been instrumental in guiding the conservation of numerous plant species and ecosystems. Examples include habitat restoration planning for rare and endangered plant species, invasive species management, and the design of protected areas to maximize plant diversity preservation (Bonebrake *et al.,* 2018; Rønsted *et al.,* 2023).

Early applications of SDMs in plant conservation predominantly focused on defining the habitat preferences of individual species and mapping their current distributions. Classic modelling algorithms such as MaxEnt and BIOCLIM paved the way for subsequent developments. Researchers employed these models to identify critical habitats, protect endangered species, and inform land-use planning (Kariyawasam *et al.,* 2019). Over time, the field witnessed a transition from single-species models to multispecies approaches, recognizing the ecological interdependencies among plants and their interactions with other organisms (Veselova &

Gaziulusoy 2021). A significant leap forward has been the integration of high-resolution remote sensing data, which provides detailed information on vegetation cover, land use, and climate variables (Hamilton & Casey 2016). Furthermore, the incorporation of climate change projections into SDMs has become a vital aspect of contemporary plant conservation (Littlefield *et al.,* 2019). Spatial scale considerations are another noteworthy development in the field (Vilà-Cabrera *et al.,* 2019).

Climate change is a major driver of ecological shifts, impacting species distribution and biodiversity globally. Iran, with its diverse ecosystems and endemic species, faces significant challenges due to climate change. A study reveals significant altitudinal shifts in endemic species, emphasizing the importance of identifying high-diversity regions for targeted conservation efforts (Noori *et al.,* 2024). The warming Hyrcanian climate threatens the English yew in Northern Iran, with SDM projecting severe habitat loss by 2050 and 2070 (Alavi *et al.,* 2019). Management strategies, including assisted migration and genetic diversity conservation, are crucial for their survival (Erfanian *et al.,* 2021).

SDM predicts varying habitat suitability for Iranian *Prunus* species under different climate scenarios, emphasizing the need for tailored conservation and cultivation strategies to safeguard their genetic diversity (Zeraatkar & Khajoei Nasab, 2023). *Astragalus* genus distribution and diversity in Iran are identified as hotspot areas for conservation, emphasizing the need to address conservation gaps, particularly in regions not covered by global biodiversity hotspots (Maassoumi & Ashouri, 2022).

Climate change also impacts tree species in Hyrcanian forests, posing challenges for forest management and conservation (Niknaddaf *et al.,* 2023). SDM helps identify biodiversity hotspots, guiding conservation efforts in Hyrcanian Mountain Forests (Taleshi *et al.,* 2019; Mahmoodi *et* *al.,* 2023; Ahmadi *et al.,* 2023). Understanding tree species distributions aids in planning effective conservation strategies along elevation gradients. Lastly, SDM reveals the inadequacy of current protected areas in conserving endemic mountain flora in Iran, emphasizing the need for expansion and realignment of protected areas to mitigate future biodiversity loss (Limaki *et al.,* 2021).

Our review serves as a foundational step towards a more focused and comprehensive examination of Species Distribution Models (SDMs) in the context of plant conservation, particularly within Iran. While this review provides valuable insights into the broader field of SDMs and their practical applications, our ultimate goal is twofold. Firstly, we aim to conduct a more detailed review of SDM applications specifically tailored to Iran's unique biodiversity and conservation challenges. Secondly, we intend to identify the most effective SDM approaches for this specific context, ensuring that conservation strategies are optimally aligned with the distinct ecological and environmental characteristics of the region.

MATERIALS AND METHODS

An extensive search was conducted across reputable academic databases, including Scopus, Web of Science, and Google Scholar. These databases were chosen for their comprehensive coverage of scientific literature. A search strategy was employed using a combination of relevant keywords and variations thereof. These search terms were used: “Species Distribution Modeling”, “Habitat Suitability Modeling”, “Ecological Niche Modeling”, “Plant Conservation”, “Plant Biodiversity”, “Climate Change”, “Overexploitations”, “Land Use”, “Remote Sensing”, “Machine Learning”, “MaxEnt”, “Random Forest”, “Gradient Boosting” and “Ensemble Modeling”.

Articles that directly addressed the application of SDM to plant conservation or were closely related to the subject matter were considered. Inclusion was limited to articles published from the inception of SDM techniques to the latest available data up to September 2023. Only peer-reviewed articles from reputable academic journals, conference proceedings, or scholarly books were included in the review. Articles published in English were included due to accessibility for the intended readership. Relevant data were extracted from the selected articles, including study objectives, methodology, key findings, and implications for plant conservation.

Each selected article underwent a rigorous assessment to evaluate its quality and relevance. The aim was to ensure the inclusion of high-quality research and mitigate bias. Articles were evaluated for the rigor of their methodology and the clarity of their contributions to the field of plant conservation through SDMs. The findings and insights from the selected articles were synthesized and organized into thematic sections within the review article. Key advancements, trends, and emerging topics in SDMs for plant conservation were identified and presented.

RESULTS AND DISCUSSION

To provide a comprehensive overview of the current state of Species Distribution Models (SDMs) in plant conservation, we reviewed a total of 64 articles. The selected studies span from the inception of SDM techniques in the early 2000s to the latest available data as of 2023. These articles were sourced from a range of academic databases, ensuring a broad representation of research within the field. The geographic context of the studies is diverse, covering 21 countries. Notably, the highest number of studies originated from the USA (15 studies), followed by China (8 studies) and Iran (6 studies), as plotted in Figure 1. This geographic distribution underscores the global relevance of SDMs while also highlighting regions where these techniques have been prominently applied.

To provide a clear understanding of the temporal distribution of research, we analysed the number of studies published over time. The data reveals a significant increase in publications, with a peak in 2017 when 10 studies were published (Figure 2). This trend indicates growing interest and advancements in the application of SDMs in plant conservation.

Advancements in data collection

Data collection is a fundamental component of SDMs, and recent advancements in technology and methodologies have greatly improved the quality and quantity of data available for modelling plant species distributions.

Herbarium specimens undergo a remarkable transformation as they journey into the digital realm, becoming accessible resources through platforms like GBIF and SEINet. These repositories burgeon with images and invaluable data, spawning a wave of opportunities (Heberling, 2022; Marsico *et al.,* 2020). Rare plant specimens, once confined to cabinets, now fuel the development of habitat suitability models and prognosticate range shifts (Molano-Flores *et al.,* 2023). Extracted occurrence data from these specimens emerge as linchpins for species regression analyses and the assessment of conservation statuses (Besnard *et al.,* 2018). Portals such as iDigBio, GBIF, and others burgeon with this wealth of information, serving as vital reservoirs that plug gaps in the distribution of elusive plants (Saran *et al.,* 2022). In the domain of SDMs, these repositories serve as pivotal data fountains, frequently tapped for species occurrence data modelling (Ribeiro *et al.,* 2022). Moreover, herbaria-based localities prove invaluable in Strategic Species Assessments

(SSAs), acting as substitutes or supplements in modelling species distributions. They guide field surveys, unveil new populations (de Queiroz *et al.,* 2012; McCune, 2016), foretell future range changes (Erfanian *et al.,* 2021; Shay *et al.,* 2021), dissect climate change impacts (Abbott *et al.,* 2017; Dangremond *et al.,* 2022), and play a crucial role in shaping conservation strategies for rare species (Qazi *et al.,* 2022).

Remote sensing technologies, including satellite and aerial imagery, have provided a wealth of high-resolution data on vegetation cover, land use, and climate variables. This spatially explicit information is invaluable for characterizing the environment (Pricope *et al.,* 2019). UAVs (Unmanned Aerial Vehicles) equipped with sensors and cameras enable researchers to collect fine-scale, real-time data on plant communities and habitat characteristics. These platforms are particularly useful for monitoring and assessing plant populations in remote or challenging terrain (Castellanos-Galindo *et al.,* 2019). Citizen science initiatives and crowdsourced data collection platforms have expanded the spatial and temporal coverage of species observations. These efforts engage the public in data collection, providing valuable insights into plant distributions and phenology (Giovos *et al.,* 2019).

Environmental DNA (eDNA) techniques involve the collection and analysis of genetic material shed by organisms into their environment. In plant conservation, eDNA can be used to detect the presence of rare or elusive plant species in aquatic or terrestrial habitats (Johnson *et al.,* 2023). Camera traps and acoustic recording devices are increasingly used to capture data on plant-associated wildlife, which can indirectly inform plant distribution models by providing insights into herbivory, seed dispersal, and pollination (Caravaggi *et al.,* 2020). Field-deployed sensors can capture real-time data on environmental conditions, including soil moisture, temperature, and light levels. These sensors contribute to more accurate and continuous monitoring of plant habitats (Rühm *et al.,* 2023).

Modelling algorithms and approaches

SDM relies on a variety of modelling algorithms and approaches, each with its strengths and limitations. Advances in computational methods have provided ecologists and conservationists with a diverse toolkit for understanding and predicting plant species distributions.

MaxEnt is a widely used algorithm known for its ability to handle presence-only data effectively. It estimates a probability distribution by maximizing entropy subject to constraints defined by environmental variables (Gao *et al.,* 2021). Random Forest is an ensemble machine learning method that combines multiple decision trees to make predictions. It is robust, handles complex interactions, and can accommodate both presence-absence and presence-only data (Gao & Zhou, 2020). Gradient boosting algorithms, such as XGBoost and LightGBM, have gained popularity for their predictive accuracy and ability to handle large datasets. They are used in SDMs to model complex relationships between species and environmental variables (Chen *et al.,* 2020).

GLMs provide a statistical framework for modelling species distributions and are appreciated for their interpretability. They are particularly useful when simpler models are preferred or when the relationships between variables are well-understood (Lee, 2021). Deep learning methods, including neural networks and convolutional neural networks (CNNs), are increasingly applied to SDMs, especially for image-based data and complex spatial relationships (Brunsdon, 2020). Bayesian modelling approaches, such as hierarchical models and Bayesian networks, are used in SDMs to incorporate uncertainty and account for complex spatial dependencies (Oyster *et al.,* 2018). Ensemble modelling combines predictions from multiple algorithms to improve accuracy and robustness. It is a common practice in SDMs to mitigate the limitations of individual algorithms (Tanner *et al.,* 2017). Functional trait-based modelling focuses on the traits of plant species and how they relate to environmental conditions. This approach can provide mechanistic insights into plant distributions (Classen *et al.,* 2017).

Incorporating demographic data into SDMs, especially under climate change scenarios, offers a more refined understanding of species' potential distributions and extinction risks. Demographic factors such as growth rates, survival, and reproductive success play crucial roles in species resilience to changing environments. (Dullinger *et al.,* 2012) demonstrated this by integrating demographic data into SDMs for high-mountain plants, which allowed for better predictions of species' future distributions and informed more targeted conservation strategies.

Incorporating climate change: Integration into plant SDMs

Incorporating climate change data and scenarios into plant SDMs is critical for understanding how shifting environmental conditions may impact plant species distributions and, consequently, for effective conservation planning. Recent advancements in climate modelling and ecological modelling techniques have allowed for more accurate assessments of these potential changes.

Integrating climate data into SDMs involves using historical climate records and future climate projections to assess how changing temperature and precipitation patterns will influence plant distributions (Araújo *et al.,* 2019). Researchers often use various emission scenarios, such as those outlined by the Intergovernmental Panel on Climate Change (IPCC), to model potential climate futures and their impact on plant species (Masson-Delmotte *et al.,* 2021). In a study assessing alpine plant species in the European Alps, researchers used SDMs and climate change scenarios to predict upward shifts in species' ranges due to warming temperatures (Harvey *et al.,* 2017). A study on oak tree species in the United States utilized SDMs and climate projections to predict significant shifts in oak species ranges over the next century, highlighting potential conservation challenges (Iverson *et al.,* 2019).

Researchers have used climate data to identify vulnerable plant species and predict how changes in temperature and precipitation might affect their distributions. This information is vital for conservation planning (Beaumont *et al.,* 2016). Some studies go beyond single-species modelling to investigate community-level responses to climate change, considering interactions among multiple plant species (Ovaskainen *et al.,* 2016). Research on high-altitude plants in the Southern Alps of New Zealand used SDMs to project range contractions due to climate warming, emphasizing the need for conservation action (McPherson, 2022).

Spatial scale and plant conservation

Spatial scale plays a crucial role in SDM, especially in the context of plant conservation. The choice of scale can significantly influence the accuracy of predictions and the effectiveness of conservation planning.

Spatial scale refers to the size or extent of the geographic area over which data are collected and analysed in SDMs. It is a fundamental consideration because it determines the level of detail and precision in modelling plant species distributions (Wang *et al.,* 2017). Fine-scale models focus on small geographic areas and provide detailed information about local habitat suitability. These models are valuable for site-specific conservation decisions and understanding microhabitat preferences of plant species. Broad-scale models cover larger geographic regions and are useful for identifying broad distribution patterns and regional conservation priorities. They are often employed for landscape-level planning (Danino *et al.,* 2016). Different ecological processes operate at different scales. For example, seed dispersal may be influenced by fine-scale landscape features, while climate change impacts may manifest at broader scales. Choosing the appropriate scale aligns modelling with the relevant ecological processes (Rocchini *et al.,* 2017). Mismatch between the scale of data collection and the scale of ecological processes can lead to ecological fallacies. For instance, making local conservation decisions based on broad-scale models can result in ineffective strategies (Simião-Ferreira *et al.,* 2018).

To address the scale issue, researchers often employ multi-scale modelling approaches. These approaches integrate information from different spatial scales to provide a comprehensive understanding of species distributions (Sanguet *et al.,* 2022). In plant conservation, spatial scale considerations are vital when prioritizing protected areas, designing corridors for habitat connectivity, and assessing the impacts of land-use changes (Liang & Song, 2022). Climate change modelling often requires dynamic scaling, considering temporal scales alongside spatial scales, to project how plant species distributions may shift over time (Graham *et al.,* 2019).

The effectiveness of SDMs varies significantly with the spatial scale of application. Fine-scale models, such as those applied in microhabitat studies, can capture detailed species responses to local environmental gradients and microclimatic variations. For example, (Steinbauer *et al.,* 2018) used fine-scale SDMs to analyse the impacts of climate change on plant species in the European Alps, highlighting how these models can identify microrefugia where species might survive despite broader climatic shifts. On the other hand, broad-scale models are more suitable for understanding regional shifts in species distributions and are often used in large-scale conservation planning.

Conservation applications of SDMs in plant

Species Distribution Models (SDMs) are powerful tools in plant conservation, providing critical insights into habitat suitability, potential distribution shifts, and identifying priority areas for conservation efforts. This section delves into various real-world applications of SDMs, illustrating their utility in conservation planning and management.

Remote sensing data can significantly enhance SDMs by supplying comprehensive environmental data such as land cover, vegetation indices, and climate variables. This data provides broad-scale context, helping to infer habitat conditions and landscape features crucial for modelling species distributions. However, remote sensing often lacks species-specific detail, which may limit the accuracy of ecological niche modelling, particularly for species with specialized habitat requirements. To address these limitations, combining remote sensing with ground-truthing and high-resolution ecological data is essential, allowing for more precise modelling of species distributions.

SDMs are also valuable in managing invasive species by predicting potential distributions based on historical data and assessing habitat permeability. For instance, (Van Nuland *et al.,* 2016) utilized SDMs to predict the spread of invasive plants in the Hawaiian Islands, aiding in the development of strategies to mitigate their impact on vulnerable native habitats.

Case Studies

Orchid Conservation in China

In their study, Li *et al.* (2022) used MaxEnt, a machine learning SDM, to assess habitat suitability for endangered orchid species such as *Cymbidium tortisepalum* Fukuy. and *Paphiopedilum dianthum* Tang & F.T.Wang. By integrating environmental variables such as temperature, precipitation, and soil type, the model identified key conservation areas with high habitat suitability. This detailed approach helps prioritize sites for in-situ conservation and potential reintroduction programs, aligning closely with the theoretical frameworks discussed earlier.

Climate Change Impact in the European Alps

Steinbauer *et al.* (2018) employed ensemble modelling, combining outputs from multiple SDMs to predict potential range shifts and habitat loss for rare alpine plants under various climate change scenarios. This method, integrating fine-scale climate and topographic data, allowed for a comprehensive assessment of future habitat suitability and the identification of potential microrefugia, providing actionable insights for conservation planning.

Restoration in Australia's Murray-Darling Basin

In this case, Gawne *et al.* (2020) used species distribution models based on Bioclim and other correlative models to guide the selection of planting sites for native species. The SDMs incorporated data on soil moisture, elevation, and historical plant distributions to identify areas most suitable for restoration efforts. This approach enhanced habitat restoration by ensuring that plantings were conducted in areas with optimal conditions for survival and growth.

Conservation in the Azores Archipelago

Rocha-Ortega *et al.* (2020) applied MaxEnt models to prioritize conservation actions for rare endemic plants in the Azores. By analysing species distribution against climate variables and land use data, the study identified critical areas for establishing new protected zones, ensuring the conservation of these unique species in the face of environmental change.

Enhancing Habitat Connectivity in Fragmented Landscapes

Liu *et al.* (2018) utilized SDMs to assess and enhance habitat connectivity for plant species in fragmented landscapes. By modelling potential movement corridors and identifying habitat patches critical for maintaining genetic flow, this study provided a foundation for conservation actions aimed at reducing species isolation and promoting long-term survival.

Species Distribution Models (SDMs) in Iran

Species Distribution Models (SDMs) have been instrumental in understanding the distribution and conservation needs of various plant species in Iran. The following case studies illustrate the effectiveness of SDMs in guiding conservation strategies and management actions across different regions and ecosystems in Iran.

Mofarrah in Western Iran

The study on mofarrah *Nepeta crispa* Willd. demonstrated the effectiveness of SDMs in identifying current habitat suitability and forecasting future range shifts due to climate change. The model indicated that elevation, temperature, geology, and precipitation are critical factors influencing the distribution of *N. crispa*. As a result, it was suggested that conservation efforts should prioritize areas above 2000 m a.s.l., where suitable habitats are likely to persist under changing climatic conditions (Mahmoodi *et al.,* 2022).

Brant's oak and Climate Change

Research on *Quercus brantii* Lindl. in western Iran utilized ensemble modelling to assess the potential impacts of climate change on the species' distribution. The results revealed a significant vulnerability of *Q. brantii* to climate change, projecting a substantial loss of suitable habitats by 2070 under the most pessimistic scenario. This emphasizes the urgency for proactive conservation measures, such as protecting climate refugia and enhancing habitat connectivity, to mitigate the anticipated range contractions (Safaei *et al.,* 2021).

Crop Wild Relatives (CWRs) and Aegilops *species*

The study on crop wild relatives, particularly focusing on goatgrasses *Aegilops* L. species, employed MaxEnt modelling to predict range changes under various climatic scenarios. The findings indicated mixed responses, with some species experiencing range contractions and others expansions. This variability underscores the need for dynamic conservation planning that can adapt to the changing distributions of these valuable genetic resources, ensuring their preservation and potential utility for future crop breeding (Hosseini *et al.,* 2022).

Hyrcanian temperate forests

A study in the Hyrcanian temperate forests highlighted the importance of understorey plant species for biodiversity conservation. SDMs were used to predict the occurrence of these species based on climate, soil, and canopy cover variables. The results showed that while climate variables are pivotal in determining species distributions, changes in canopy cover due to forest management could either mitigate or exacerbate the effects of climate change on different understorey plant groups. This points to the need for tailored forest management practices that consider the specific ecological requirements of shade-adapted and sun-adapted species (Naqinezhad *et al.,* 2022).

Artemisia sieberi *in Central Iran*

Research on *Artemisia sieberi* Besser in central Iran compared the effectiveness of SDMs using bioclimatic variables derived from remote sensing data versus traditional instrumental records. The study found that models incorporating remote sensing data significantly outperformed those based solely on instrumental records, highlighting the value of up-to-date, high-resolution data for enhancing model accuracy. This demonstrates the potential of remote sensing technologies to improve conservation planning by providing reliable predictions for habitat management (Amiri *et al.,* 2020).

Brant's oak distribution across Iran

The study on the distribution of Brant's oak *Quercus brantii* Lindl. across different geographical extents used various SDMs, including Random Forest, Generalized Linear Model, and Maximum Entropy, to project future habitat suitability under climate change scenarios. The results indicated a likely decline in potential habitats for Brant's oak across all examined spatial scales, reinforcing the need for scale-specific conservation strategies that address both local and regional challenges in habitat preservation (Mirhashemi *et al.,* 2023).

Overall, these case studies underscore the critical role of SDMs in informing conservation strategies in Iran. By providing precise predictions of species distributions and identifying priority areas for conservation, SDMs offer essential guidance for developing effective management plans to protect biodiversity in diverse ecosystems.

Challenges and limitations of SDM in plant conservation

High-quality data on plant occurrences and environmental variables are crucial for accurate SDMs. However, such data may be scarce, biased, or incomplete, especially in remote or understudied regions (Liu *et al.,* 2019). The choice of spatial scale in SDMs can be challenging, and mismatches between the scale of the model and the scale of ecological processes can lead to inaccurate predictions (Shaikh *et al.,* 2021).In many SDMs analyses, one could assume that species are in equilibrium with their environment, but this assumption may not hold true, especially in rapidly changing environments due to factors like climate change or habitat degradation (Adhikari *et al.,* 2019). Incorporating climate change scenarios into SDMs introduces uncertainty, as future climate conditions are unpredictable. This can affect the accuracy of predictions related to plant distribution shifts (Yu *et al.,* 2019).

SDMs often do not account for biotic interactions, such as competition or mutualism, which can significantly influence plant distributions (Wen *et al.,* 2016). Overfitting occurs when models are overly complex and fit noise in the data, leading to poor generalization to new locations or conditions (Lee-Yaw *et al.,* 2022). Models built in one geographic region may not perform well in others due to differences in environmental conditions, leading to challenges in transferring knowledge across regions (Sillero & Barbosa, 2021). SDMs often assume species' distributions are static, but evolutionary processes, such as adaptation and migration, can influence plant distribution patterns over time (Escobar & Craft, 2016).

The potential applicability of SDMs in identifying conservation gaps within countries is a significant aspect worth highlighting. SDMs can serve as valuable tools for identifying areas that are underrepresented or not adequately covered within conservation efforts (Cha *et al.,* 2021; Zhong *et al.,* 2021). By utilizing SDMs, researchers and conservationists can pinpoint regions where species richness is high but conservation efforts are low or insufficient. These models can help prioritize areas for conservation interventions, directing resources toward areas that are ecologically significant yet overlooked in conservation planning.

In the context of Iran, for instance, employing SDMs can aid in identifying specific regions that harbour unique or endangered plant species but are currently not adequately protected or considered in conservation strategies. This knowledge is instrumental in guiding policy-making and resource allocation to fill these conservation gaps and ensure the preservation of the country's rich plant diversity. Highlighting the role of SDMs in pinpointing conservation gaps within countries like Iran adds depth to the discussion by showcasing the practical utility of these models beyond predictive purposes, emphasizing their crucial role in guiding targeted and effective conservation actions.

Conclusion

Species Distribution Models (SDMs) indeed possess a versatile applicability beyond plant conservation, extending their utility across diverse organismic groups and ecosystems. Their adaptability allows for the exploration and understanding of species distributions and environmental relationships across various taxa, including animals, microbes, and even entire ecological communities. Whether studying the habitat preferences of mammals, the range shifts of birds due to climate change, or the distributions of disease vectors, SDMs serve as powerful tools for understanding and predicting species' responses to environmental changes. Moreover, these models find applications in conservation biology, epidemiology, invasive species management, and ecosystem restoration, among others. For instance, in conservation, SDMs aid in identifying critical habitats for endangered species and help design protected areas. In epidemiology, they assist in mapping disease risk and understanding disease transmission dynamics. Their versatility in predicting species distributions and understanding ecological relationships makes SDMs invaluable across multiple fields of study and conservation efforts.

In conclusion, SDMs have proven to be invaluable tools for advancing plant conservation efforts by offering a data-driven approach to comprehending, projecting, and mitigating the effects of environmental changes on plant species. Recognizing the pivotal role of SDMs, recommendations for various stakeholders emerge. Researchers are encouraged to persist in refining and enhancing

SDM techniques while tackling data quality issues and embracing new data sources. Further exploration into integrating biotic interactions and evolutionary dynamics into SDMs is advocated to augment predictive accuracy. Policymakers are urged to acknowledge the value of SDMs in conservation planning, earmarking resources for data collection, modelling, and monitoring endeavours, with an emphasis on incorporating SDM-based predictions into policy and land-use planning to ensure the sustainability of plant conservation efforts. Conservation practitioners are encouraged to harness the potential of SDMs to steer on-the-ground conservation actions, encompassing habitat restoration, invasive species management, and the design of protected areas. Additionally, fostering collaborations with researchers is pivotal to ensure the seamless integration of the latest SDM advancements into conservation strategies, culminating in a holistic approach to safeguarding plant biodiversity.

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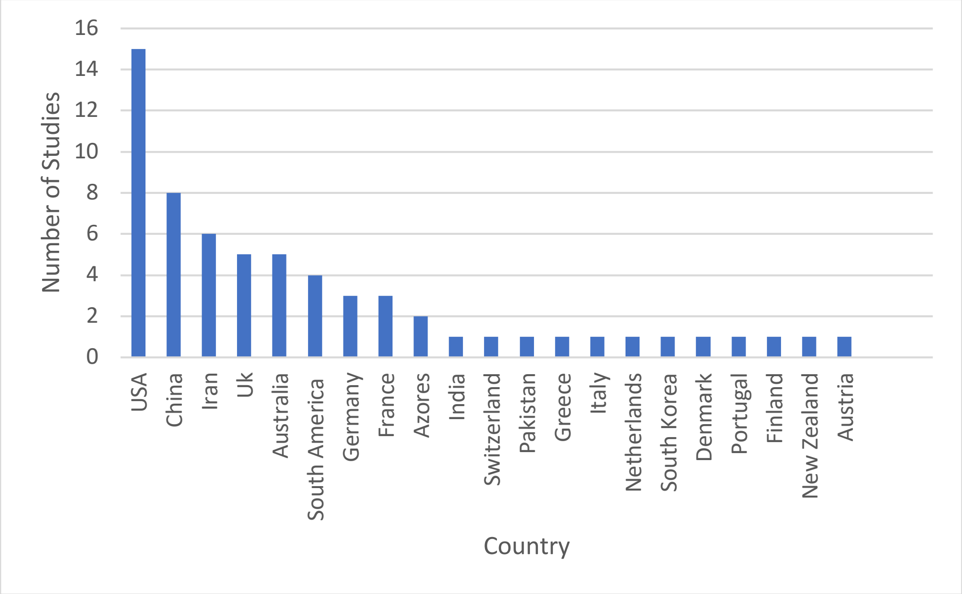

Fig. 1 - Distribution of studies by country. / Distribuzione degli studi per nazione.

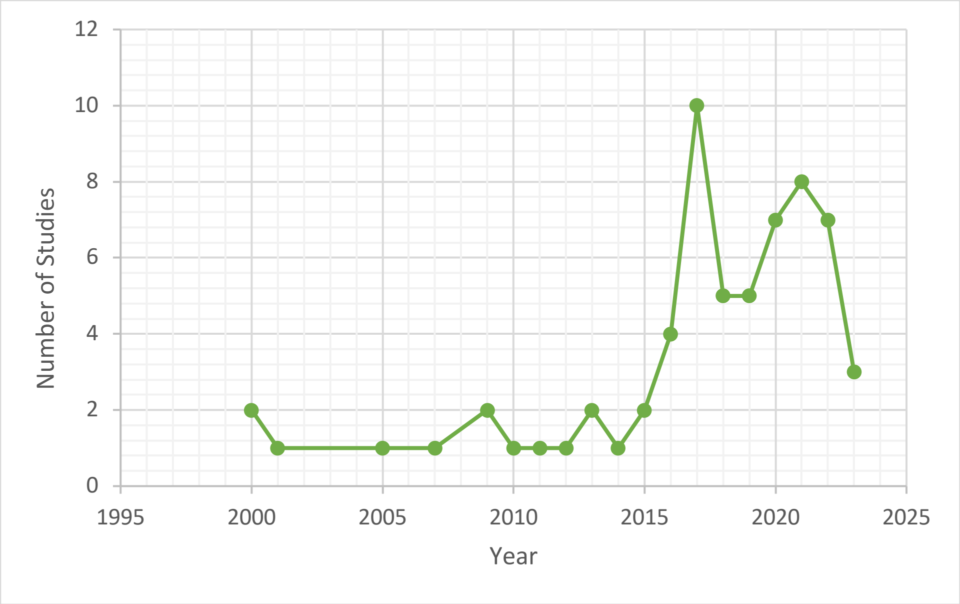

Fig. 2 - Number of studies employing SDMs published from 2000 to 2023. / Numero degli studi che hanno utilizzato gli SDM pubblicati dal 2000 al 2023.