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Research article (Araştırma makalesi)

Predicting spatial patterns of *Cuculus canorus* under climate change in Türkiye

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Abstract: Climate change is reshaping species distributions worldwide, with migratory birds representing one of the most vulnerable groups in this process. The Common Cuckoo (*Cuculus canorus*), a species of high ecological importance, is widely distributed across Eurasia but is increasingly threatened by habitat loss and climatic shifts. In this study, we applied the MaxEnt algorithm to predict the current and future distribution of the cuckoo in Türkiye under present and projected climate conditions. In addition to bioclimatic predictors, topographic variables were included in the modeling framework. Pearson correlation analysis was used to minimize multicollinearity, and variable contributions were evaluated through jackknife tests. The model performed strongly (AUC = 0.81), and response curves indicated that temperature and precipitation were the primary determinants of habitat suitability. Projections for the year 2100 under SSP3-7.0 and SSP5-8.5 scenarios revealed substantial contractions of suitable areas, with no new habitat gains. The extent of climatically suitable habitat is predicted to decline from 631001 km² at present to 285035 km² under SSP3-7.0 and to 151822 km² under SSP5-8.5. Losses were most pronounced at lower elevations, consistent with thermophilization and upslope range shifts. The results highlight potential refugia as critical targets for conservation, while also emphasizing the importance of considering host species distribution, habitat connectivity, and migratory stopover sites in management strategies. This study provides the first comprehensive, spatially explicit projection of cuckoo distribution in Türkiye, offering novel insights into the species' vulnerability to climate change.
Keywords: Climate scenarios, Common cuckoo, Habitat suitability, MaxEnt, Species distribution modeling

İklim değişikliğine bağlı olarak *Cuculus canorus* türünün Türkiye'deki mekansal dağılımının tahmin edilmesi

Öz: İklim değişikliği dünya genelinde türlerin dağılımını yeniden şekillendirmektedir. Göçmen kuşlar bu değişim sürecinin en hassas gruplardan birini oluşturmaktadır. Yüksek ekolojik öneme sahip bir tür olan guguk kuşu (*Cuculus canorus*), Avrasya genelinde yayılış göstermekte ancak habitat kaybı ve iklimsel değişimlerden giderek daha fazla etkilenmektedir. Bu çalışmada, Türkiye'deki guguk kuşu dağılımını mevcut ve gelecekteki iklim koşulları altında tahmin etmek amacıyla MaxEnt algoritması uygulanmıştır. Modellemede biyoklimatik değişkenlere ek olarak topoğrafik değişkenler kullanılmıştır. Değişken seçiminde çoklu bağlantıyı azaltmak için Pearson korelasyon analizi uygulanmış, değişken katkıları ise jackknife testleriyle değerlendirilmiştir. Model güçlü bir performans sergilemiştir (AUC = 0.81) ve tepki eğrileri sıcaklık ve yağış değişkenlerinin habitat uygunluğunda belirleyici olduğunu göstermiştir. 2100 yılı için SSP3-7.0 ve SSP5-8.5 senaryoları altında yapılan projeksiyonlar, yeni kazanım olmaksızın uygun alanlarda ciddi daralmalar öngörmektedir. Mevcut durumda 631001 km² olan uygun habitat alanı, SSP3-7.0 senaryosunda 285035 km²'ye, SSP5-8.5 senaryosunda ise 151822 km²'ye düşmektedir. Bu kayıplar özellikle düşük rakımlarda yoğunlaşmış olup, termofilizasyon ve yükseltiye doğru dağılım kaymaları ile uyumludur. Bulgular, iklim değişikliğine karşı görece stabil kalabilecek refugia alanlarının koruma açısından kritik olduğunu ortaya koymakta; aynı zamanda konak türlerin dağılımı, habitat bağlantısı ve göç sırasında kullanılan konaklama alanlarının da dikkate alınması gerektiğini vurgulamaktadır. Bu çalışma, Türkiye'de guguk kuşunun dağılımına yönelik ilk kapsamlı ve mekânsal projeksiyonu sunarak, türün iklim değişikliğine karşı kırılganlığına dair yeni bilgiler sağlamaktadır.
Anahtar kelimeler: İklim senaryoları, Guguk kuşu, Habitat uygunluğu, MaxEnt, Tür dağılım modellemesi

1. Introduction

Climate change is one of the most critical drivers of biodiversity loss worldwide, altering temperature and precipitation regimes, intensifying extreme events, and reshaping the spatial structure of ecosystems (Lee et al., 2023; Acarer and Mert, 2025). These environmental disruptions are compounded by anthropogenic land-use changes, which accelerate habitat degradation and fragmentation, ultimately reducing ecological connectivity, dispersal opportunities, and long-term species survival (Haddad et al., 2015; Kaya et al., 2025).

Wildlife is highly sensitive to these pressures. As habitats become fragmented into smaller, isolated patches, many species face reduced access to resources, declining reproductive success, and heightened extinction risks (Bellard et al., 2012). Birds are especially responsive indicators of such changes due to their ecological diversity, migratory behavior, and dependence on habitat quality. Numerous studies demonstrate that climate change has

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already shifted avian distributions, with many species moving poleward or upward in elevation to track suitable conditions (Chen et al., 2011; Evcin, 2024a). However, not all species can adapt at the same pace, resulting in mismatches in distribution, declines in population sizes, and altered community structures (Both et al., 2006).

Among these species, the Common Cuckoo (*C. canorus*) holds a prominent place in Eurasian avifauna. It is widely distributed across Europe, Asia, and Africa, and is a common breeder in Türkiye (Ertan, 1999). However, as with many other bird species, its populations are increasingly threatened by habitat loss, land-use change, and the accelerating impacts of climate change (Kirwan et al., 2010). Understanding how the distribution of this species may shift under future climate conditions is essential for both biodiversity conservation and anticipating broader ecological consequences.

Beyond its broad geographic range, the Common Cuckoo exhibits a highly specialized reproductive strategy as an obligate brood parasite. Female cuckoos lay their eggs in the nests of particular passerine hosts, often producing eggs that mimic host egg colour and pattern to avoid rejection (Davies and Brooke, 1989). Individual females typically specialize on one host species—forming distinct "gentes"—and their egg traits reflect coevolutionary selection pressures from specific hosts (Brooke and Davies, 1988). Host species vary widely in their ability to discriminate and reject foreign eggs, with some showing strong rejection of poorly matched eggs, while others exhibit high tolerance (Davies and Brooke, 1989). This long-standing arms race shapes both mimicry and defensive strategies, mediated by the costs of mistaken rejection and the benefits of accepting or rejecting parasitic eggs (Lotem, 1993). Consequently, the spatial distribution of cuckoos is indirectly constrained not only by habitat structure but also by the availability and ecological traits of suitable hosts. Understanding these interactions is therefore critical for predicting future shifts under climate and land-use change.

Species distribution models (SDMs) provide a powerful framework for addressing this challenge (Özdemir, 2024). By linking species occurrences with environmental predictors, SDMs estimate the potential distribution of species under current and projected future conditions. The Maximum Entropy (MaxEnt) algorithm, in particular, has been widely adopted due to its robustness with presence-only data and strong predictive performance (Phillips et al., 2017; Çıvğa et al., 2024). Recent studies applying SDMs under climate change scenarios have shown not only shifts in suitable habitat ranges but also increasing risks of habitat contraction and fragmentation, with direct implications for conservation strategies (López-Hernández et al., 2025; Wang et al., 2025).

Building on this framework, the present study models the current and future potential distribution of the Common Cuckoo in Türkiye using the MaxEnt approach. Climate projections based on the SSP3–7.0 and SSP5–8.5 scenarios were incorporated to explore how the species' range may change by the end of the century. We hypothesize that while suitable habitats for the cuckoo will persist, their extent and spatial configuration will undergo significant shifts under climate change. The originality of this study lies in providing the first nationwide, spatially explicit assessment of the Common Cuckoo's distribution in Türkiye under both present and future climatic conditions, offering critical insights for species conservation and long-term biodiversity planning.

2. Materials and methods

2.1. Study area and occurrence data

The study focused on modeling the potential distribution of the Common Cuckoo (*Cuculus canorus*) across the entire territory of Türkiye. To achieve this, we combined both field observations (collected locally) and nationwide occurrence records.

Field sampling was conducted in the Mount Ida (Kaz Dağı), located in northwestern Türkiye. This region is among Türkiye's biodiversity hotspots due to its heterogeneous topography, rich flora, and diverse bird communities. During the breeding season, standardized point count surveys were applied, and individuals of the Common Cuckoo detected visually or acoustically were recorded at systematically distributed sampling points. These local data provide reliable, high-quality field observations for the modeling framework.

To extend the spatial coverage beyond Mount Ida and ensure that the model represents Türkiye as a whole, additional species records were obtained from the Global Biodiversity Information Facility (GBIF) (GBIF.org, 2025). The data were carefully screened to remove duplicates, erroneous coordinates, and records outside the known distribution range. After cleaning, GBIF records and field observations were merged into a single occurrence dataset.

This combined dataset enabled the modeling of the current and future potential distribution of the Common Cuckoo throughout Türkiye, while Mount Ida field data strengthened the ecological relevance and reliability of the models by providing locally verified observations.

2.2. Variable selection and predictive modeling

To characterize the environmental factors influencing the distribution of the Common Cuckoo, both topographic and climatic variables were incorporated into the modeling framework. A digital elevation model (DEM) with a spatial resolution of 30 m was obtained from the NASA Earthdata repository (NASA, 2018). Based on this DEM, a suite of topographic variables was derived, including slope, aspect, topographic position index, aspect suitability index, shadow index, and solar radiation index. These variables capture fine-scale heterogeneity in terrain, which is known to strongly influence microclimatic conditions and habitat suitability. Since the climatic predictors were available at ~1 km resolution, all topographic variables were resampled to the same resolution to ensure spatial consistency among environmental layers.

In addition, 19 bioclimatic variables with a resolution of 30 arc-seconds (~1 km) were downloaded from the WorldClim database (Fick and Hijmans, 2017), covering both present-day climatic conditions and future climate projections. For future scenarios, only projections for the year 2100 were considered, specifically under the SSP3–7.0 and SSP5–8.5 pathways. Together, these datasets provided a comprehensive representation of environmental gradients relevant to the cuckoo's ecology. These predictors were selected because microclimatic and regional climatic patterns are the primary abiotic drivers of cuckoo habitat suitability at broad spatial scales; this is consistent with previous SDM applications for avian species.

To minimize multicollinearity among predictors, pairwise Pearson correlation analysis was applied using R Software

(Posit Team, 2025; R Core Team, 2025). When two variables showed high correlation (r > 0.8), one was excluded from the modeling process (Özdemir et al., 2020). The selection between correlated variables was guided by ecological relevance, drawing on literature evidence and species-specific considerations to retain those most likely to influence the cuckoo's distribution. This approach ensured both statistical robustness and ecological interpretability. Although the cuckoo's breeding ecology depends indirectly on host distributions, the modelling scope of the present study is restricted to abiotic predictors, which represent the primary climatic and topographic constraints on national-scale suitability. Host-associated refinements are therefore identified as an avenue for future research rather than omitted due to oversight.

Species distribution modeling was performed using the Maximum Entropy (MaxEnt) algorithm, which predicts potential species distributions based on presence-only data and associated environmental variables. Operating under the principle of maximum entropy, the model identifies the probability distribution that is most spread out while remaining consistent with the constraints imposed by observed species occurrences and environmental predictors (Phillips et al., 2017). Regularization was applied to prevent overfitting, thereby enhancing the model's generalizability. The output consisted of continuous habitat suitability maps, ranging from 0 (unsuitable) to 1 (highly suitable).

To convert these continuous predictions into binary habitat suitability maps, a thresholding approach was employed. Specifically, the Jenks natural breaks classification method was used to determine data-driven thresholds that define natural groupings within the suitability values. This allowed the resulting maps to clearly distinguish between suitable and unsuitable habitats, providing ecologically meaningful outputs for conservation planning and comparative analyses under current and future climate scenarios.

Model performance was evaluated using the Area Under the Curve (AUC) of the receiver operating characteristic (ROC). AUC values close to 1 indicate strong discriminatory capacity, while values approaching 0.5 reflect random performance (Evcin, 2023). The robustness of MaxEnt, particularly its ability to generate reliable predictions from limited and presence-only data, underscores its suitability for assessing the distribution of the Common Cuckoo across Türkiye and under projected climate change scenarios.

3. Results

A Pearson correlation analysis was conducted to evaluate multicollinearity among predictors. Variables with correlation coefficients greater than 0.80 were excluded (Özdemir et al., 2020; Çıvğa, 2025; Tekeş et al., 2025). The remaining predictors were then retained for model development (Figure 1).

Marginal response curves for the selected predictors are presented in Figure 3, illustrating the logistic suitability of *C. canorus* along gradients of mean annual temperature (bio1), annual temperature range (bio7), mean temperature of the driest quarter (bio9), annual precipitation (bio12), slope, and topographic position index (tpi).

Species distribution modeling for *C. canorus* was performed in MaxEnt using the selected predictors. After excluding variables with negligible contributions or potential bias, as determined by jackknife tests, the final model was obtained. The model achieved an AUC value of 0.81, indicating a robust predictive performance.

The relative importance of predictors in the final model was assessed through jackknife analysis. The results (Figure 2) demonstrate the individual contribution of each environmental variable to model gain.

Model projections were generated for both current climatic conditions and future scenarios (SSP3-7.0 and SSP5-8.5 for the year 2100). Jenks natural breaks analysis of the current suitability surface identified a threshold value of 0.340932, which was subsequently applied to all projections. Habitat suitability maps were thereby converted into binary representations of suitable and unsuitable areas (Figures 4–6).

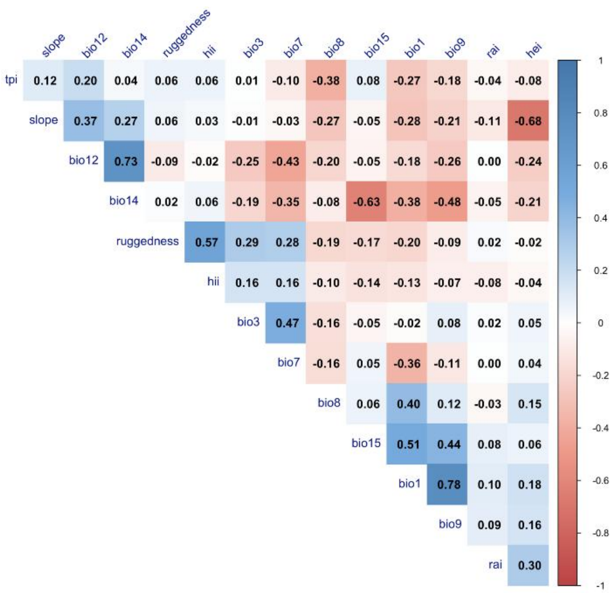

Figure 1. Pearson correlation matrix of environmental variables (variables with correlation coefficients >0.80 were excluded from the final model)

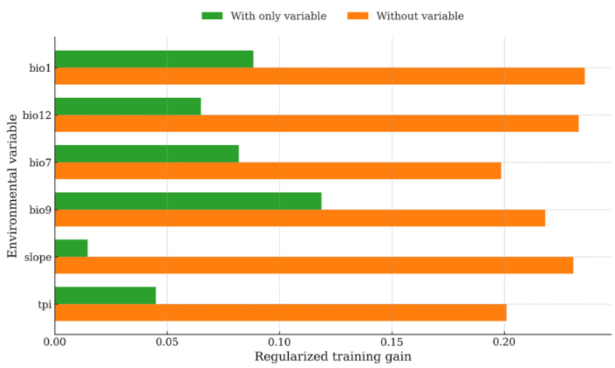

Figure 2. Jackknife test of variable importance for *C. canorus*. Green bars indicate the gain when each variable is used in isolation, and orange bars indicate the gain when the variable is omitted

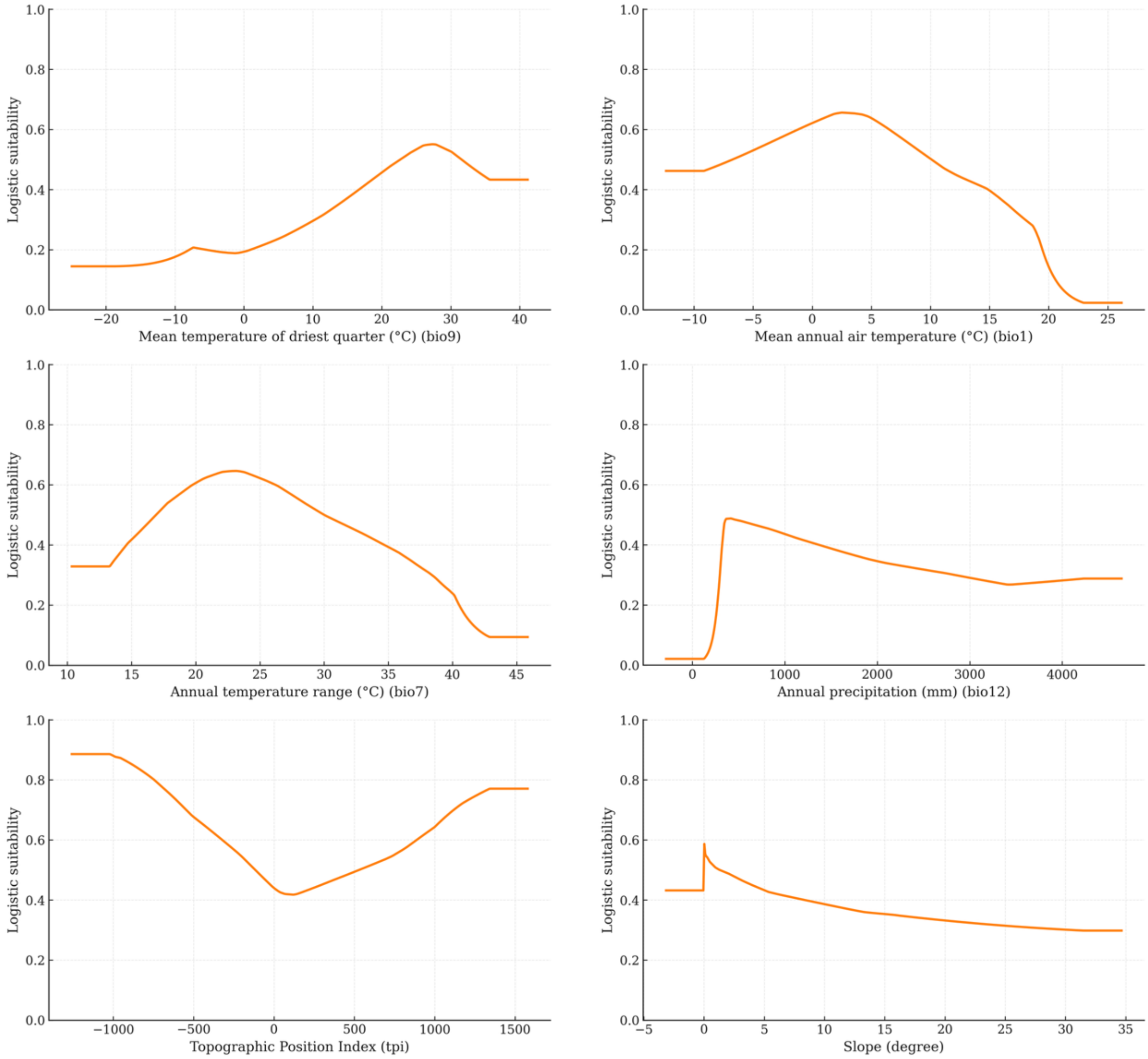

Figure 3. Marginal response curves of environmental predictors included in the final model. The curves show the logistic suitability of *C. canorus* in relation to each predictor (bio1, bio7, bio9, bio12, slope, and tpi)

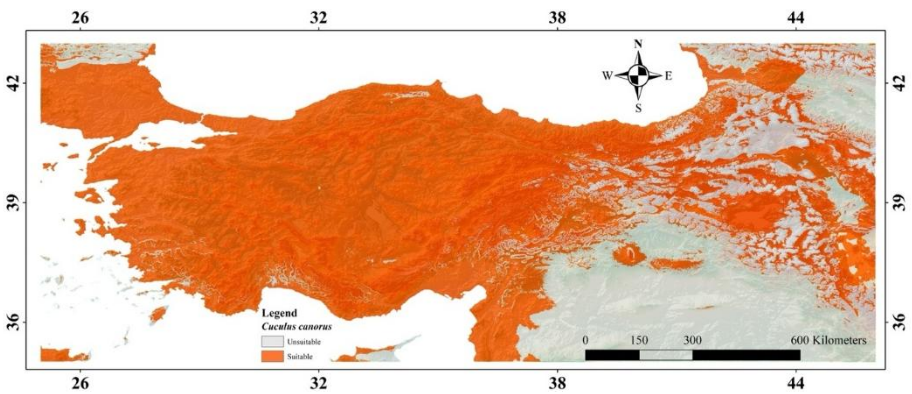

Figure 4. Current habitat suitability map of *C. canorus* based on MaxEnt predictions and thresholded using the Jenks natural breaks value (0.340932)

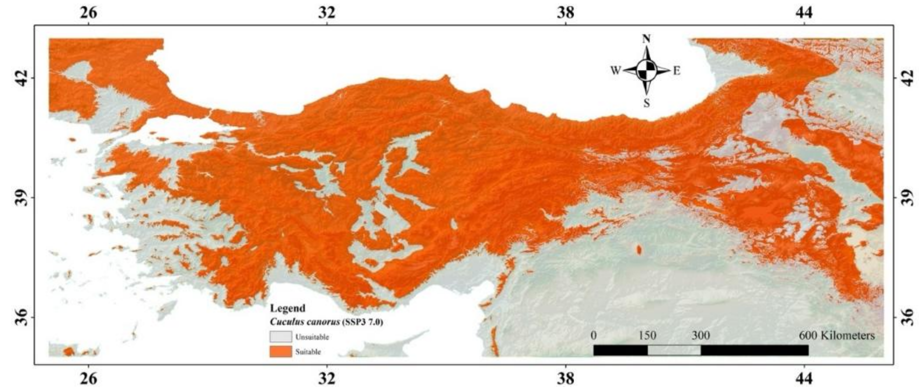

Figure 5. Projected habitat suitability map of *C. canorus* under the SSP3-7.0 climate scenario for the year 2100, thresholded using the Jenks natural breaks value (0.340932)

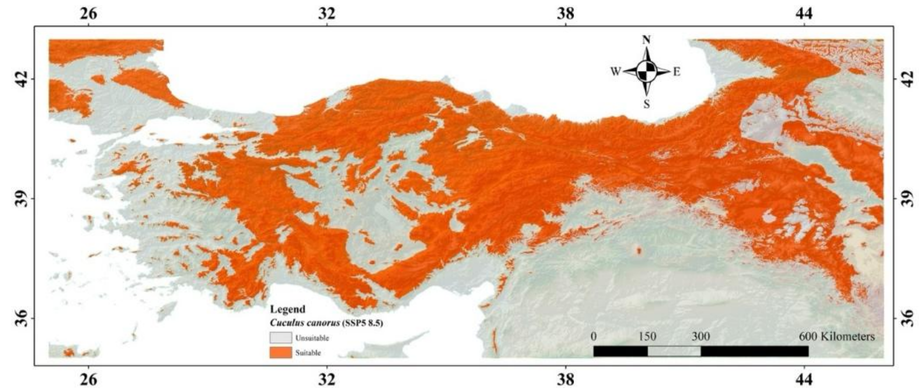

Figure 6. Projected habitat suitability map of *C. canorus* under the SSP5-8.5 climate scenario for the year 2100, thresholded using the Jenks natural breaks value (0.340932)

The spatial analysis revealed a marked contraction of climatically suitable habitats under both scenarios. In the present climate, suitable habitat covered 631001 km². Under SSP3-7.0, this area decreased to 285035 km², and under SSP5-8.5 it further declined to 151822 km². No habitat gains were identified in either scenario, while losses amounted to 345966 km² under SSP3-7.0 and 479179 km² under SSP5-8.5. Stable unsuitable areas expanded from 347793 km² at present to 499793 km² under SSP3-7.0 and 826972 km² under SSP5-8.5 (Table 1).

4. Discussion and conclusions

The modeling framework adopted in this study provides several methodological refinements compared with many previous MaxEnt applications to birds (Süel, 2019). In addition to conventional bioclimatic variables, we incorporated fine-scale topographic predictors such as slope and the topographic position index, which act as proxies for local environmental heterogeneity often overlooked in broad-scale distribution models. This integration enabled structural features of the landscape - likely influencing nest-site availability and predator avoidance for both cuckoos and their hosts - to be captured. Furthermore, instead of applying a single arbitrary threshold, Jenks natural breaks were applied to delineate suitable and unsuitable habitats, providing an ecologically interpretable cut-off for binary maps. Multicollinearity was controlled using Pearson correlation analysis, and among highly correlated predictors we retained those identified in previous ecological studies as most influential for *C. canorus* distribution. Combined with jackknife analysis, this ensured both statistical robustness and ecological plausibility of the final model.

The projections consistently revealed a contraction of suitable habitats under future climate scenarios. Losses were most pronounced at lower elevations, indicating an upslope shift in suitable climatic space. Such patterns are consistent with broader evidence of thermophilization, whereby communities progressively shift toward species associated with warmer conditions (De Frenne et al., 2013; Duque et al., 2015; Evcin, 2024b; Liu et al., 2024). The strong contributions of temperature variables (bio1, bio9) in our model highlight the sensitivity of cuckoo distributions to thermal conditions, supporting the interpretation that climate warming will progressively restrict breeding habitats to higher and cooler sites. However, elevational shifts may be limited by fragmentation of suitable patches and the absence of continuous habitat corridors, a challenge also reported in other avian studies within the region (Keten et al., 2020; Uyar et al., 2025).

Table 1. Area (km²) of suitable and unsuitable habitats for *C. canorus* under current and future climate scenarios. Stable, loss, and gain categories indicate changes in suitability between present and future projections.

Scenario	Present	SSP370	SSP585
Unsuitable (0)	347793	693759	826972
Suitable (1)	631001	285035	151822
Total Area	978794	978794	978794
Transition	Stable suitable	285035	151822
	Loss (suitable → not)	345966	479179
	Gain (not → suitable)	0	0
	Stable unsuitable	347793	499793

For migratory species such as *C. canorus*, climate change exerts additional pressures through its indirect effects on host communities. Host availability and breeding phenology are critical determinants of cuckoo reproductive success. Recent studies have shown that host species have advanced their breeding timing more rapidly than cuckoos, resulting in mismatches that reduce parasitism success (Møller et al., 2011). Historical evidence from Britain indicates that cuckoos have shifted host usage in response to such ecological pressures, with reed warblers increasingly parasitized as other hosts declined (Brooke and Davies, 1987). These dynamics suggest that the niche of *C. canorus* is constrained not only by climatic suitability but also by the abundance and distribution of suitable hosts (Soler et al., 2009; Kleven et al., 1999). The evolution of host-specific gentes, each adapted to mimic the eggs of particular host species, further illustrates the tight dependency of cuckoo persistence on host availability. These host-dependent dynamics highlight that the realized suitability of the cuckoo is shaped not only by climatic envelopes but also by biotic interactions operating at finer ecological scales. Accordingly, the selection of abiotic predictors was based on large-scale climatic and topographic constraints that primarily define the species' fundamental niche, whereas host-mediated interactions are acknowledged as realized niche determinants that lie beyond the scope of the present climate-driven modelling framework (Schulze-Hagen et al., 2009).

The maps obtained in this study reveal potential refuge areas where suitable habitats can persist despite climate change. These areas are critical for the long-term survival of the species and should be prioritized in conservation planning. Areas that overlap with existing protected areas or where ecological connections can be strengthened are particularly important for supporting the species' mobility and ensuring population sustainability. The maintenance of connectivity is especially important given that cuckoos must also navigate long-distance migrations, relying on the availability of stopover habitats for refueling and recovery (Schmaljohann et al., 2022). Loss of suitable breeding habitat combined with pressures on migratory stopovers could amplify declines, underscoring the need for integrative conservation strategies.

Although our findings align with global patterns of migratory bird declines due to climate change, species-specific modeling studies of cuckoos remain scarce, especially in Türkiye. Most distribution modeling has prioritized large, charismatic birds, leaving brood parasites underrepresented despite their ecological and evolutionary importance. By integrating bioclimatic predictors with detailed topographic variables, using ecologically informed variable selection, and connecting projections to both climatic constraints and host dependencies, this study offers new insights into the vulnerability of *C. canorus* at the southern edge of its range. Future research should expand this framework by explicitly including host species distributions and land-use factors, preferably through joint species distribution models, to better evaluate the survival prospects of cuckoos amid accelerating climate change.

Our results demonstrate that the *C. canorus* is highly vulnerable to ongoing climate change, with suitable habitats projected to contract sharply by the end of the century. The integration of fine-scale topographic predictors alongside bioclimatic variables provided a more ecologically realistic picture of distributional constraints. At the same time, the application of data-driven thresholds improved interpretability of habitat maps. The consistent loss of low-elevation habitats and the lack of newly emerging suitable areas highlight the risks of range restriction and fragmentation. Given the cuckoo's reliance on host species and migratory connectivity, these pressures are likely to be compounded by indirect ecological effects. Conservation measures should therefore focus on safeguarding climatically stable refugia, enhancing habitat connectivity, and integrating host dynamics into management planning. Regionally, the prioritization of mid- to high-elevation forested refugia, reinforcement of ecological corridors, and preservation of riparian vegetation represent actionable management steps that could buffer the species against ongoing climatic shifts. This study represents the first nationwide spatial projection for the species in Türkiye and provides a framework for more comprehensive, multi-species approaches that link climate, habitat, and ecological interactions in future biodiversity assessments.

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