DOI: 10.29050/harranziraat.1740997
Harran Tarım ve Gıda Bilimleri Derg. 2025, 29(3): 529-548.

Research Article/Araştırma Makalesi

Climate change will increase the habitat suitability of *Bidens frondosa* L. in Türkiye: Implications for future invasion and management

Türkiye'de Bidens frondosa L.'nın iklim değişikliğine bağlı artan dağılımı: Gelecekteki istila ve yönetim için çıkarımlar

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To cite this article:
Farooq, S. (2025). Climate Change Will Increase the Habitat Suitability of Bidens frondosa L. in Türkiye: Implications for Future Invasion and Management. Harran Tarım ve Gıda Bilimleri Dergisi, 29(3): 529-548.

DOI: 10.29050/harranziraat.1740997

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Received Date:
12.07.2025
Accepted Date:
21.08.2025

ABSTRACT

Bidens frondosa (Devil's beggarticks) is an invasive plant species originating from North America, which poses significant ecological and economic risks across its introduced range. The species is present in Türkiye; however, its future spread has not been modeled yet. Therefore, this study predicted habitat suitability for *B. frondosa* in Türkiye under current and future climate scenarios utilizing the Maximum Entropy (MaxEnt) model. The mode was trained and tested using 7,646 occurrence records and 8 environmental variables. The model predicted the habitat suitability with high accuracy (AUC = >0.9). The model predicted that moisture availability in the driest quarter will be the critical determinant of habitat suitability under current and future climatic conditions. Model projected that B. frondosa could colonize 56% of Türkiye's terrestrial area under current climate with significant suitable habitats located in the northern and western areas of the country. Future climate predictions indicate that the species will extend its distribution range, especially under the high-emission SSP5-8.5 scenario, with a predicted movement towards the eastern and southern regions of the country. The findings highlight potential ecological consequences of *B. frondosa* invasion, especially its competition with native plant species and its risk to agriculture. Proactive management techniques, including climate-smart invasive species eradication, are crucial to minimize projected expansion and preserve Türkiye's biodiversity and agricultural economy.

Key Words: *Bidens frondosa*, Climate change, Habitat suitability modeling, Invasive species, Maximum Entropy (MaxEnt) model

ÖZ

Bidens frondosa (Devil's beggarticks), Kuzey Amerika kökenli bir istilacı bitki olup taşındığı bölgelerde önemli ekolojik ve ekonomik riskler oluşturmaktadır. Bu tür Türkiye'den rapor edilmiş; ancak gelecekteki potansiyel yayılımı henüz modellenmemiştir. Bu nedenle, mevcut çalışmada, Maksimum Entropi (MaxEnt) modeli kullanarak mevcut ve gelecekteki iklim senaryoları altında Türkiye'de *B. frondosa*'nın potansiyel habitat uygunluğu tahmin edilmiştir. Model, 7.646 varlık kayıtları ve 8 çevresel değişken kullanılarak eğitilmiş ve test edilmiştir. Model, habitat uygunluğunu yüksek doğrulukla tahmin etmiştir (AUC = >0.9). Ayrıca, en kuru çeyrekteki nem miktarının, mevcut ve gelecekteki iklim koşulları altında habitat uygunluğunun belirleyici faktörü olacağı öngörülmüştür. Model, *B. frondosa*'nın mevcut iklim altında Türkiye'nin kara yüzey alanının %92'sini kolonize edebileceğini ve ülkenin kuzey ve batı bölgelerinde önemli uygun habitatların bulunduğunu tahmin etmiştir. Gelecekteki iklim tahminleri, türün, özellikle yüksek emisyon senaryosu (SSP5-8.5) altında, doğu ve güney bölgelerine doğru yayılacağını göstermektedir. Bulgular, *B. frondosa* istilasının ekolojik sonuçlarını, özellikle yerli bitki türleriyle olan rekabetini ve tarım üzerindeki risklerini vurgulamaktadır. İstilacı türlerin iklim dostu yönetimi gibi proaktif yönetim teknikleri, öngörülen yayılımı en aza indirmek ve Türkiye'nin biyolojik çeşitliliğini ve tarım ekonomisini korumak için büyük önem taşımaktadır.

Anahtar Kelimeler: *Bidens frondosa*, İklim değişikliği, Habitat uygunluk modeli, İstilacı türler, Maksimum Entropi (MaxEnt) modeli

Introduction

Certain plant species hosted by the country's flora can thrive inside or outside agricultural areas and could prove harmful. Currently, an estimated 1,600 to 1,800 weed species are considered harmful globally. These plants reduce agricultural productivity and quality. Weeds are taxa that people come across during all stages of life (Üstüner & Tekbudak, 2025). *Bidens frondosa* L. (Devil's beggarticks) is an invasive annual species originating from North America (Abdullah et al., 2025; Popay, 2014). Currently, it has a global distribution with established populations in several European countries, parts of Asia and North Africa, Australia, and New Zealand (Coşkunçelebi et al., 2007; Danuso et al., 2012; Gladunova et al., 2016; Khapugin et al., 2022; Pan et al., 2016). It primarily invades moist, nutrient-dense environments, including riverbanks, lakeshores, ditches, and disturbed wetlands. Furthermore, it is often observed along roadsides or the edges of rivers and lakes (Popay, 2014; Qureshi & Anwar, 2025). Extensive spread and invasion of the species can be attributed to abundant seed production (Brändel, 2004; Ronzhina, 2017; Yan et al., 2016) and effective propagation (Cao et al., 2018). Thorny seeds attach to animals and people and float on water, which facilitate extensive dispersal (Brändel, 2004; Popay, 2014). A significant portion of the seeds (40–65%) may retain viability (Popay, 2014), which aggravate invasion.

Bidens frondosa invasion has severe ecological consequences as it displaces native flora including its congener *B. tripartite* (Vasilyeva & Papchenkov, 2011). Superior competitive ability of *B. frondosa* decreases habitat availability for native species, resulting in loss of biodiversity in invaded wetlands, river valleys, and meadows (Gladunova et al., 2016; Khapugin et al., 2022; Ronzhina, 2017; Vasilyeva & Papchenkov, 2011; Yan et al., 2016). Rapid range expansion allows *B. frondosa* to monopolize essential resources like light, water, and nutrients, limiting the establishment of native flora (Khapugin et al., 2022; Ronzhina, 2017). Furthermore, *B. frondosa* exploits its allelopathic potential for competitive superiority (Wang et al., 2014). Consequently, the rapid spread and widespread colonization of *B. frondosa* poses substantial risks to the integrity of wetlands and riparian ecosystems; hence, increasing concerns for conservation efforts.

In addition to ecological consequences, *B. frondosa* invades agricultural lands and reduces crop yields (Kim et al., 2011; Rho & Lee, 2004; Sharma & Singh, 2000; Umurzokov et al., 2024). It has invaded several agricultural regions of Belgium and Italy, becoming a weed in maize, sugar beet, and rice fields (Popay, 2014). The species competes with crops for nutrients and space, reducing yields and increasing management expenses (Pan et al., 2017; Wei et al., 2017). *Bidens frondosa* invades rice fields and irrigation canals in Asia, with models indicating that uncontrolled infestations may lead to production losses and necessitate increased weed management efforts (Kim et al., 2011; Umurzokov et al., 2024).

Biological invasions and climate change are regarded as significant threats to global biodiversity (Hulme, 2017; Roy et al., 2023). These elements of global change may interact to amplify their impact as climate change could enhance the invasive potential of species (Bosch-Belmar et al., 2024). Rising temperatures, altered precipitation patterns, and an increase in extreme weather events may facilitate the establishment and spread of invasive species in regions that were previously inhospitable (Lawlor et al., 2024). Recent study suggested that climate change could increase the invasiveness of *B. frondosa* and similar species by modifying their growth patterns and phenology (Xiao et al., 2025). Experimental warming enhanced the reproductive output of *B. frondosa* and extend its flowering duration, providing it with a competitive edge over less adaptable native species (Cao et al., 2018). Habitat suitability models predicted that *B. frondosa* will expand its distribution under climate change (Xiao et al., 2025). Climate change may open new opportunities for *B. frondosa* to invade areas in Europe and Asia, including Anatolia, that are currently too cold but may become suitable in the coming decades.

Although *B. frondosa* is a relatively recent invader in Türkiye (Coşkunçelebi et al., 2007), it is already displaying traits of a troublesome invasive species (Tad et al., 2015). It was first reported in 2007 from northeastern Black Sea region and surveys conducted less than a decade after its initial report revealed that it had established substantial populations across the Eastern and Central Black Sea regions, extending from Trabzon to Artvin and advancing 40–50 km inland in several areas (Tad et al., 2015). The Black Sea coastal zone, characterized by significant rainfall and abundant waterways, provides ideal conditions for *B. frondosa*, which is now prevalent in multiple locations within the area. *Bidens frondosa* has increasingly invaded agricultural lands and orchards, with reports of its spread in hazelnut groves, kiwi orchards, and vegetable fields along the Black Sea coast (Karaköse et al., 2018; Terzioğlu & Ergül Bozkurt, 2020). The cultivation of these crops, particularly hazelnuts, is of significant economic importance to Türkiye (Temizyurek-Arslan, 2023), and a widespread invasion of *B. frondosa* could result in substantial economic costs. Dense infestations in agricultural peripheries may inhibit crop growth and reduce yields. Although *B. frondosa* has not yet emerged as a major agricultural pest, its presence in key crop-producing regions highlights a potential threat to agriculture, highlighting the need for proactive control measures.

Species distribution models (SDMs) are widely employed tools in ecological research, utilized to predict the potential geographic distribution of species based on environmental variables and species occurrence records (Elith & Leathwick, 2009). Among various SDM algorithms, Maximum Entropy (MaxEnt) modeling is extensively favored due to its robustness, accuracy, and effectiveness in predicting distributions from limited presence-only data (Merow et al., 2013; Phillips et al., 2006). MaxEnt models generate informative and reliable habitat suitability maps, offering valuable insights into potential species invasions under current and future climatic conditions.

Bidens frondosa could spread beyond the Black Sea region, posing a significant threat to Türkiye under changing climate. The ability of the species to thrive in various microhabitats suggests that it has the potential to colonize a wide range of niches throughout the country. Global warming may further increase the susceptibility of regions outside the humid Black Sea area to invasion. Nevertheless, the species may silently expand into these regions, much as it did along the Black Sea coast without intervention. In response to these concerns, this study assessed the habitat suitability of *B. frondosa* in Türkiye under both current and future climatic conditions (SSP1-2.6 and SSP5-8.5 scenarios) by employing MaxEnt model. This approach identified potential invasion "hotspots" that may become vulnerable to invasion. The comprehensive risk mapping generated by this study provides valuable insights into early warning systems and the development of targeted management strategies.

Materials and Methods

Species Occurrence Data

Occurrence records for *B. frondosa* were retrieved from the Global Biodiversity Information Facility (GBIF). A total of 66,335 occurrence records were initially obtained from GBIF database (GBIF, 2022). The collected data covered the species’ native and introduced range, ensuring that model calibration included the full environmental spectrum of *B. frondosa*. Afterwards, rigorous data cleaning was performed to improve accuracy and minimize geographic sampling bias. Records lacking coordinates or exhibiting evident geolocation errors were eliminated. Duplicate data (e.g., multiple entries from the same place) were eliminated, and spatial thinning was used to retain just one occurrence per cell. This spatial filtering reduces model overfitting to record clusters by ensuring a more uniform representation across space (Chapman, 2005). Following the cleaning and thinning process, 7,646 unique occurrence records were retained for modeling.

Environmental Predictors

Nineteen bioclimatic variables (Bio1–Bio19) were obtained from the WorldClim v2.1 global climate database as environmental predictors (Fick & Hijmans, 2017). These bioclimatic variables are extracted from monthly temperature and precipitation data, reflecting yearly trends, seasonality, and extreme conditions (e.g., annual mean temperature, temperature of the coldest month, precipitation seasonality, etc.). WorldClim climatic norms from 1970 to 2000 were used as a historical baseline, with a spatial resolution of 30 arc-seconds (about 1 km^2). The use of high-resolution (~1 km) climate dataset allowed to capture precise environmental variability relevant to the habitat requirements of *B. frondosa*. Before modeling, multicollinearity among variables was assessed using correlation analysis. Strongly correlated variables with a correlation coefficient of more than 0.7 were eliminated. The environmental variables with the least correlation were bio2 (mean diurnal range), bio4 (temperature seasonality), bio8 (mean temperature of the wettest quarter), bio9 (mean temperature of the driest quarter), bio15 (precipitation seasonality), bio16 (precipitation of the wettest quarter), bio17 (precipitation of the driest quarter), and bio18 (precipitation of the warmest quarter). The correlation among these environmental variables is given in Figure 1.

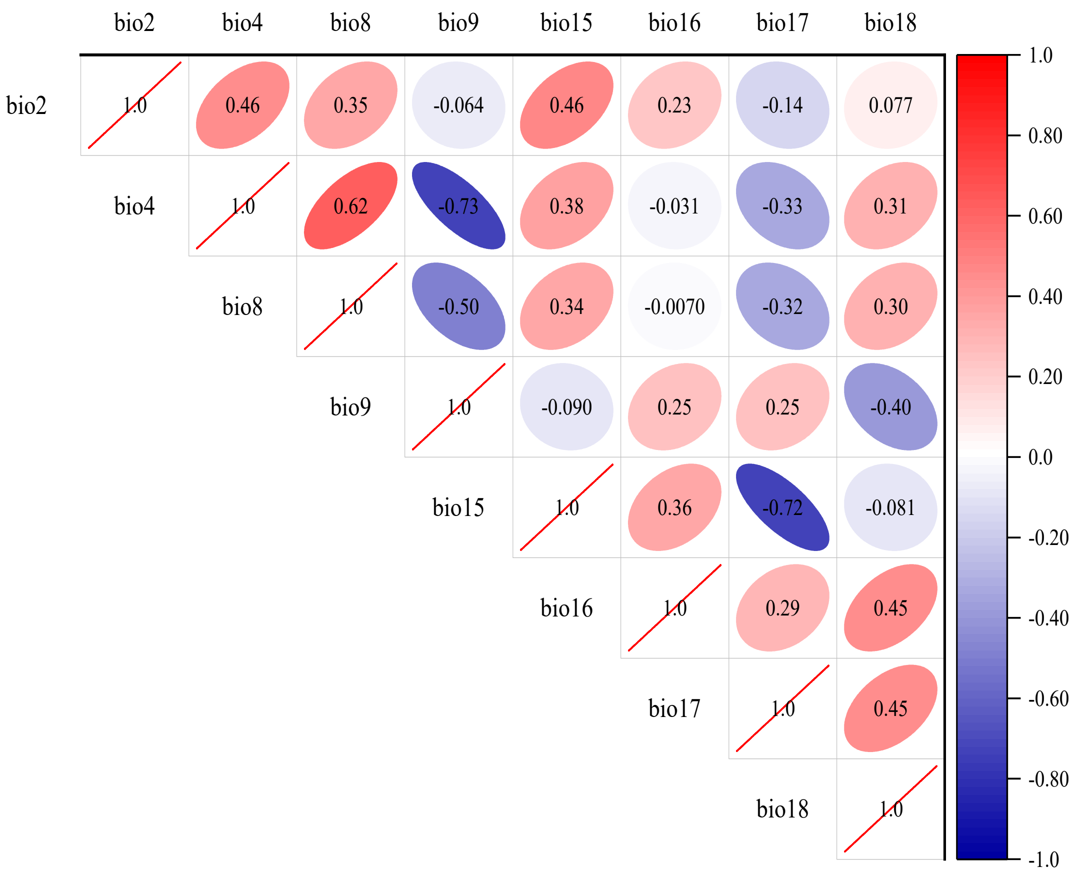

Figure 1. Correlation among the environmental variables used to predict the habitat suitability of *Bidens frondosa* in Türkiye

Climate Projections

Future data of the environmental variables used to predict the habitat suitability under current climate were collected from WorldClim based on the Coupled Model Intercomparison Project Phase 6 (CMIP6). Future climate data generated by BCC-CSM2-MR general circulation model was used in the study. Two future emissions scenarios, i.e., SSP1-2.6 (a low-emissions, climate-mitigating trajectory) and SSP5-8.5 (a high-emissions, "business-as-usual" trajectory), which delineate the lower and upper bounds of anticipated radiative forcing by 2100 were included in the study. Bioclimatic variables were acquired for each scenario for four future time intervals centered on the midpoints of 2030, 2050, 2070, and 2090. The 20-year intervals correspond to 2021–2040, 2041–2060, 2061–2080, and 2081–2100, respectively. Future climate data was also downloaded at 30 arc-second resolutions to align with present climate data. The future bioclimatic layers from BCC-CSM2-MR were used as input for the MaxEnt model to forecast habitat suitability for each scenario and time period. This approach enabled to analyze both near and late-century changes in suitable habitat in Türkiye. All future climate rasters were standardized to align with the coordinate system, resolution, and extent of the existing climate data for accurate model projection.

MaxEnt Modeling and Calibration

Maximum Entropy approach (MaxEnt) was used to simulate the potential geographical distribution of *B. frondosa* in Türkiye (Phillips et al., 2006). MaxEnt is especially successful for presence-only data and is known for its strong predicting ability with restricted or biased occurrence data (Yackulic et al., 2013). The model was trained on a global scale, using 7,646 clean occurrences with 8 environmental layers. The training included species' actual environmental niche throughout its native and invasive ranges, which is crucial for forecasting its potential spread in new areas. MaxEnt software (version 3.4.4) was used with 5000 iterations and 10,000 background points randomly selected from the training area. A comprehensive parameter optimization process was followed to mitigate overfitting and enhance model complexity (Radosavljevic & Anderson, 2014). The 'kuenm' R package (Cobos et al., 2019) was used to construct and assess various candidate models utilizing distinct feature class combinations and regularization multipliers. Tested feature classes (FC) encompassed linear (L), quadratic (Q), hinge (H), product (P), and threshold (T) features in diverse combinations (e.g., L, LQ, LQH, LQHP, etc.), while regularization multiplier (RM) values were adjusted (e.g., ranging from 1 to 5). Each candidate model was analyzed using a subset of occurrence data for calibration and a separate dataset for validation, while evaluating model performance and complexity. Akaike's Information Criterion modified for small sample sizes (AICc) was employed to identify the optimum model from the candidate set (Akaike, 1973). Model selection adhered to the principle of selecting the simplest model that adequately fits the data (Ding et al., 2018; Radosavljevic & Anderson, 2014). The model with the lowest delta.AICc (i.e., $\Delta AICc \approx 0$) was selected as the final model. The optimal model identified in the calibration procedure included a feature class combination of LQHP with a regularization multiplier of 5 (Figure 2). This configuration was considered optimum due to the smallest AICc, indicating an effective equilibrium between model fit and complexity, hence preventing overfitting. The final MaxEnt model was subsequently trained utilizing all occurrences with the optimized parameters.

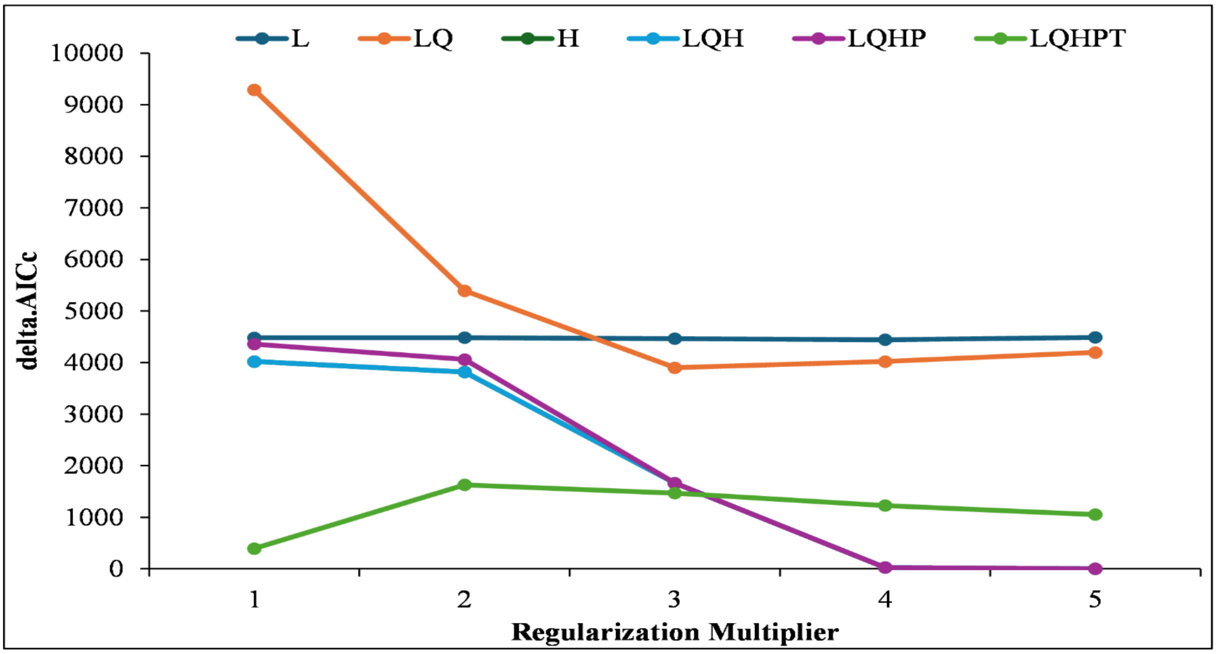

Figure 2. Delta.AICc values of different regularization multiplier values and feature class combinations used to optimize MaxEnt model

Software and Analysis Tools

The modeling exercise was conducted utilizing MaxEnt software (version v3.4.4) (Phillips et al., 2006). Data preparation, model optimization, and evaluation were conducted inside the R statistical environment (R Core Team, 2023). The 'kuenm' package (version 1.1.5) was utilized for automating MaxEnt calibration, model selection, and projection procedures (Cobos et al., 2019). Occurrence data were processed and refined utilizing SDMtoolbox for spatial thinning (Brown, 2014).

Habitat Suitability Classification

The continuous habitat suitability outputs from MaxEnt ranging from 0 to 1, indicating likelihood of occurrence were categorized into four ordinal categories for better understanding. This framework employs a threshold-based classification of the habitat suitability index (HSI) and aligns with categories utilized in similar invasive species investigations (Liu et al., 2025). A threshold, i.e., unsuitable (HSI = 0–0.2), moderately suitable (HSI = 0.2–0.4), suitable (HSI = 0.4–0.6), and highly suitable (HSI > 0.6) was developed for categorizing habitat suitability. The selection of 0.2 as a threshold for differentiating "suitable" from "unsuitable" habitat is a reasonable criterion, ensuring that only regions with a minimal level of the suitability are acknowledged. Higher categories divide the residual gradient into low-to-moderate, moderate, and high suitability. The reclassification was carried out using ArcGIS Spatial Analyst tools, generating binary masks for each category. These categorization maps enabled to measure and compare the magnitude of each suitability class under current and future conditions.

Spatial Analysis of Habitat Changes

Changes in habitat suitability of *B. frondosa* were analyzed by comparing the suitability maps of future scenarios with the current baseline. Future suitability maps were overlaid onto the current suitability to identify regions of habitat expansion, contraction, and stability for each future period and scenario. Habitat expansion is characterized as regions considered unsuitable (HSI < 0.2) that transition to any suitable category (HSI > 0.2) in a future scenario. Habitat contraction is characterized as regions presently classified as at least moderately appropriate (HSI > 0.2) that will become unsuitable (HSI < 0.2) in the future. M ap algebra procedure was employed to calculate these changes. Binary expansion and contraction maps were constructed for each scenario and time slice. The spatial extent (area in square kilometers) of each category was determined using Zonal Geometry tools and by tabulating pixel counts for each class. This facilitated the estimation of the potential gain or loss of suitable habitat for *B. frondosa* under various climate change scenarios. Furthermore, regional patterns of change by were determined by overlaying the expansion/contraction results onto the administrative boundaries of Türkiye to identify regions that may see the most significant increases or declines in suitability. All area assessments were conducted with the Cylindrical equal-area conic projection for Türkiye to ensure accurate area measurements.

Results and Discussion

Model Performance and Key Predictors

The MaxEnt model used to predict habitat suitability for *B. frondosa* achieved high prediction accuracy. The high AUC value (> 0.9) indicated its exceptional classification ability (Figure 3). Similarly, high True Skill Statistic (TSS) and Cohen's Kappa values indicated significant agreement between predicted and observed distributions (Figure 3). These metrics demonstrate that the model is reliable for predicting current and future habitat suitability of *B. frondosa*.

The Jackknife analysis indicated that moisture availability will be the primary factor influencing potential spread of *B. frondosa*. The contribution of precipitation during the driest quarter (bio17) to the model was 67.86% (Table 1), indicating that the species depends on adequate moisture during the driest quarter. Temperature seasonality (bio4, 11.82%) and the mean temperature of the driest quarter (bio9, 9.80%) were the other most important predictors, whereas other variables had comparatively little impacts (Table 1). Permutation importance emphasized the relevance of dry-quarter climate. Mean temperature of the driest quarter (22.41%), precipitation of the wettest quarter (20.94%), and precipitation of the driest quarter (14.63%) exhibited the highest permutation importance (Table 1). In conclusion, *B. frondosa* favors moist, disturbed habitats, growing in areas with moderate temperature variation and reduced severity of dry-season drought.

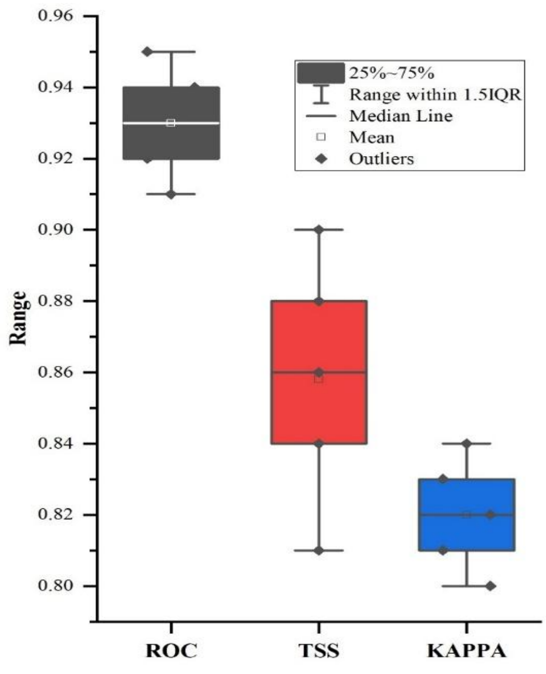

Figure 3. Evaluation metrics used test the predictive accuracy of Maxent model employed to predict the habitat suitability of *Bidens frondosa* in Türkiye. ROC = Area under the receiving operating characteristics curve, TSS = true skill statistics, KAPPA = Cohen's Kappa

Table 1. Contribution towards model training and permutation importance of the environmental variables used to predict the habitat suitability of *Bidens frondosa* in Türkiye employing MaxEnt model

Variable	Contribution to model (%)	Permutation Importance (%)
bio2 - mean diurnal range	0.22	1.76
bio4 - temperature seasonality	11.82	11.07
bio8 - mean temperature of the wettest quarter	4.76	16.47
bio9 - mean temperature of the driest quarter	9.80	22.41
bio15 - precipitation seasonality	0.99	4.58
bio16 - precipitation of the wettest quarter	4.06	20.94
bio17 - precipitation of the driest quarter	67.86	14.63
bio18 - precipitation of the warmest quarter	0.50	8.14

Model indicated that availability of moisture during the driest quarter will be a primary factor that restricts habitat suitability (Table 1). Earlier studies have indicated that *B. frondosa* mostly inhabits moist, disturbed habitats, including ditches, marshes, and rivers (Abdullah et al., 2025; Khapugin et al., 2022). Furthermore, modeling studies have indicated that moisture availability is the main variable influencing the spread of invasive plants in Mediterranean climates (Pfeifer-Meister et al., 2016; Wilson Brown & Josephs, 2023), which corroborates current results. Similarly, a study in Türkiye's Black Sea region indicated that *B. frondosa* is mostly located in areas with significant precipitation, particularly along to the coastline (Tad et al., 2015). Experiential data from environmental preference studies in Western Siberia and Europe indicated that *B. frondosa* colonizes open alluvial habitats, such as riverbanks and mudflats, favoring moist ground conditions (Khapugin et al., 2022). Climate change may offer both opportunities and challenges for *B. frondosa* invasion, influenced by regional precipitation patterns and the intensity of warming scenarios; however, current modeling approach indicated that moisture availability during the driest quarter will remain a crucial limiting factor for *B. frondosa* distribution in Türkiye.

Current Habitat Suitability Distribution

The model forecasted that *B. frondosa* may potentially colonize a significant part of Türkiye. The model simulations revealed that about 8.3% of the country's land area is unsuitable for the species under current climatic conditions. If dispersal constraints are overcome, 92% of the country's land area has a suitable climate for the establishment of *B. frondosa*. Quantitative analysis indicated that 42% of Türkiye (327.8 thousand km²) is suitable, whereas 14.3% (111.9 thousand km²) is classified as highly suitable for *B. frondosa* under current climate (Table 2). Given the importance of precipitation during the driest quarter, these optimum regions likely correspond to areas with more rainfall, such as parts of northern and western Türkiye. Figure 4 illustrates the geographical distribution of the current climatic niche of *B. frondosa*, mostly including river valleys, marshes, and humid coastal regions, characterized by moderate temperatures and significant precipitation.

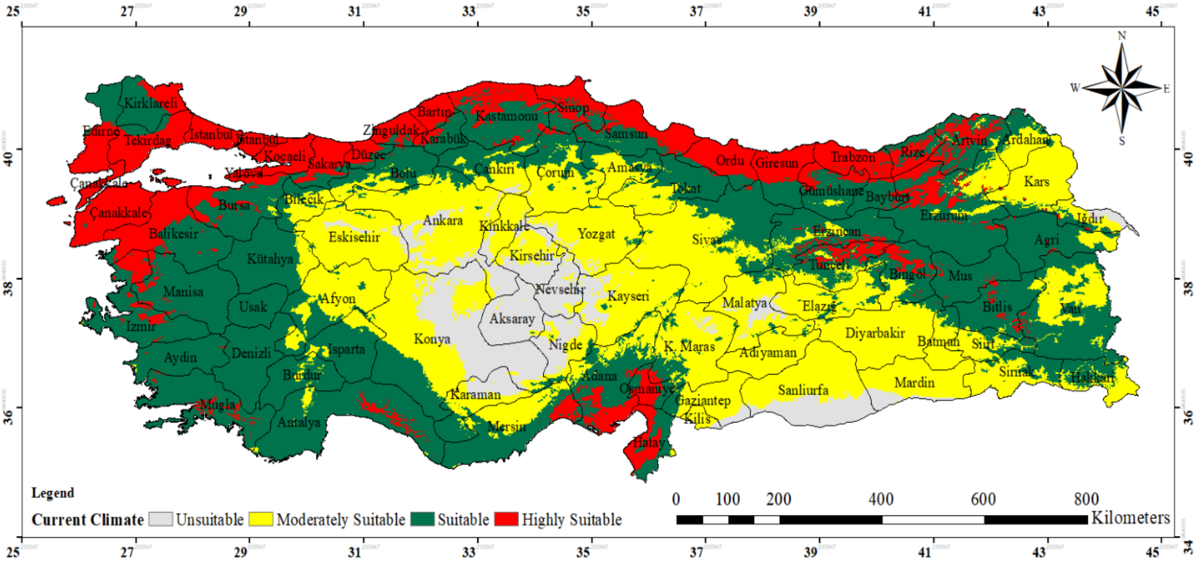

Figure 4. Habitat suitability of *Bidens frondosa* in Türkiye under current climatic conditions

Table 2. Area (km^2 and % of total land surface area) corresponding to different habitat suitability categories predicted by MaxEnt model for *Bidens frondosa* in Türkiye under current and future climatic conditions.

Habitat Suitability	Current	2021-2040	2041-2060	2061-2080	2081-2100
SSP1-2.6					
Unsuitable	64.3 (8.25)	62.3 (7.98)	75.0 (9.62)	33.8 (4.33)	91.3 (11.70)
Moderately Suitable	275.9 (35.38)	239.6 (30.73)	271.7 (34.84)	210.5 (26.99)	240.3 (30.81)
Suitable	327.8 (42.03)	375.4 (48.14)	307.0 (39.36)	329.2 (42.21)	288.1 (36.94)
Highly Suitable	111.9 (14.34)	102.6 (13.15)	126.2 (16.18)	206.4 (26.47)	160.3 (20.55)
SSP5-8.5					
Unsuitable	-	58.4 (7.49)	85.1 (10.91)	49.7 (6.37)	80.8 (10.37)
Moderately Suitable	-	198.1 (25.40)	226.9 (29.09)	228.0 (29.24)	244.7 (31.37)
Suitable	-	341.4 (43.77)	324.2 (41.57)	350.6 (44.95)	284.8 (36.52)
Highly Suitable	-	181.9 (23.33)	143.7 (18.42)	151.6 (19.44)	169.6 (21.74)

The values in parentheses represent the percentage of total land surface area

Projected Habitat Suitability Under Future Climates

The model predicted significant spatial and quantitative changes in the habitat suitability for *B. frondosa* in Türkiye under different future climate scenarios. Figure 5 illustrates the spatial distribution of habitat suitability, while Table 2 summarizes the changes in area for each suitability class. Both scenarios (SSP1-2.6 and SSP5-8.5) indicate that *B. frondosa* will maintain or expand its distribution in Türkiye, although with some temporal fluctuations.

Overall suitable areas are predicted to experience slight expansion during 2021-2040 under SSP1-26 scenario. The percentage of land classified as unsuitable will decrease to 7.98% (from the current 8.25%), while the suitable category is predicted to expand to 48.1% of the country (up from 42.0%) (Table 2). Nonetheless, the region of high suitability will suffer a little contraction in the short-term (to around 13.2% from the current 14.3%) (Table 2), indicating that while distribution range of *B. frondosa* may expand, some currently suitable regions may initially become less favorable. Habitat suitability will experience a slight contraction by mid-century (2041–2060). Unsuitable areas are predicted to increase to 9.62%, while the suitable areas contract to 39.4%, falling below the current baseline (Table 2). Significantly, the highly suitable areas will increase to 16.2%. The most significant growth is predicted during late 21st century (2061–2080), where only 4.33% of Türkiye is classified as unsuitable (a four-fold reduction from the present), and 26.5% of the land area is classified as highly suitable for *B. frondosa* (almost twice under current climate; Table 2). The aggregate of suitable and highly suitable areas during this period reaches 68.7% of the country, compared to 56.4% under current climate. The mid-late century increase under SSP1-2.6 suggests that moderate warming, together with possible increases in precipitation, creates more favorable circumstances over most of Türkiye. By the end of century (2081–2100), the model forecasts a minor contraction of highly suitable habitat under SSP1-2.6 compared to 2061-2080. Highly suitable areas will decrease to 20.6%, while unsuitable areas will increase to 11.7% (Table 2). In summary, the late-century climate under SSP1 may be somewhat less favorable than the optimal mid-century conditions. Nonetheless, *B. frondosa* will maintain a broader suitable range compared to the current climate. Figure 5 indicate that *B. frondosa* will expand into new regions of central and eastern Türkiye by mid-century, followed by a contraction in some places by 2100 when climatic conditions stabilize or slightly worsen.

Habitat suitability for *B. frondosa* is predicted to undergo significant changes under the high emission scenario (SSP5-8.5). Climate change will improve habitat suitability in several areas during 2021–2040. The highly suitable class is predicted to increase to 23.3% of the country from 14.3% under current climate (Table 2). This indicates that early-stage warming under SSP5-8.5 creates new ideal conditions, possibly by reducing cold limitations in some high-altitude or northern regions. The percentage of moderately suitable areas will decrease from 35.4% to 25.4%, with several regions transitioning from moderate to suitable or high suitability classifications (Table 2). The unsuitable area will decrease to 7.5% (little below the present level), suggesting a slight net range increase. Nevertheless, this tendency will reverse during mid-century (2041–2060). *Bidens frondosa* will experience a contraction in optimum habitat due to peak warming compared with 2021-2040. The proportion of highly suitable land will decrease to 18.4%, while the total unsuitable area will increase to 10.9%, passing the current baseline compared with 2021-2040 (Table 2). This mid-century decline indicates that increasing high heat and/or drought conditions under high emission scenario might exceed the plant's physiological tolerance in certain regions, rendering previously suitable habitats less hospitable. The model forecasted a recovering trend by the late century (2061–2080) where only 6.4% of land is considered unsuitable (the lowest level of unsuitability recorded in this scenario), while the suitable area reaches its peak (44.95%), and highly suitable area reach to 19.4% (Table 2). This late-century growth under high emission scenario indicates adaptation to continuously warmer conditions or changes in precipitation that enhance late-season moisture availability. The suitable range will diminish marginally by the end of century (2081–2100). Unsuitable regions are predicted to increase to 10.4%, while suitable areas will decrease (suitable = 36.5%, highly suitable = 21.7%) (Table 2). Habitat suitability is forecasted to experience more significant boom-and-bust cycles under high emission scenario, characterized by early expansion, mid-century contraction, and late-century re-expansion, while remaining broadly widespread. *Bidens frondosa* is projected to occupy a greater area in the high suitability category compared to the present climate under high emission scenario (21.7% against 14.3%). The projected habitat maps (Figure 5) show considerable expansion into new regions by 2040, a more fragmented distribution by 2060, and a continuation of extensive suitable areas (notably in the eastern and northern regions of Türkiye) by 2100.

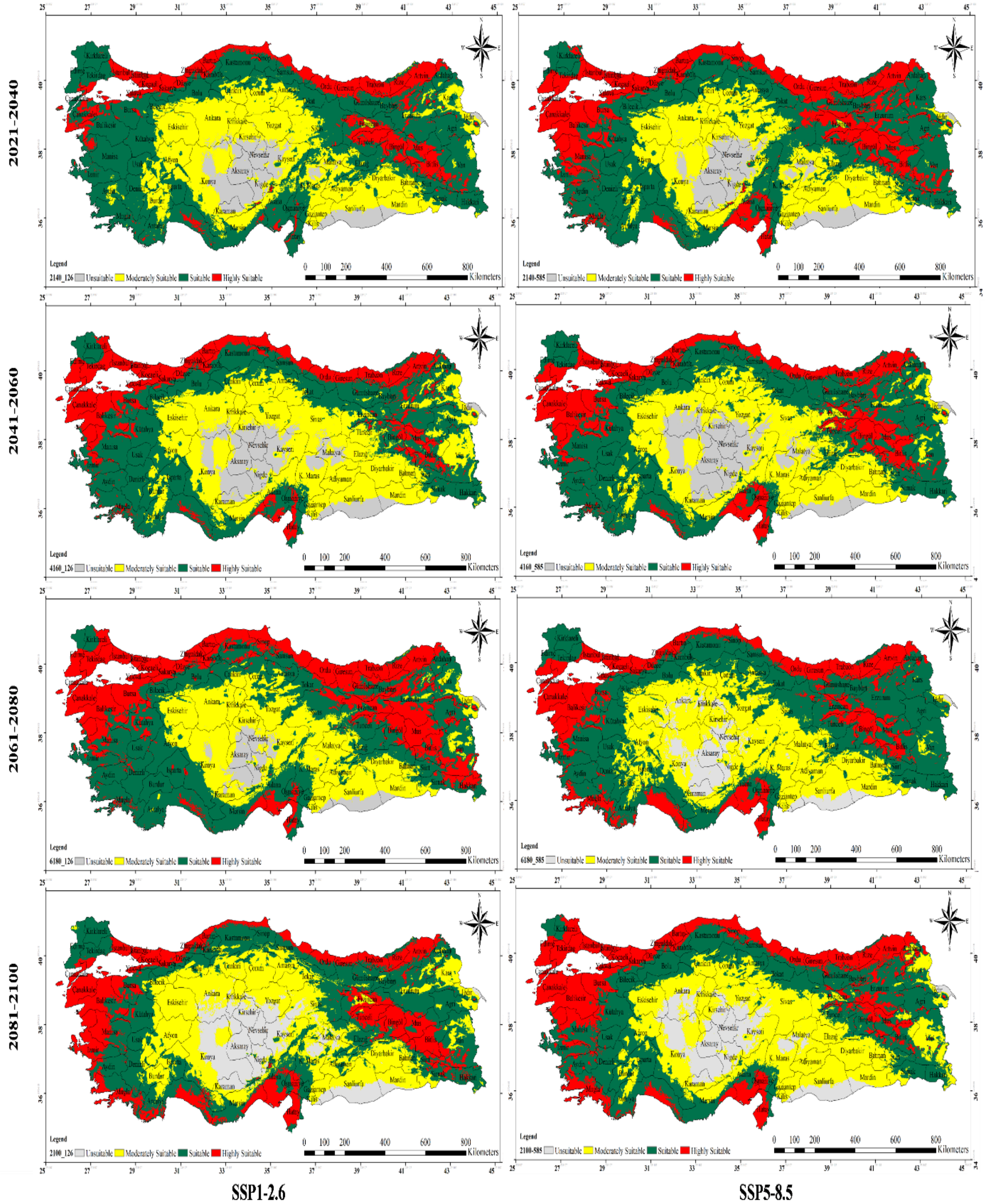

Figure 5. Habitat suitability of *Bidens frondosa* in Türkiye under future climatic conditions of Türkiye

Despite the changes in suitability classifications, a significant amount of *B. frondosa* habitat is projected to stay stable across time. Significantly, no regions currently classified as suitable transition to total unsuitable in any future scenario (the S→U transition is 0 km² for all times; Table 3). Similarly, none of the currently highly suitable regions are projected to become entirely unsuitable (HS→U = 0; Table 3). This suggests that fundamental climatic niche of *B. frondosa* in Türkiye, once established, tends to survive even under severe climate change. Most grid cells retain their current or a nearby suitability class when projected into the future. A significant portion of land that is moderately suitable in the present climate remains moderately suitable in each future period, about 175,000–203,000 km² under low emission scenario and 192,000–222,000 km² under high emission scenario (MS→MS in Table 3). Cells that are now suitable often continue to be suitable (S→S), with 230,000–272,000 km² maintaining that classification under SSP1 and somewhat reduced stable suitable areas (204,000–258,000 km²) under SSP5 (Table 3).

Table 3. Transition into the areas of different suitability categories under future climatic conditions

Transition	**SSP1-2.6**				**SSP5-8.5**			
U - U	51118	52995	32424	59408	47259	56114	41773	53464
U - MS	13218	11345	31914	4929	17075	8227	22563	10875
U - S	0	0	0	0	0	0	0	0
U - HS	0	0	0	0	0	0	0	0
MS - U	11135	22043	1362	31856	11173	28993	7892	27368
MS - MS	203310	222080	176820	192498	174705	195436	192361	204446
MS - S	60436	30392	95640	48604	87787	50244	73850	40889
MS - HS	1018	1379	2079	2940	2231	1225	1791	3184
S - U	0	0	0	0	0	0	0	0
S - MS	23078	38002	1727	42818	6341	23168	13110	29337
S - S	272026	257797	230339	204167	245550	250777	255389	232660
S - HS	0	31870	95607	80671	75778	53734	59153	65660
HS - U	0	0	0	0	0	0	0	0
HS - MS	32587	266	0	1	0	19	0	5
HS - S	42865	18668	3175	35231	7971	23128	21250	11167
HS - HS	68913	92877	108640	76587	103843	88663	90567	100643

Here U = unsuitable, MS = moderately suitable, S = suitable and HS = highly suitable

Some regions are predicted to expand to upper suitability categories throughout time. Several regions predicted unsuitable under current climate will become climatically suitable for *B. frondosa*, largely transitioning into the moderately suitable category. Under low emission scenario, 22,563 km² of currently unsuitable land is expected to change to moderate suitable by the late century (Table 3). No direct transitions from unsuitable to suitable or highly suitable were predicted in the model output, indicating that newly colonized regions often transitioned from moderate suitability. Furthermore, several regions currently categorized as moderately suitable are expected to improve to an upper suitability category. About 95,640 km² of currently moderately suitable areas will transition to suitable category during 2041–2060 under low emission scenario (Table 3), and around 2,079 km² of moderately suitable habitat will become highly suitable within this period. The relevant values are about 48,604 km² transitioning from moderate to suitable and approximately 2,940 km² from moderate to highly suitable by mid-century under high emission scenario. A substantial fraction of the area now considered suitable is expected to evolve into high-quality hotspots. By mid-century, 95,607 km² of land currently considered suitable is projected to become highly suitable under low emission scenario, and about 80,671 km² under high emission scenario (Table 3). This accounts for the substantial increase in highly suitable habitat seen in Table 2.

Figure 6 presents the temporal alterations in different habitat suitability classes, illustrating the trajectories of unsuitable, moderately suitable, suitable, and highly suitable categories under climate change. A significant increase in highly suitable habitat is expected under both scenarios, peaking in the mid to late 21st century, while the extent of unsuitable habitat remains relatively small, with only minor mid-century fluctuations.

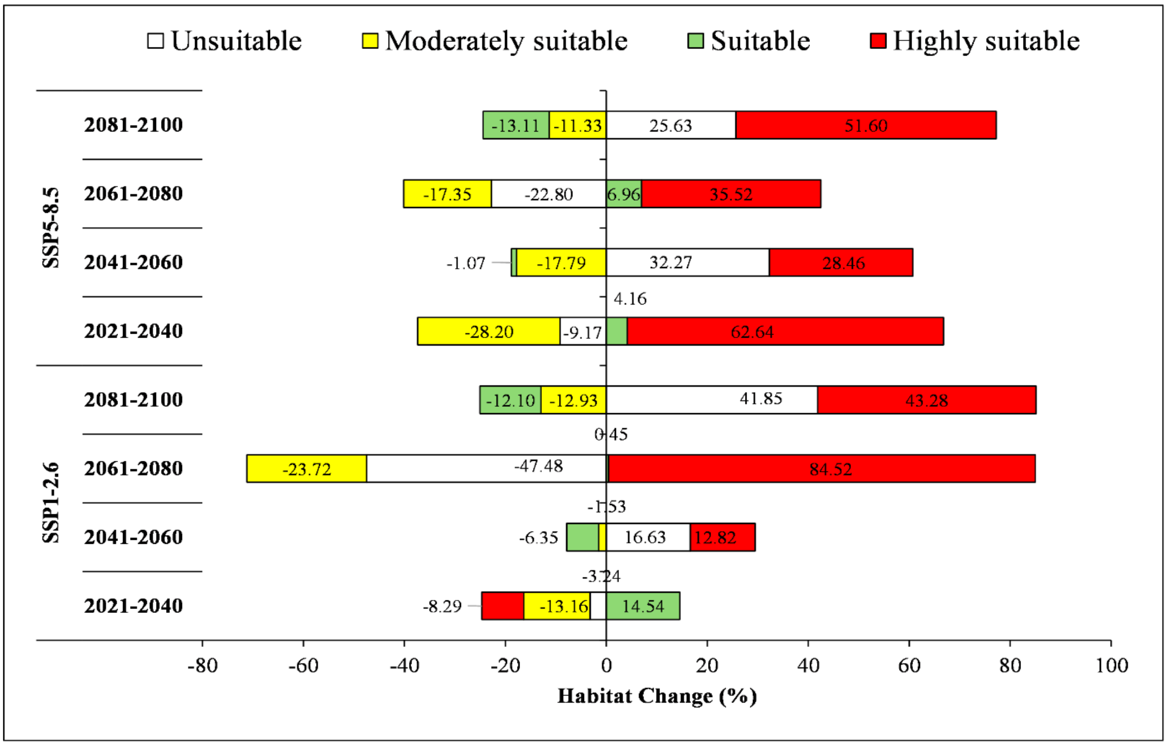

Figure 6. Changes in different habitat suitability classes of *Bidens frondosa* in Türkiye under changing climate

The expected geographical changes in the distribution of *B. frondosa* in Türkiye are mostly influenced by moisture availability in the driest quarter, identified as the most significant environmental predictor (67.86% model contribution). This finding aligns with earlier studies indicating that precipitation patterns, particularly during critical periods, serve as vital factors influencing invasive species dispersal patterns (Xiao et al., 2025). The species' need on sufficient moisture during droughts indicates its biological preference for damp, disturbed environments like as ditches, marshes, and riverbanks (Xiao et al., 2025).

Figure 7 presents a spatial analysis of habitat changes illustrating areas of habitat gain (newly suitable regions), loss (currently suitable areas that become unsuitable), and stable persistence. The maps indicate that newly acquired suitable areas are distributed across different regions of Türkiye under projected future climates, often around the edges of the existing range. Habitat losses (shown in red) are rather confined; nonetheless, under some losses are evident in areas of the existing range under high emission scenario. Nevertheless, a substantial proportion of the country stays consistently stable, highlighting the resilience of *B. frondosa*'s core range (Figure 7).

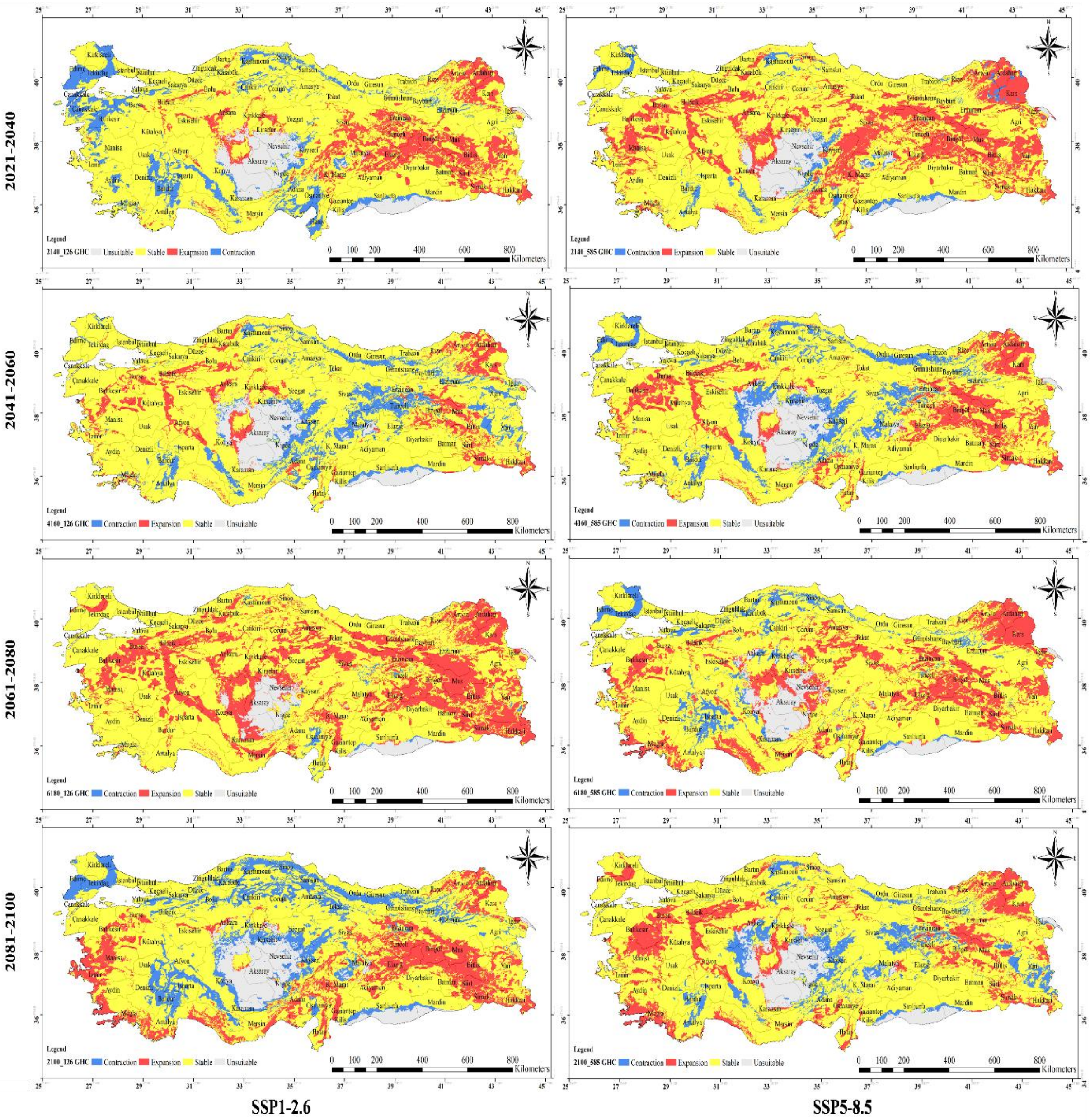

Figure 7. General habitat change of *Bidens frondosa* in Türkiye under changing climate

Similarly, Figure 8 presents a quantitative analysis of overall habitat change. Habitat of *B. frondosa* in Türkiye is expected to experience significant changes in coming decades under low emission scenario. From 2021 to 2040, 13.76% of the habitat is projected to expand, 9.89% will contract, and 69.80% will stay unchanged. During the mid-century (2041–2060), the expansion rate marginally decreases to 9.62%, however stability rises to 73.46%, signifying a very stable ecosystem in this period. A significant rise in expansion (28.89%) is expected between 2061 and 2080, with a marked decrease in contraction (0.80%), indicating a major range expansion. In the latter two decades of the century (2081–2100), expansion decreases to 17.59%, contraction increases to 14.10%, and stability reduces to 60.70%, indicating increased habitat turnover. The percentage of unsuitable regions stays consistently low, varying between 4.16% and 7.62%. These projections indicate a predominant tendency of habitat expansion for *B. frondosa* in a low-emissions scenario, particularly in the mid-to-long future, characterized by episodes of stability and turnover (Figure 8).

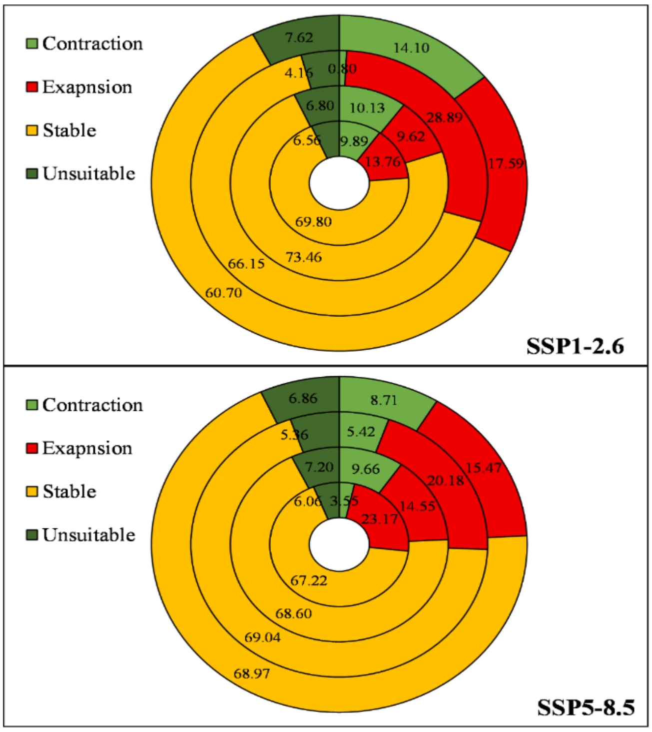

Figure 8. General habitat change of *Bidens frondosa* in Türkiye under changing climate. The circles represent 2021-2040, 2041-2060, 2061-2080, and 2081-2100 periods from outside to inward, respectively

Bidens frondosa is projected to undergo significant habitat alterations in Türkiye throughout the 21st century under high emission scenario as well. Habitat expansion is most significant at 23.17% during 2021-2040, with a small 3.55% contraction and 67.22% staying stable, suggesting good conditions for colonization. Nevertheless, habitat expansion decreases to 14.55% during 2041-2060, whereas contraction increases substantially to 9.66%, indicating an increase in regional heterogeneity in habitat suitability. Habitat expansion increases to 20.18% during 2061-2080, while contraction decreases to 5.42%, with 69.04% of the habitat remaining unaffected. Habitat expansion decreases to 15.47% during 2081-2100, contraction rises to 8.71%, and 68.97% stays stable. The proportion of unsuitable areas varies considerably between 5.36% and 7.20%. Despite certain periods of increased contraction, the species has a consistent capacity for growth under high emission scenario, especially in the early to mid-century, suggesting that warmer and more varied temperatures may facilitate its colonization throughout various parts of Türkiye (Figure 8).

The modeling outcomes indicate significant ecological and management implications for Türkiye's ecosystems. The increase in suitable habitat from 56.4% to 68.7% of Türkiye's land area under low emission scenario by 2061-2080 indicates a significant potential ecological shift. This growth threatens native biodiversity through many mechanisms identified in invasive species (Powell et al., 2011). *Bidens frondosa* may create monocultures that decrease the resistance of ecosystems to climate change, modify fire regimes, and disturb native plant species (Qureshi & Anwar, 2025; Xiao et al., 2025). The species' capacity to colonize places previously considered unsuitable (22,563 km^2 shifting from unsuitable to moderately suitable by the century's end) suggests a possible invasion into novel ecosystem types. This growth may impact on essential habitat interactions for native species and modify the supply of ecosystem services (Khapugin et al., 2022).

The expected expansion into agricultural zones, including hazelnut orchards and vegetable fields in the Black Sea region, together with predicted habitat expansion, presents considerable economic threats (Tad et al., 2015). Invasions caused by climate change could reduce agricultural production and elevate management expenses (Colberg et al., 2024; Hulme, 2017). The species' rapid establishment and substantial seed production ability facilitate rapid colonization of disturbed agricultural areas (Ronzhina, 2017; Wang et al., 2014). Hence, it is essential to implement climate-smart invasive species management techniques that include climate change considerations into every stage of prevention, detection, and control initiatives to address the projected range expansion of *B. frondosa*.

Sophisticated monitoring systems (Zaka & Samat, 2024) must be implemented in projected expanding regions, especially in eastern and southeastern Türkiye, where centroid changes are most significant. Early detection and rapid response initiatives have greatest efficacy when implemented before the establishment of significant populations of species (Martinez et al., 2020; Reaser et al., 2020). Climate projections need to guide predictive monitoring by concentrating surveillance on regions with increased predicted suitability in future scenarios. Citizen science networks (Crall et al., 2015)may be combined with professional monitoring to improve detection capabilities across Türkiye's diverse landscapes. Training initiatives must focus on land managers, agricultural workers, and outdoor enthusiasts in high-risk regions identified using habitat suitability models.

Climate-informed preventive methods must include changing invasion pathways under climate change (Colberg et al., 2024). This involves managing the trade and transportation of plants across regions with varying climatic suitability, since climate change may enable establishment in places previously deemed unsuitable (Duflot et al., 2018). Coordinated efforts at the landscape scale are important because of the expected extensive geographic expansion. Management initiatives must prioritize the prevention of corridor development between existing and projected suitable regions. Priority must be given to controlling satellite populations and infestations along distribution routes. The incorporation of climate forecasts into the national invasive species policy is crucial. The invasive species management strategy in Türkiye should clearly include climate change scenarios into risk assessments and management priority. International collaboration is essential due to the cross-border characteristics of climate change and biological invasions. Collaboration with neighboring countries may enhance early detection abilities and prevent re-invasion. Investment in research should focus on understanding climate-invasion relationships, formulating climate-adapted management strategies, and enhancing predictive skills. Long-term monitoring procedures are essential to confirm model predictions and adjust management strategies appropriately.

Centroid shift analysis revealed the potential movement in the geographic center of highly suitable habitats for *B. frondosa* in Türkiye under climate change (Table 4). The centroid is currently located at 40.38° N, 32.74° E (in north-central Türkiye). Nevertheless, it is expected to migrate eastward and southward in future. The centroid is projected to experience a significant initial shift of around 302 km to the east by 2021–2040 (reaching ~36.30° E), indicating a fast eastward extension of the suitable range under low emission scenario. This may relate to the colonization of eastern Anatolian areas that are now very cold. Migration gradually slows by mid-century, where centroids move around 27 km to the southeast. A further eastward movement (~194 km) is expected between 2061 and 2080, followed by a southeast shift (~170 km) from 2081 to 2100 (centroid at 39.26° N, 34.10° E; Table 4). The overall results indicate a general shift toward the east-southeast of Türkiye under low emission scenario.

The centroid shifts are somewhat less apparent under the high emission scenario. The centroid shifts about 164 kilometers to the east by 2021-2040. Similarly, it is expected to relocate 132 km to the southeast by 2041–2060 and an additional 126 km farther southeast by 2061–2080. Notably, the centroid is expected to experience a minor southward shift (net shift of around 57 km from the present) by 2081–2100. This indicates that after initial eastward migration, highly suitable regions may shift westward or southward by the end of century under high emission scenario. Both scenarios demonstrate a southeasterly shift in the core habitat of *B. frondosa* (Table 4).

Table 4. Centroid shifts in the habitat of *Bidens frondosa* in Türkiye under future climate conditions compared to the current climate

Scenario	Longitude	Latitude	Shift (km)	Cardinal Direction Shift
Current	32.74212	40.37879	0	S
SSP126_2021_2040	36.30025	40.2465	302.3663	E
SSP585_2021_2040	34.57789	39.92678	164.0969	E
SSP126_2041_2060	33.00093	40.23589	27.12489	SE
SSP585_2041_2060	34.11721	39.83525	131.7869	SE
SSP126_2061_2080	34.97408	40.02279	193.8596	E
SSP585_2061_2080	33.86872	39.64828	125.851	SE
SSP126_2081_2100	34.09895	39.26007	170.1932	SE
SSP585_2081_2100	32.94583	39.88972	57.13686	S

S = south, E = east, SE = southeast

The centroid shift analysis indicated a consistent migration tendency towards the east and south under both climate change scenarios, with initial eastward shifts of 302 km in the low emission scenario and 164 km in the high emission scenario over the period 2021-2040. This pattern of directional change illustrates several interrelated processes. The impacts of climatic velocity are significant, as organisms follow their optimal climate conditions over the geographic space (Burrows et al., 2014; Corlett & Westcott, 2013; Serra-Diaz et al., 2014). The eastward shift probably aligns with areas where moisture availability during arid periods is sufficient or improves under future climate projections (Danuso et al., 2012; Suehiro et al., 1984). Studies on climate-induced range shifts reveal that species often migrate toward regions characterized by reduced climatic change velocities and more favorable precipitation patterns (Littlefield et al., 2019).

Topographic and geographical variables also affect migratory trends (Moeslund et al., 2013). The complex geography of Türkiye creates diverse climatic conditions, with eastern areas likely offering more favorable moisture regimes as Mediterranean-type climates undergo spatial shifts (Karahasan & Pinar, 2023). The southerly aspect of migration may indicate the species' capacity to follow ideal temperature-moisture combinations over latitudinal gradients (Abbasi et al., 2024).

The predicted regional alterations in the geographic distribution of *B. frondosa* pose a considerable challenge for Türkiye's biodiversity conservation and ecosystem management. The species may expand in 68.7% of the country under low emission scenarios, principally influenced by moisture availability patterns, requiring urgent and comprehensive management measures. Success in mitigating these consequences relies on the successful implementation of climate-smart invasive species management which involves predictive modeling, adaptive management strategies, and landscape-scale coordination. The opportunity for effective prevention is rapidly decreasing, necessitating urgent action to save Türkiye's native ecosystems and agricultural systems from this increasing threat.

Conclusion

The predicted spread of *B. frondosa* in Turkey under current and future climate scenarios indicates considerable threats. Habitat suitability models suggest that the species has the potential to extend its range over most of the country, especially in the humid Black Sea area, where it has already established populations. Climate change (particularly high emission scenario) is expected to intensify its spread by increasing moisture availability and extending the species' growth season. The colonization of *B. frondosa* presents significant threats to Turkey's ecosystems and agriculture, especially in economically significant regions like hazelnut and kiwi orchards. As the species expands into new areas, it may displace native plant species, alter local biodiversity, and raise agricultural management expenses. The study highlights the need for immediate action through climate-informed monitoring, early detection, and specific management strategies to reduce the ecological and economic impacts.

Ethics approval and consent to participate

Not applicable as the study is not a clinical trial and did not include any patients.

Conflicts of interest

The author has declared no conflicts of interest.

Authors' contributions

Conceptualization, S.F.; methodology, S.F.; software, S.F.; validation, S.F.; formal analysis, S.F.; investigation, S.F.; resources, S.F.; data curation, S.F.; writing—original draft preparation, S.F.; writing—review and editing, S.F.; visualization, S.F. All authors have read and agreed to the published version of the manuscript.

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