

SPECIES DISTRIBUTION MODELING OF THREE ECONOMICALLY VALUABLE TREE SPECIES UNDER CLIMATE CHANGE SCENARIO IN THE SOUTHERN REGION OF PUNJAB, PAKISTAN

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Abstract

Southern Punjab, Pakistan, comprises riparian belts, irrigated plains, semi-arid agroforestry zones, and desert margins where key tree species are increasingly affected by climate and land-use pressures. This study used species distribution modelling (SDM), GIS-based spatial analysis, and trait ecology to assess current and future habitat suitability for *Vachellia nilotica*, *Dalbergia sissoo*, a widely planted species, and *Tecomella undulata*. Species presence records were obtained from field surveys, Punjab Forest Department records, and GBIF, while bioclimatic (BIO1–BIO19), topographic, edaphic, hydrological, and land-use predictors were incorporated into MaxEnt (v3.4.4) models optimized using ENMeval/SDMtune with spatial block cross-validation and bias correction. Suitability outputs were mapped in ArcGIS and projected to mid-century climate scenarios (SSP2-4.5 and SSP5-8.5). Trait analyses in R evaluated tree height, DBH, and leaf morphological attributes across ecological zones. Model performance was high (AUC: *V. nilotica* = 0.999 ± 0.002 ; *D. sissoo* = 0.985 ± 0.004 ; *T. undulata* = 0.988 ± 0.003). Temperature–precipitation gradients, particularly annual means and moisture availability in wettest and warmest quarters, were the major drivers of suitability along with hydrological factors. Predicted distributions indicated stable and climatically flexible core ranges for *V. nilotica*, riparian-restricted suitability for *D. sissoo* following river and canal networks, and localized arid-zone persistence for *T. undulata* with limited expansion under future climates. Overall trait–occurrence correlations were weak, with slight positive effects of leaf area in *D. sissoo* and stem diameter in *T. undulata*. The results emphasize species-specific management needs, including riparian corridor protection for *D. sissoo*, desert-habitat conservation for *T. undulata*, and climate-responsive agroforestry planning for *V. nilotica*.

Key words: Species distribution modelling; MaxEnt; Climate change; Habitat suitability; GIS; Riparian ecosystems; Trait ecology

Introduction

Climate change is increasingly altering the spatial distribution, regeneration potential, and long-term survival of tree species across arid and semi-arid landscapes. Rising temperatures, changing precipitation regimes, increased frequency of heat waves, and intensified land-use pressure are reshaping suitable habitats for many ecologically and economically important plant species (Franklin, 2023). In regions where forests and agroforestry systems already exist under water stress, even moderate changes in temperature and moisture availability may influence species establishment, growth, and persistence. Therefore, identifying present and future habitat suitability is essential for climate-resilient conservation planning, restoration, and sustainable forest management (Rathore & Sharma, 2023).

Species distribution models (SDMs) provide an effective framework for assessing how environmental variables influence the potential distribution of species. By linking known occurrence records with climatic, topographic, edaphic, hydrological, and land-use predictors, SDMs can estimate suitable habitats under current conditions and project possible shifts under future climate scenarios. Among different SDM approaches, MaxEnt is widely used for presence-only occurrence data

because it performs well with limited records and allows the integration of multiple environmental predictors. When combined with Geographic Information Systems (GIS), MaxEnt outputs can provide spatially explicit maps that are useful for conservation prioritization, afforestation planning, and climate adaptation strategies (Riva *et al.*, 2024). Southern Punjab, Pakistan, represents an important but environmentally vulnerable region for tree species conservation and agroforestry development. The region includes riparian corridors along rivers and canals, irrigated alluvial plains, semi-arid agricultural systems, and desert margins linked with the Thal and Cholistan landscapes. These ecological zones support several tree species that contribute to soil stabilization, shade, fodder, fuelwood, timber, biodiversity conservation, and rural livelihoods. However, increasing climatic variability, groundwater stress, irregular monsoon rainfall, land conversion, and unsustainable harvesting are creating new challenges for the survival and regeneration of native and economically valuable tree species in the region (Finn *et al.*, 2024).

Southern Punjab is characterized by strong climatic variability, which includes irrigated plains, semi-arid agricultural systems and desert margins. There is growing influence of increasing temperatures and extended heat waves and changed monsoon patterns in the region. These climatic fluctuations are harsh to indigenous tree species.

Declines in river levels and changes in precipitation regimes have enhanced the risks of dieback in *Dalbergia sissoo*, and the timing of the monsoons has changed in relation to regeneration in *Vachellia nilotica*. Even slight shifts in the season of precipitation may lead to significant habitat loss of *Tecomella undulata*. Most of the climatic stressors are supplemented by anthropogenic pressures like agricultural development, sand mining, and unsustainable harvesting which worsen the issues across the locality (Guisan *et al.*, 2025).

Although these species have ecological and economic value, their potential responses to future climate change in Southern Punjab remain insufficiently quantified. Much of the existing regional work on tree species is descriptive or limited to individual species, while fewer studies combine field occurrence data, global biodiversity records, bias-corrected SDM methods, GIS-based spatial mapping, and trait-level ecological interpretation (Gilani *et al.*, 2020; Khan *et al.*, 2022; Green *et al.*, 2022). Moreover, the role of morphological traits such as tree height, diameter at breast height, leaf length, leaf width, and leaf area remains poorly understood in relation to species occurrence and environmental suitability (Lee *et al.*, 2026). Integrating trait analysis with SDM can help determine whether broad-scale distribution patterns are mainly controlled by climatic and hydrological variables or morphological variation also contributes to local adaptation.

In Southern Punjab, riparian areas, irrigated and semi-arid agroforestry ecosystems, and desert-margin ecosystems are increasingly affected by interacting climatic and land-use changes, which directly influence species survival and regeneration. Even though *D. sissoo*, *V. nilotica*, and *T. undulata* are ecologically and economically important, their survival in the face of climate change has not been quantitatively evaluated. An examination of the Pakistani literature indicates three key gaps: (i) most studies are descriptive and species-specific (Gilani *et al.*, 2020); (ii) few studies combine field surveys and GBIF data with bias-corrected, spatially validated SDMs; and (iii) few studies use morphological trait data to explain adaptive responses (Khan *et al.*, 2022). These gaps create considerable uncertainty in climate-resilient forestry planning and necessitate an effective, spatially explicit, and trait-sensitive modelling framework (Farashi & Alizadeh-Noughani, 2023).

The hypotheses of this study are that the distribution of *D. sissoo*, *V. nilotica*, and *T. undulata* depends heavily on climatic and hydrological gradients and relatively weakly on morphological traits as a comparatively species-general adaptive factor. The objectives of the current study were to identify the most important climatic, hydrological, edaphic, and land-use factors determining the contemporary distributions of these species in Southern Punjab as well as modelling their current and future suitability with various CMIP6 climatic scenarios (Ashraf *et al.*, 2016) using a calibrated and bias-corrected framework of MaxEnt. The study also explored relationships between environmental factors and morphological traits (Madsen-Hepp *et al.*, 2023) and drew conclusions about possible adaptation mechanisms. Finally, the study provides species-specific conservation and climate-adaptation recommendations to help preserve the riparian corridors, agroforestry and restore desert ecosystems in the area (Johnson *et al.*, 2023).

Materials and Methods

Study area and target species: The study was conducted in Southern Punjab, Pakistan, a region characterized by strong ecological and climatic heterogeneity. The area includes riparian belts along the Indus River and its canal systems, irrigated alluvial plains, semi-arid agroforestry landscapes, and desert landscapes associated with the Thal and Cholistan regions. Climatically, Southern Punjab falls within an arid to semi-arid zone influenced by the South Asian monsoon. Mean annual temperature generally ranges between 24°C and 28°C, while summer temperatures frequently exceed 45°C. Annual precipitation is relatively low and variable, ranging approximately from 150 mm to 400 mm, with most rainfall occurring during the monsoon season from July to September. These conditions make the region highly suitable for examining climate-driven shifts in tree species distribution, particularly for species adapted to riparian, semi-arid, and desert ecosystems (Giachello *et al.*, 2025) (Fig. 1).

For ecological interpretation, the study area was considered across four major habitat types: riparian corridors, irrigated alluvial plains, semi-arid agroforestry systems, and arid and desert habitats. These zones represent the main environmental gradients influencing tree distribution in Southern Punjab, especially moisture availability, soil type, hydrological access, salinity, and heat stress. Field surveys were conducted across these habitat types to ensure that the occurrence data included the environmental variability relevant to the selected species (Safdar & Ahmad, 2025). Three economically and ecologically important tree species were selected for modelling: *V. nilotica*, *D. sissoo*, and *T. undulata*. These species were chosen because they represent contrasting ecological strategies within Southern Punjab. *V. nilotica* is a semi-arid generalist and nitrogen-fixing species widely used in agroforestry, rangeland rehabilitation, fuelwood production, and saline-soil management. *D. sissoo* is a valuable riparian hardwood species associated with riverbanks, canals, and moist alluvial soils, making it highly relevant for riparian restoration and rural timber production. *T. undulata* is a planted species widely cultivated in the alluvial plains of Pakistan and is also adapted to arid environments, where it contributes to dune stabilization, biodiversity conservation, and hardwood resources (Waheed *et al.*, 2024). Together, these species provide a useful ecological gradient for assessing climate sensitivity in Southern Punjab. *V. nilotica* represents broad semi-arid adaptability, *D. sissoo* represents hydrologically dependent riparian habitats, and *T. undulata* represents desert-adapted persistence under high temperature and low moisture conditions. This comparative selection allows the study to evaluate how different functional tree types may respond to current and future climatic conditions across arid and semi-arid landscapes (Arshad *et al.*, 2022).

Data acquisition and environmental variables: The data of occurrence of species in the three validated sources were received: (i) Punjab Forest Department, (ii) field surveys conducted between March–June 2023, comprising riparian, semi-arid, and desert-margin areas of Southern Punjab, and (iii) GBIF datasets. The three species were chosen because they represent three contrasting ecological zones of Southern Punjab: riparian (*D. sissoo*), semi-arid (Mushtaq *et al.*, 2021), and desert (Arshad *et al.*, 2022) habitats, making them suitable indicators for assessing

climate-driven distributional change across contrasting environments. Hydrological influence was represented using river and canal buffer layers generated at 100 m, 200 m, and 500 m distances. These buffers were treated as separate binary predictor layers rather than being combined into a single multi-distance proximity raster. Each buffer layer was coded as presence or absence of proximity to a river or canal within the specified distance threshold. This approach allowed the model to evaluate whether short-, medium-, or broader-distance hydrological proximity contributed differently to habitat suitability, particularly for moisture-dependent species such as *D. sissoo*. Table 1 provides a summary of the environmental predictors in the species distribution models, their ecological relevance, and the data sources used to assemble the ecological predictors (Durrani *et al.*, 2024).

Coordinate data were standardized to WGS84, projected to UTM Zone 43N, and filtered for accuracy by removing records with spatial uncertainty >500 m, duplicates within 100 m, and projection errors. Spatial thinning at 5–10 km was applied to minimize sampling autocorrelation, resulting in 156 occurrences for *D. sissoo*, 142 for *V. nilotica*, and 114 for *T. undulata*. To reduce sampling bias, 10,000 Target Group Background (TGB) points were generated following Waheed *et al.*, (2024). A complete environmental predictor set was assembled (Table 1), comprising bioclimatic variables (BIO1–BIO19) from WorldClim v2.1, representing temperature means, seasonality, and moisture extremes relevant to the arid–semi-arid monsoon climate of Southern Punjab. Topographic variables (slope, aspect; SRTM DEM), hydrological layers (100–500 m buffers around rivers/canals), soil classes (salinity/texture), and land-use

categories were incorporated to represent habitat structure and edaphic constraints. Highly correlated climate variables ($|r| > 0.7$ and $VIF > 5$) were excluded, and all raster layers were resampled to 2.5' (~4.5 km) and projected to WGS84, ensuring compatibility across datasets.

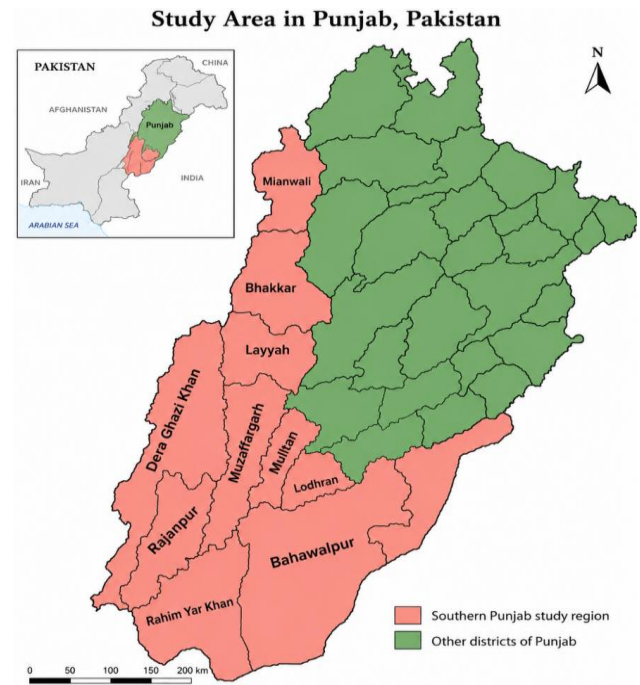


Fig. 1. The map of Southern Punjab, Pakistan illustrating the main districts (Bahawalpur, Multan, Dera Ghazi Khan, and Sahiwal) and the border of the study area. The study areas are outlined by map lines which do not necessarily represent accepted national boundaries.

Table 1. Environmental predictors and preprocessing.

Code	Variable (unit/type)	Ecological rationale (per species)	Source (native res)	Model res/CRS
BIO1	Annual mean temperature (°C, cont.)	Baseline energy constraint affects growth/metabolism (DS/AN/TU)	WorldClim v2.1 (2.5')	2.5', WGS84
BIO8	Mean temp. of wettest quarter (°C, cont.)	DS: warmer monsoon enhances establishment on moist alluvium	WorldClim v2.1 (2.5')	2.5', WGS84
BIO10	Mean temp. of warmest quarter (°C, cont.)	TU: heat-stress thresholds constrain suitability; AN tolerates high heat	WorldClim v2.1 (2.5')	2.5', WGS84
BIO12	Annual precipitation (mm, cont.)	Moisture availability baseline; AN peak at intermediate moisture	WorldClim v2.1 (2.5')	2.5', WGS84
BIO14	Precipitation of driest month (mm, cont.)	TU regeneration is limited under very low dry-season moisture	WorldClim v2.1 (2.5')	2.5', WGS84
BIO15	Precipitation seasonality (CV, cont.)	AN: semi-arid generalist—hump-shaped response to aridity variability	WorldClim v2.1 (2.5')	2.5', WGS84
BIO16	Precipitation of wettest quarter (mm, cont.)	DS: riparian recruitment tracks monsoon/wet-quarter intensity	WorldClim v2.1 (2.5')	2.5', WGS84
BIO18	Precipitation of warmest quarter (mm, cont.)	Heat–moisture interaction; informs stress vs. growth windows (AN/TU)	WorldClim v2.1 (2.5')	2.5', WGS84
BIO19	Precipitation of coldest quarter (mm, cont.)	Cold-season soil moisture carryover for perennial survival (DS/AN)	WorldClim v2.1 (2.5')	2.5', WGS84
Slope	Slope (degrees, cont.)	Micro-water balance and soil depth limit establishment on steep sites	SRTM 30 m	2.5', WGS84
Aspect	Aspect (categorical/continuous)	Insolation differences can modify local heat/water stress	SRTM 30 m	2.5', WGS84
LULC	Land use/land cover (categorical)	Habitat context: irrigated agriculture vs. natural scrub/forest (all)	PFD 2017 (vector)	2.5', WGS84
Soil class	Salinity/alkalinity and texture (categorical)	AN tolerant of saline/alkaline; DS/TU more selective	SSP 2018 (vector)	2.5', WGS84
Hydro buffers	River/canal buffers 100/200/500 m (binary)	DS riparian affinity; irrigation influence near canals	PID 2019 (vector)	2.5', WGS84

Modeling, spatial, and trait analysis: Species distributions were modelled using MaxEnt v3.4.4 to estimate habitat suitability from presence-only occurrence data and environmental predictors. Model tuning in R was conducted using regularization multipliers (0.5–4) and combinations of feature classes (L, Q, H, P). The models that performed best were chosen by $\Delta AICc$ as well as test AUC and the 10% training omission rate in accordance with the recommended SDM calibration procedures of semi-arid species (Khanum *et al.*, 2013). Five-fold spatial block cross-validation was used to reduce spatial autocorrelation and improve model generality by partitioning the study region into riparian, irrigated, semi-arid, and desert spatial blocks. The final models were run 10 times using logistic output and clamping to reduce unrealistic extrapolation. Model performance was evaluated using AUC, True Skill Statistic (TSS), and training/test omission rates, while variable contributions were assessed using jackknife and permutation-importance tests (Green *et al.*, 2022).

For the trait-based analysis, species occurrence was coded as a binary response variable, where presence records were assigned a value of 1 and background or absence points were assigned a value of 0. To separate the influence of broad climatic predictors from morphological traits, a two-step logistic modelling approach was used. First, a baseline logistic model was fitted using the main climatic predictors identified from the MaxEnt analysis. Second, morphological traits, including tree height, diameter at breast height, leaf length, leaf width, and leaf area, were added to the model as additional predictors. The improvement in model fit and the significance of trait coefficients were then examined to determine whether morphological variables explained additional variation in occurrence after accounting for climatic effects. The general model structure was:

Occurrence ~ climatic predictors + morphological traits:

This approach allowed the study to evaluate whether or not morphological traits contributed independently to species occurrence beyond the effects of macro-climatic suitability.

The present climatic conditions (1970–2000) and future scenarios in a time span of 2050–2070 were simulated using CMIP6 scenarios SSP2-4.5 (2050 intermediate stabilization) and SSP5-8.5 (2050 high emissions). An analysis of the environment based on MESS and MOP determined environmental analogues and hazardous extrapolation region (Ali *et al.*, 2017). The final habitat suitability maps were produced in ArcGIS Pro 2.6.2 in both continuous and binary formats, and uncertainty surfaces were calculated using replicate variance. Morphological traits were measured for field-sampled individuals, including tree height, diameter at breast height (DBH), leaf length, leaf width, and leaf area, across four ecological zones: (i) riparian belts, (ii) irrigated plains, (iii)

semi-arid agroforestry systems, and (iv) desert margins. Trait data were analyzed in R 4.2. Descriptive statistics summarized trait variation, Pearson correlation assessed linear relationships between traits and species presence, and binary logistic analysis determined whether or not traits significantly increased the probability of occurrence after the effects of climatic predictors were removed. This integrated modelling-trait framework provided the possibility to evaluate whether species distribution was caused predominantly by climatic and hydrological gradients or morphological traits offered adaptive benefits (Kailash *et al.*, 2022).

Results

Model performance (MaxEnt): The MaxEnt models showed high predictive performance for all three target species, as indicated by their AUC values (Table 2).

V. nilotica showed the most favorable performance ($AUC = 0.999 \pm 0.002$), indicating that it discriminates between appropriate and inappropriate habitats almost perfectly. *D. sissoo* ($AUC = 0.985 \pm 0.004$) and *T. undulata* ($AUC = 0.988 \pm 0.003$) were also found to have strong predictive capabilities, indicating strong discrimination under the selected model settings. These high AUC scores support strong predictive performance, although transferability to future climatic conditions should be interpreted together with spatial cross-validation and extrapolation diagnostics.

Jackknife test of AUC values of *V. nilotica*, *D. sissoo*, and *T. undulata* indicated the importance of environmental factors in the MaxEnt models (Fig. 2). The jackknife resultant curves indicate some of the environmental forces which influence species distributions. For *T. undulata*, the BIO10 (mean temperature of the warmest quarter) and BIO12 (annual precipitation) and BIO13 (precipitation of the wettest month) variables made the most substantial contribution and indicated that the warm-season temperature and precipitation of the wet months of the year are relevant towards identifying its habitat suitability in arid regions. *V. nilotica* had a more balanced reaction, and a few variables had similar effects, indicating its generalist character and wide ecological adaptability to different climatic situations. By comparison, *D. sissoo* was extremely sensitive to such variables as BIO5 (maximum temperature of the hottest month) and BIO7 (annual temperature range), showing that it was sensitive to thermal stability and the presence of riparian moisture (Yousaf *et al.*, 2022). In all three species, temperature and precipitation proved to be the most important factors affecting distributions. All these results support the significance of climatic drivers on habitat suitability, especially with the species-specific response to environmental gradients based on existing and prospective conditions during climate changes.

Table 2. Model performance statistics (AUC, significance, and classification) for the three target species using MaxEnt.

Model	Area under the curve (AUC)	Model performance	p-value
<i>Vachellia nilotica</i>	0.999 ± 0.002	Excellent (highly accurate prediction)	<0.05
<i>Dalbergia sissoo</i>	0.985 ± 0.004	Excellent (high sensitivity and specificity)	<0.05
<i>Tecomella undulata</i>	0.988 ± 0.003	Excellent (robust model performance)	<0.05

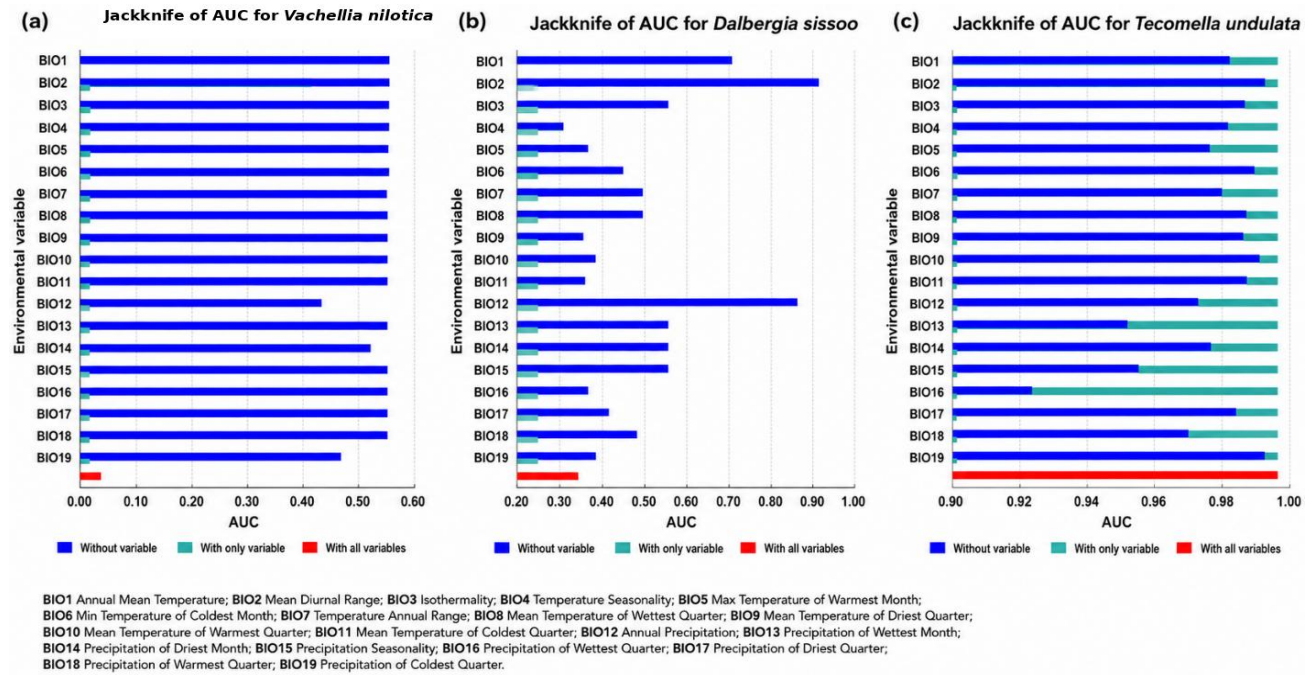


Fig. 2. Jackknife test of AUC of *Vachellia nilotica* (a), *Dalbergia sissoo* (b), and *Tecomella undulata* (c) to show different levels of significance in MaxEnt models.

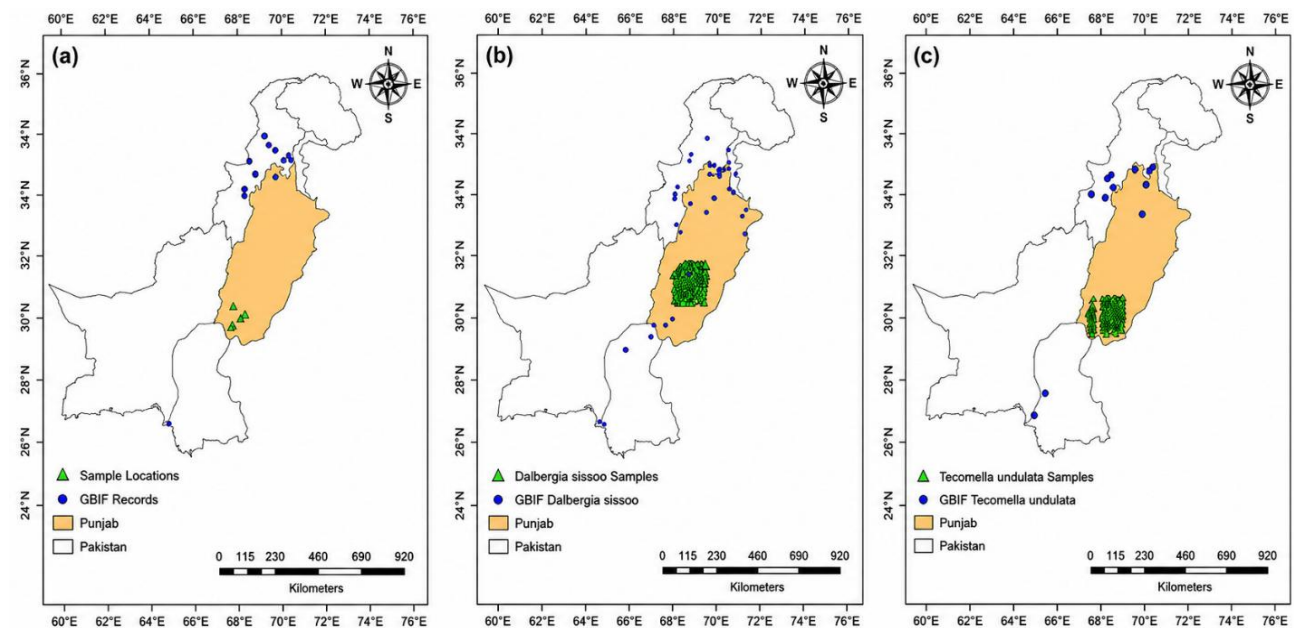


Fig. 3. Geographic distribution of occurrence records and field sample locations for the three studied tree species in Punjab, Pakistan: (a) *Vachellia nilotica*, (b) *Dalbergia sissoo*, and (c) *Tecomella undulata*. Green triangles indicate field sample locations, blue circles represent GBIF occurrence records, the shaded area indicates Punjab Province, and the outer boundary represents Pakistan.

Species occurrence and spatial data (ArcGIS): Figure 3 shows a spatial distribution and sample points of *V. nilotica*, *D. sissoo*, and *T. undulata* in Pakistan according to field survey and GBIF data. The maps of the spatial distributions of the three target tree species in Pakistan give a complete picture of how the species occur in the country, considering both the field-collected data and the GBIF records (Mathur and Mathur, 2023). The species *V. nilotica* presents a wide ecological distribution with GBIF data being offered through Punjab, Khyber Pakhtunkhwa, and Sindh. The field sampling points are clustered in southern Punjab, which means that the species is adaptive to various semi-arid,

riparian, and irrigated habitats. This broad distribution indicates its ecological potential and adaptation to different moisture and temperature conditions.

D. sissoo has a more concentrated and narrower distribution with most of the occurrences concentrated in the river systems of the central Punjab. This trend is in line with its ecological favourability of wetlands or riparian habitats where the water supply is predictable to facilitate its growth and regeneration (Khalil *et al.*, 2021). *T. undulata* in turn is characterized by a very limited range (Mushtaq *et al.*, 2021). The distribution of field samples is with the arid deserts of Thal and Cholistan whereby the GBIF points are scattered.

This restricted distribution accentuates the specialization to harsh conditions of high temperatures, extreme aridness and low precipitation. All these spatial patterns are indicative of unique ecological solutions: *V. nilotica* as a ubiquitous generalist, *D. sissoo* as a riparian hydrophilic, and *T. undulata* as a desert-adapted xerophytic.

Trait–occurrence correlations (R): Pearson correlation analysis was used to determine the correlations between morphological characteristics and species occurrence (Table 3). The correlation analysis showed that morphological characteristics generally had weak relationships with species occurrence. The correlations for *V. nilotica* were low and non-significant ($r = -0.037$), meaning that the environmental factors like water availability and the soil conditions were the two most dominant factors in its occurrence (Samie *et al.*, 2020). *D. sissoo* showed a stronger relationship with leaf characteristics, exhibiting a weak positive correlation between leaf area and occurrence ($r = 0.094$, $p = 0.035$). This suggests that larger leaves have an advantage in a moist riparian habitat. In the case of *T. undulata*, a significant but weak correlation between stem diameter and occurrence was observed ($r = 0.128$, $p = 0.013$), suggesting that greater stem diameter may be weakly associated with occurrence under dry conditions. Morphological traits therefore showed limited explanatory strength, while climatic and hydrological factors remained the dominant controls (Mathur *et al.*, 2023).

Table 3. Pearson correlations between species occurrence (1/0) and morphological traits.

Species	Trait	r	p-value
<i>Vachellia nilotica</i>	Tree height	−0.029	0.520
	Tree diameter	−0.033	0.467
	Leaf length	−0.035	0.435
	Leaf width	−0.018	0.685
	Leaf area	−0.037	0.413
<i>Dalbergia sissoo</i>	Tree height	0.006	0.895
	Tree diameter	0.026	0.555
	Leaf length	0.074	0.100
	Leaf width	0.087	0.053
	Leaf area	0.094	0.035
<i>Tecomella undulata</i>	Tree height	0.048	0.354
	Tree diameter	0.128	0.013
	Leaf length	0.017	0.742
	Leaf width	0.012	0.810
	Leaf area	0.039	0.449

Significance codes: “*” $p < 0.05$; “.” $p < 0.10$; n.s. = Not significant

Figure 4 demonstrates the distribution trends of the key morphological characteristics of the species through the use of histograms and boxplots (Khalil *et al.*, 2021). The histograms of density curves and box plots are used to show the distribution of the main morphological characteristics of the trees. The height of all trees (left) is moderately skewed to the right, with most trees ranging from 15 to 25 meters, and a few larger trees indicating a prevalence of medium-sized trees. Diameter (middle) also has a skewed distribution, with most stems having a diameter of 2m and fewer thick stems, as indicated by the long tail and boxplot outliers. Leaf area (right) is highest at moderate values, indicating slight variation and functional uniformity. These distributions are characterized by populations whose members are mostly of medium size with stable leaf characteristics, typical of semi-arid and riparian environments.

Habitat suitability mapping (ArcGIS + MaxEnt): Figure 5 presents the current and future habitat suitability of *V. nilotica* based on the MaxEnt model. Under current climatic conditions, the species shows a concentrated zone of high suitability in Pakistan and adjoining northwestern parts of the Indian subcontinent. The yellow suitability area indicates that *V. nilotica* currently occupies climatically favorable habitats, mainly associated with semi-arid and irrigated landscapes where seasonal moisture and moderate environmental stress support its growth. The future projection shows that the suitable habitat remains broadly located within the same geographic region, but the suitability surface becomes more spatially variable. Some parts of the currently suitable area appear to shift toward lower or mixed suitability classes, suggesting that future climatic changes may cause local fragmentation or reduction in habitat quality. However, the continued presence of suitable zones indicates that *V. nilotica* may retain a relatively stable core distribution due to its ecological tolerance and adaptability to semi-arid conditions. Overall, the model suggests that *V. nilotica* is likely to remain a comparatively climate-resilient species in the study region, although peripheral habitats may become vulnerable under future climate change. Conservation and management efforts should therefore focus on maintaining core suitable habitats, supporting agroforestry use, and monitoring marginal populations that may be affected by increasing temperature and changing precipitation patterns (Ullah *et al.*, 2022). The persistence of core suitable areas indicates comparatively broad climatic tolerance, while marginal habitats should remain a priority for monitoring and adaptive management.

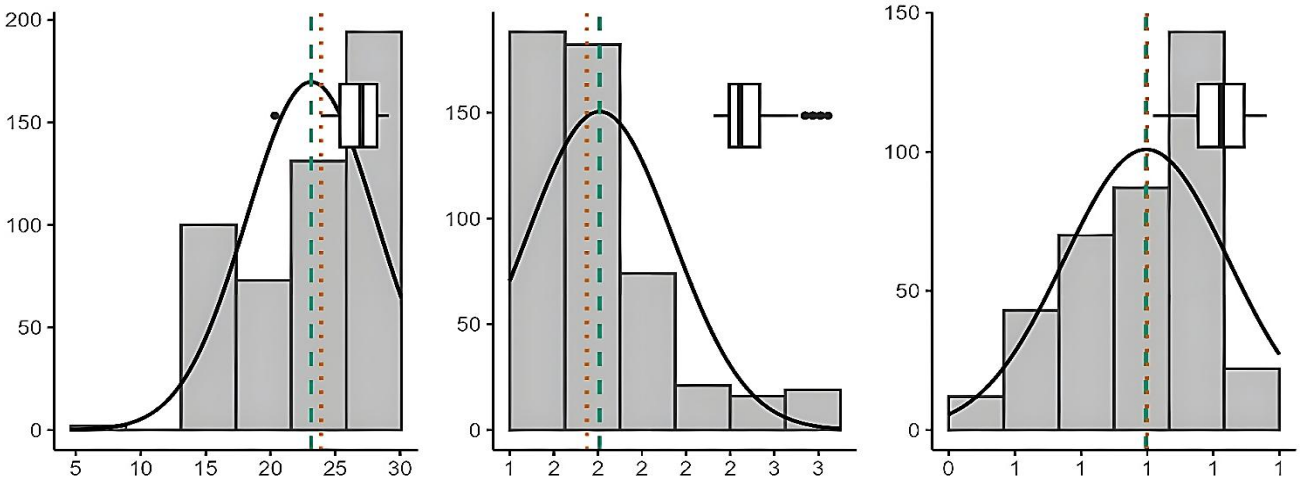


Fig. 4. Distribution of tree morphological traits with density curves and boxplots.

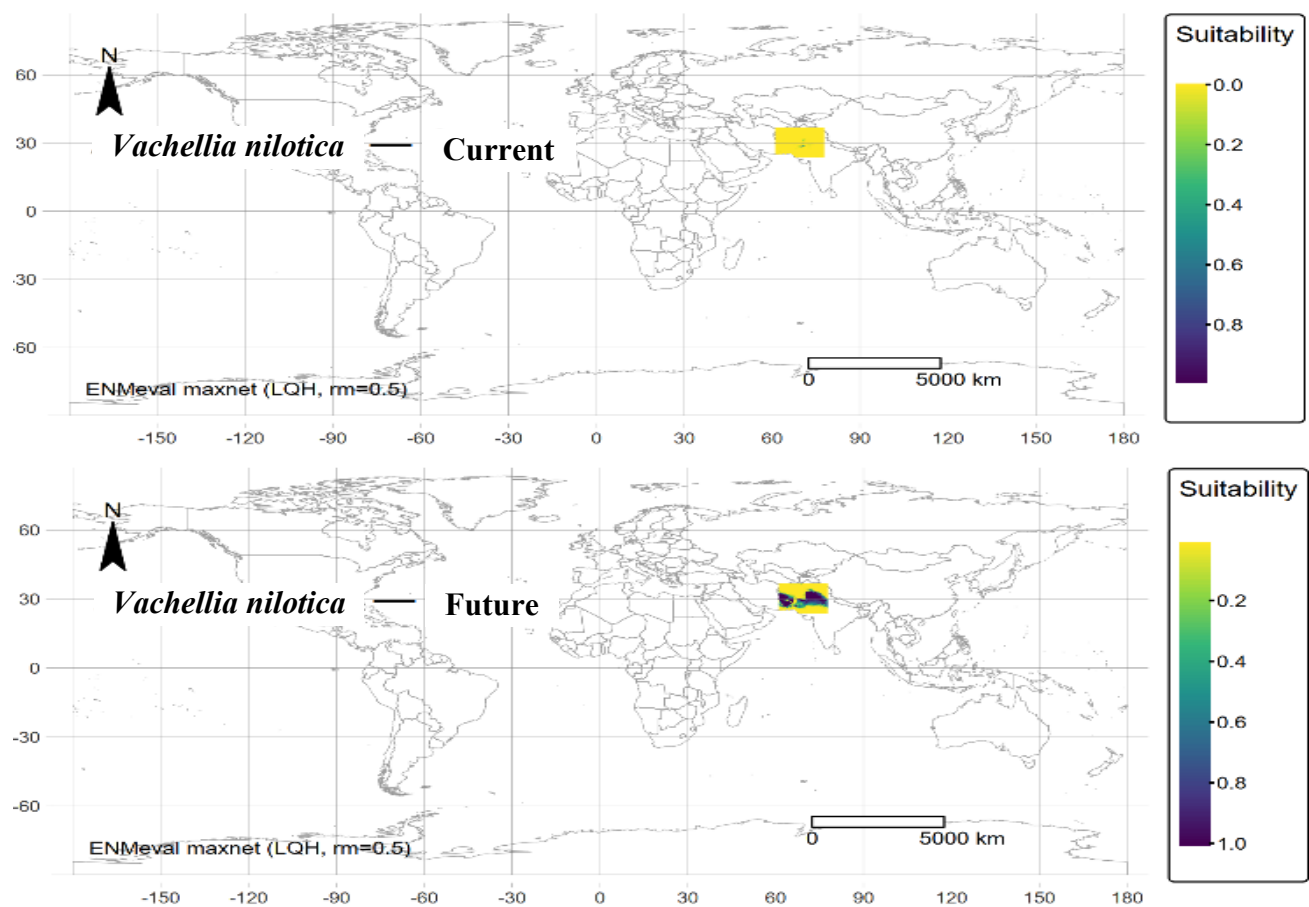


Fig. 5. Current and future habitat suitability of *Vachellia nilotica* (MaxEnt Model).

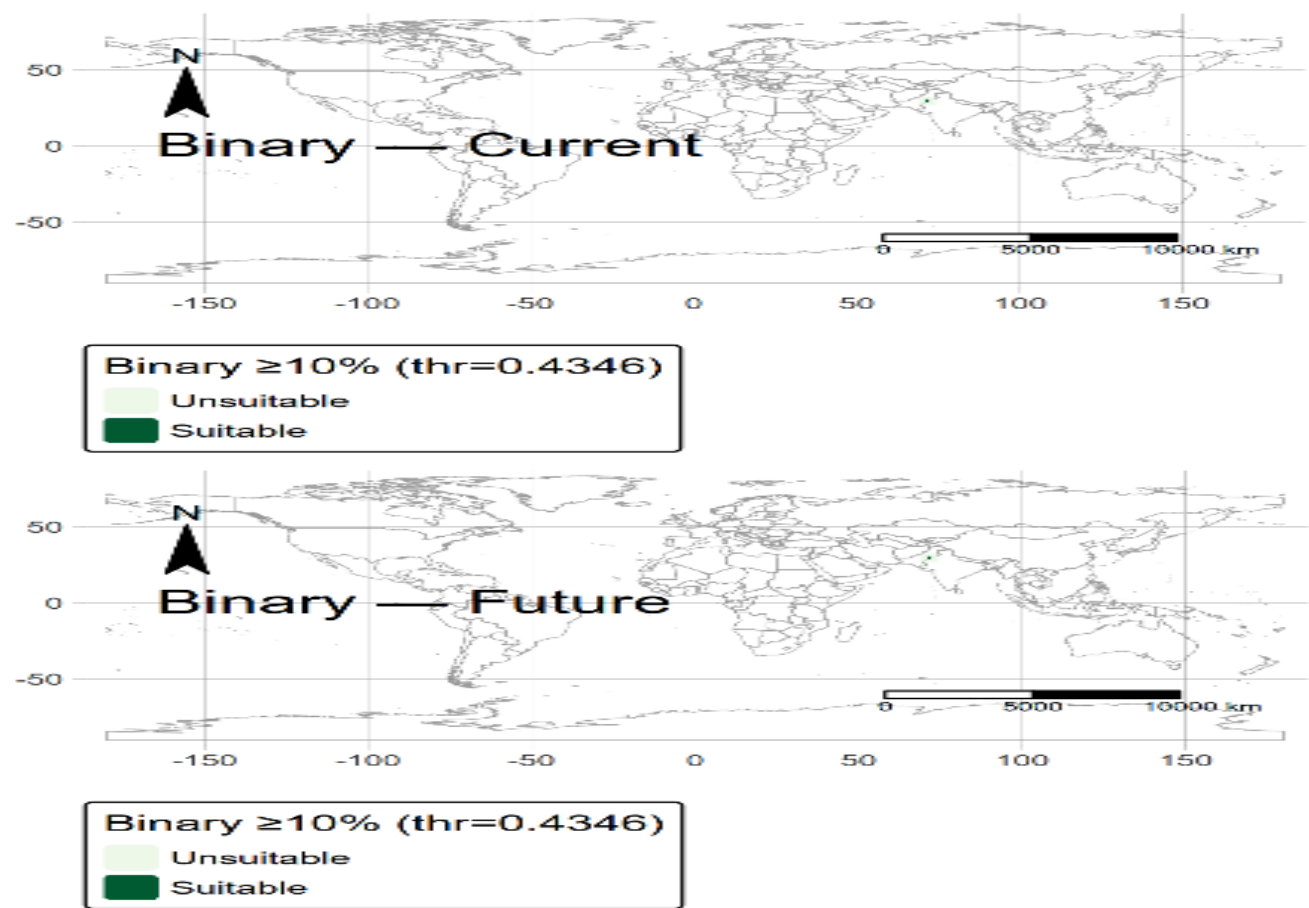


Fig. 6. Current and future habitat suitability of *Tecomella undulata* (MaxEnt Model).

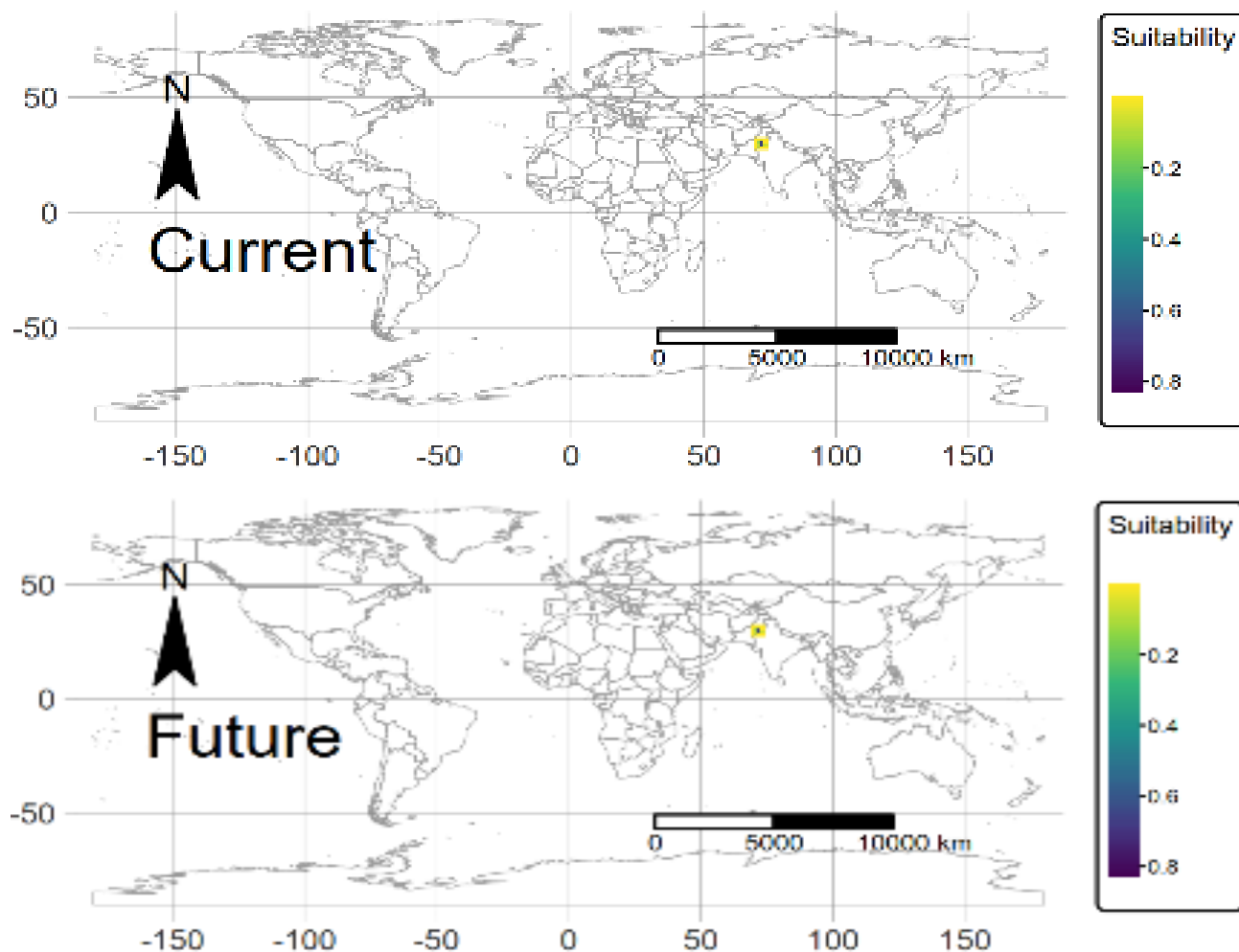


Fig. 7. *Dalbergia sissoo* habitat suitability under current and future climates.

The current and future patterns of habitat suitability of *T. undulata* reveal that it has a limited distribution in arid and semi-arid areas (Fig. 6). Under current climatic conditions, *T. undulata* has a restricted distribution in arid areas of southern Pakistan and adjoining northwestern parts of the Indian subcontinent, according to the habitat suitability maps. This distribution is consistent with its persistence under high temperature and low moisture conditions. Future projections show that suitable regions remain relatively localized, with very limited spatial expansion. Protection of arid habitats, sustainable land use, assisted regeneration, and site-specific conservation will therefore be important for maintaining populations under future climatic conditions.

The current and future patterns of habitat suitability of *D. sissoo* reveal suitability concentrated around riparian and water-supported areas (Fig. 7). Future projections show relatively limited spatial variation, suggesting that suitable habitat is likely to persist mainly along river and canal networks. Riparian protection, sustainable land use, and water management will therefore be important for maintaining suitable habitat in the long term. Under current climatic conditions, *D. sissoo* shows a restricted distribution around northern India and southern Pakistan according to the habitat suitability maps, consistent with its association with riparian and sub-humid environments with adequate moisture and fertile soils.

Discussion

Model accuracy and key environmental predictors:

The MaxEnt models demonstrated very high predictive performance for all three target species, with AUC values consistently above 0.98. *V. nilotica* showed the highest AUC value, followed by *T. undulata* and *D. sissoo*. These results indicate strong discrimination between suitable and unsuitable habitats and suggest that the selected environmental predictors captured the main ecological gradients influencing species distribution in Southern Punjab. The jackknife analysis further confirmed that climatic variables, particularly temperature and precipitation-related predictors, played a dominant role in determining habitat suitability.

However, the exceptionally high AUC values, especially the value recorded for *V. nilotica*, should be interpreted with caution. Very high AUC values can sometimes occur when models are trained on geographically localized datasets or when occurrence records are spatially clustered. In such cases, the model may partly reflect spatial structure or sampling selection rather than only true ecological suitability. Therefore, although the high AUC values indicate strong model performance, they may also suggest some possibility of spatial overfitting.

To minimize this risk, the study applied spatial thinning of occurrence records, bias correction using target-group background points, and spatial block cross-validation. These steps were used to reduce spatial autocorrelation and improve the transferability of the models. Spatial block cross-validation was particularly important because it tested model performance across geographically separated blocks rather than relying only on randomly partitioned occurrence data. This approach helped ensure that the models were not simply reproducing local sampling patterns but were able to identify broader environmental suitability trends relevant to current and mid-century climate projections.

The environmental predictors identified in the models were consistent with the known ecology of the three species. *V. nilotica* showed wide responses across several variables, reflecting its generalist and semi-arid adaptive strategy. *D. sissoo* was more strongly associated with variables linked to moisture availability and thermal stability, consistent with its preference for riparian and canal-supported habitats. *T. undulata* showed stronger sensitivity to warm-season temperature and precipitation variables, supporting its status as a desert-adapted but climate-sensitive species. Overall, the model results indicate that temperature, precipitation, and moisture-related variables are the primary determinants of habitat suitability for these economically important tree species in arid and semi-arid landscapes (Safdar *et al.*, 2025).

Trait–occurrence relationships and ecological strategies: The trait–occurrence relationships observed in this study were generally weak, indicating that the measured morphological traits did not strongly explain the broad spatial distribution of the three target species. Although some weak positive associations were observed, such as leaf area in *D. sissoo* and stem diameter in *T. undulata*, these relationships were not strong enough to suggest that morphology alone determines species occurrence. Instead, the results indicate that species distribution in Southern Punjab is more strongly controlled by macro-climatic and hydrological variables, including temperature, precipitation, seasonal moisture availability, and proximity to water-supported habitats.

One reason for the weak trait correlations is the difference in spatial scale between the environmental predictors and the measured morphological traits. The climatic variables used in MaxEnt operate at a broad grid-based scale, while tree morphology often varies at much finer ecological scales, such as micro-topography, soil depth, groundwater access, canal proximity, local disturbance, and site-specific moisture conditions. As a result, important small-scale morphological responses may not be fully captured within the larger climatic grid cells used for distribution modelling.

Another possible explanation is phenotypic plasticity. Tree species may adjust leaf size, stem growth, or height in response to local environmental conditions without necessarily showing a strong relationship with regional occurrence patterns. This means that morphological traits may reflect local acclimation rather than broad-scale habitat suitability. In addition, woody species often show relatively conserved morphological characteristics because of genetic constraints and long generation times. Such

constraints may limit rapid morphological divergence even under climatic stress.

The weak trait–occurrence relationships should therefore not be interpreted as evidence that morphological traits are unimportant, rather their influence may be indirect, localized, and partly overshadowed by stronger climatic and hydrological controls. For example, *V. nilotica* appears to rely on broad ecological tolerance rather than a single dominant morphological trait. *D. sissoo* remains closely associated with riparian moisture conditions, where leaf traits may provide only a minor advantage. *T. undulata*, as a desert-adapted species, may depend more on drought tolerance and survival physiology than on externally measured traits alone.

Therefore, the weak correlations should not be interpreted as evidence that traits are unimportant, but rather that their effect may be indirect, subtle, or overshadowed by stronger climatic controls. Future studies incorporating physiological and reproductive traits may provide deeper insight into the ecological strategies of these species under climate change (Waheed *et al.*, 2025). These results are consistent with ecological opportunism of species: *V. nilotica* is a generalist and omnipresent, *D. sissoo* is a riparian and hydrophilic, and *T. undulata* is a xerophytic and less adaptable specialist.

Habitat suitability shifts and conservation implications:

It is projected that *V. nilotica* will maintain its main distribution in a core part of southern Punjab and Indus Basin areas, while peripheral habitats may become fragmented with rising temperatures and increasing monsoon variability. *D. sissoo* exhibits persistent habitat suitability along riparian margins, indicating relative persistence under future climatic conditions. There is the likelihood that *T. undulata* will have a slight contraction of its habitat and minimal expansion, which highlights its susceptibility to climatic changes. Species conservation plans must thus be species-focused: focus on agroforestry and core-habitat preservation for *V. nilotica*, water management and riparian recovery for *D. sissoo*, and site-specific conservation, including dune stabilization, assisted regeneration, and ex-situ conservation of *T. undulata*. These specific strategies will contribute to climate-sensitive afforestation and biodiversity protection of the semi-arid and arid ecosystems in Pakistan (Stuart *et al.*, 2021).

Conclusions

The study combined the MaxEnt modeling, ArcGIS mapping, and trait analysis to determine the suitability of the habitat of *V. nilotica*, *D. sissoo*, and *T. undulata* in Southern Punjab. Models performed very well (AUC > 0.98), indicating strong climatic controls on distribution. *V. nilotica* was characterized as a semi-arid generalist, *D. sissoo* a riparian-reliant species, and *T. undulata* a climate-sensitive desert specialist. The drivers of temperature and precipitation were predominant, with only limited influences of trait factors. Future projections suggest that *V. nilotica* may become more localized and fragmented at its margins, *D. sissoo* will remain concentrated along watercourses, and *T. undulata* will remain restricted and potentially vulnerable. Management should prioritize climate-responsive agroforestry, ecosystem recovery, and species-specific

conservation strategies, including dune stabilization and ex-situ conservation. This integrated approach provides species-specific information to guide adaptive afforestation, ecosystem restoration and climate-resilient forestry planning in the arid and semi-arid regions of Pakistan, although there are certain limitations in the data.

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Availability of Data and Materials: Species-occurrence data in the current study were gathered through field surveys in Southern Punjab (March to June 2023), Punjab Forest Department and Global Biodiversity Information Facility. Climatic variables (BIO1–BIO19) were obtained in WorldClim v2.1 and topographic data were obtained in the SRTM digital elevation model. The national and provincial geospatial sources provided land use, soil and hydrological layers. All the processed datasets on which the MaxEnt modelling and the GIS analysis have been performed are available from the corresponding author on request. The Punjab Forest Department data is not publicly available, because of institutional data-sharing restrictions.

Author’s Contributions: Hamna Asif collected and analyzed the data and wrote the original manuscript. Muhammad Jamil conceptualized and supervised the study. Both authors approved the final version of the manuscript.

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