



Climate-driven range shifts of Levallant's Woodpecker *Picus vaillantii* in the Western Mediterranean

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Abstract

Climate change significantly impacts avian morphological and reproductive phenologies, particularly influencing the distribution of endemic species with restricted ranges. This study explores the potential distributional shifts of the Levallant's Woodpecker, endemic to North Africa, in response to climate change. We employed ecological niche modeling to assess its range dynamics during historical periods (Last Interglacial, Last Glacial Maximum, and mid-Holocene), the present, and projected future scenarios (2050 and 2070). The analysis incorporated 68 occurrence records of the species and 15 bioclimatic variables. Our findings indicate a current equilibrium between the woodpecker and its climatic environment. Historically, the species experienced a marked range contraction during the Last Interglacial, followed by a significant expansion in the Last Glacial Maximum. The mid-Holocene distribution closely resembled the present range. Future projections, however, suggest a decline in Levallant's Woodpecker populations, with a shift towards higher altitude forests as a response to global warming impacts on their existing habitats. This study highlights the critical need for awareness about global warming and its potential threats to biodiversity, particularly forest avifauna.

Keywords Climate change · Ecological niche modeling · Quaternary · Mediterranean Basin · *Picus vaillantii*

Introduction

Forest ecosystems, crucial to Earth's biodiversity, face numerous challenges from factors like climate change, fires, CO₂ emissions, and biological disturbances, leading

to changes in their composition and increased forest mortality (Anderson-Teixeira et al. 2013; Weed et al. 2013; Abatzoglou and Williams 2016; Allen et al. 2010; Coops and Waring 2011; Fogg et al. 2014; McDowell and Allen 2015). These catastrophic events pose a significant threat to global biodiversity, particularly impacting bird species (Walsh et al. 2019).

Climate change, characterized by rising temperatures and altered precipitation patterns, is a key factor influencing avian life cycles, distribution, and migration behaviors (Peterson 2003; Lany et al. 2016; Lehikoinen et al. 2019; Perktas and Elverici 2020; Keller et al. 2020). Endemic species, especially those in restricted habitats, are particularly vulnerable to these changes (Martin et al. 2004). Additionally, high-altitude species exhibit notable shifts in response to increasing temperatures, often moving to higher, cooler altitudes, a phenomenon known as the "escalator effect" (Sekercioglu et al. 2008; Freeman et al. 2018).

Research on the impact of climate change on avian species is widespread (Guillemain et al. 2013). Indeed, these globally distributed taxa are considered the most addressed by climate research (Wormworth and Şekercioglu 2011). Changes in bird distributions are often linked to climate

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(Gregory et al. 2009; Chen et al. 2011). In that context, many studies focused on cavity-nesting birds. Their small size, their relatively high energy requirements, as well as the availability of long-term reproduction data, make these taxa excellent indicators of climate change (Thorup et al. 2007).

Woodpeckers, as indicators of forest resilience and biodiversity, are significantly affected by climate change. Their reliance on old-growth forests makes them sensitive to changes in snag density, the availability of trees with suitable diameters, and the severity of fires affecting tree density and creating open forests (Covert-Bratland et al. 2006; Saab et al. 2009; Dudley et al. 2012; Srivastava et al. 2012). The response of woodpeckers to alterations within their ecosystems can be taken as a basis for modeling the impact of future climate change on forest biodiversity (Walsh et al. 2019). They play a vital role in maintaining forest equilibrium, contributing to habitat creation for other species, regulating insect populations, and aiding in the spread of wood-rotting fungi (Drapeau et al. 2009; Damoc et al. 2014; Fayt et al. 2005; Jackson and Jackson 2004). Given their selective ecological requirements, woodpeckers are often considered excellent bioindicators of forest health (Mikusiński et al. 2001; Virkkala 2006).

This study aims to be the first to assess the impact of climate change on woodpeckers in North Africa using ecological niche modeling. Focusing on the Levaillant's Woodpecker *Picus vaillantii*, a poorly understood, endemic, high-altitude species (Badis et al. 2023), we evaluated its responses to current and past climatic conditions (Last Interglacial, Last Glacial Maximum, mid-Holocene). By understanding past responses, we aim to model and predict future distributions, thereby contributing valuable insights into the effects of climate change on avian species in this region.

Material and methods

Study species

Levaillant's Woodpecker *Picus vaillantii*, formerly considered a subspecies of the European Green Woodpecker *Picus viridis vaillantii*, is now classified as a genetically isolated species in the Picinae subfamily, endemic to Northwest Africa (Short and Sandström 1982; Perктаş et al. 2011; Pons et al. 2011; Dickinson and Remsen 2013). This myrmecophilous bird (Henine-Maouche 2016) resides in old pure and mixed forests of oak and cedar (Isenmann et al. 2005; Badis and Hamdi 2022a). In Tunisia, it frequents oak groves; it is rarely found in Aleppo pine forests in the center-west of the country (Isenmann et al. 2005). In Algeria, its distribution covers clear wooded habitats from the sea to the forests of altitude; towards the south, it reaches the Saharan Atlas and the Aurès region (Isenmann and Moali 2000).

In Morocco, Levaillant's Woodpecker is found in high, medium, and even low-altitude forest areas (Snow et al. 1998).

Occurrence data

Initially, we collected 1693 observation records from personal observation of the author MB (Badis and Hamdi 2022a, 2022b; Badis et al. 2023) using the point count method in Aurès massif forests of northeastern Algeria. Also, we obtained data from the Global Biodiversity Information Facility (GBIF 2021; <http://www.gbif.org>) and previous scientific works about the species (El Khamlichi and Sarrión Salado 2015; Henine-Maouche 2016). To correct sampling bias and reduce spatial autocorrelation, the data were rarefied with a distance of 25 km buffer zone between every two points using the package "sptthin" on RStudio v. 1.1.463 (Brown et al. 2017). After cleaning and rarefying the data, the total observation records were reduced to 68 points located in northwest Africa, with important densities at the level of the mountain ranges of the Atlas in Morocco, the forest massifs of northeastern Algeria, and those of northwestern Tunisia (Fig. 1).

Environmental layers

Nineteen bioclimatic data for current (1960–1990), past (mid-Holocene (approx. 6000 ybp), Last Glacial Maximum (LGM) (approx. 22,000 ybp), Last Interglacial (LIG) (approx. 130,000 ybp)), and future (2050 and 2070) were downloaded from Worldclim version 1.4 in 2.5 arc minute resolution (~4.6 km) (Hijmans et al. 2005; Otto-Bliesner et al. 2006). We used three general circulation model (GCM) simulations (CCSM4, MIROC-ESM, and MPI-ESM-P) for the past bioclimates of the Last Glacial Maximum and mid-Holocene. While to characterize future climatic conditions, we selected three simulations of GCM (CCSM4, MIROC-ESM, and MPI-ESM-LR) with representative concentration pathways (RCPs) of 2.6, 4.5, and 8.5. As previous studies found spatial artifacts in the form of discontinuities between neighboring pixels, we removed the variables BIO8, BIO9, BIO18, and BIO19, which correspond to the mean temperature of the wettest and driest quarters, and precipitation of the warmest and coldest quarters (Escobar et al. 2014). We masked all bioclimatic data according to dimensions of 28°–40° N and 11.17° W–14° E.

In ecological niche modeling, a correlation threshold for environmental variables is based on an equilibrium between reducing multicollinearity and retaining information generated from variables. Usually, a correlation threshold of 0.7 or higher is used, as going lower is very difficult as the number of variables might become too low, and then we will lose a lot of information (Dormann et al. 2013; Sillero and Barbosa

2021). Thus, we grouped current bioclimatic data according to correlation thresholds of 0.6, 0.7, 0.8, and 0.9 by using the “usdm” package in R (Naimi 2017). The variables included in the analysis were mean diurnal range (Bio 2), isothermality (Bio 3), temperature seasonality (Bio 4), maximum temperature of the coldest month (Bio 6), mean temperature of the coldest quarter (Bio 11), precipitations of the wettest month (Bio 13), precipitations of the driest month (Bio 14), and precipitation seasonality (Bio 15). Given that most bird species disperse up to 200 km from their birthplace (Studds et al. 2012; FitzGerald 2017), we defined an accessible area (M-area) of a ~200 km buffered minimum convex polygon outside the Levaillant’s Woodpecker dispersion range (Barve et al. 2011). This area was used to sample 10,000 background points randomly.

Ecological niche modeling

We conducted ecological niche modeling using Maxent, facilitated by the “kuenm” package in R (Phillips and Dudík 2008; Cobos et al. 2019). The occurrence data were divided into training (75%) and test (25%) sets. To determine the best models, we employed a multi-criteria approach, considering models that met a 5% training presence threshold omission rate criteria, partial ROC, and corrected Akaike information criterion (AICc) (Hurvich and Tsai 1989; Peterson et al. 2008, 2011). From these significant models, we then selected those with the lowest AICc scores, indicating the most accurate reflection of the contributions of bioclimatic variables (Gür et al. 2018). Instead of using a single final model, we took the median of the suitable areas from these top-performing models to generate the final predictions. This approach enhances the robustness of our findings by integrating insights from multiple significant models. The final predictions were run with ten replicates, cross-validating the replicate type without using extrapolation. Model performance was evaluated using the area under curve (AUC) value. For past and future scenarios, we projected these median-based predictions to each temporal scenario and transformed them into binary maps (suitable/unsuitable) based on a 10-percentile training presence logistic threshold. We opted for binary outputs in our ecological niche modeling to clearly delineate suitable habitats for the

Levaillant’s Woodpecker, using thresholds based on model calibration that align with the species’ ecological requirements and the specific aims of our conservation-focused research. This approach simplifies interpretation and aids in precise habitat identification for potential conservation actions (Escobar et al. 2018).

Results

Model calibration

In our study, we thoroughly evaluated 992 candidate models to predict the current distribution of Levaillant’s Woodpecker. This extensive set was constructed using eight regularization multiplier settings, 31 different feature class combinations, and four bioclimatic sets based on correlation thresholds. Among these, 487 models were found to be statistically significant. Notably, three models stood out as they met both the omission rate criteria and had lower AICc scores, thus striking an optimal balance between model accuracy and simplicity (Table 1). These models effectively represent an equilibrium between complexity and explanatory power.

The three selected models varied in their regularization multipliers and feature class combinations but were particularly notable for their performance in terms of predictive accuracy. As detailed in Table 1, the AUC values for these models ranged from 0.864 to 0.876, indicating a high level of predictive accuracy, significantly better than random predictions. This range of AUC values underscores the robustness of our modeling approach.

To convey the potential distribution of the species under current climatic conditions, we synthesized the results of these top models (Table 1). Medians of each niche model result were computed to create an aggregated prediction. Based on these median results, binary maps were generated using a logistic threshold value of 0.21, which corresponds to the average 10-percentile training presence. This approach provided a comprehensive view of the suitable habitats for Levaillant’s Woodpecker, reflecting a nuanced understanding of its ecological niche under current climatic conditions.

Table 1 Three best models’ characteristics (*M*, M area; 2 and 1, regularization multiplier; *F*, feature types; *L*, linear; *Q*, quadratic; *P*, product; *H*, hinge; *T*, threshold; *060 et 080*, correlation threshold of bioclimatic variables; *AICc*, Akaike information criterion with a correction

for small sample sizes; *delta_AICc*, the difference in AICc score between the best model and the model being compared; *W_AICc*, Akaike weight for AICc)

Model	Sample size	AICc	delta_AICc	W_AICc	Parameters	AUC value
M_2_F_LT_080	68	1374.2664	0	0.2516	10	0.870 ± 0.087
M_2_F_LT_060	68	1375.3728	1.1063	0.1447	4	0.864 ± 0.101
M_1_F_PH_060	68	1375.601	1.3346	0.129	6	0.876 ± 0.080

Climatic contribution

Analysis of the three best models revealed that the ecological niche of Levaillant's Woodpecker is predominantly influenced by a subset of the bioclimatic variables considered.

Table 2 Contribution and permutation of the bioclimatic variables in the best models for the Levaillant's Woodpecker

Model	Variable	Percent contribution (%)	Permutation importance (%)
M_2_F_LT_080	Bio 13	65.9	53.3
	Bio 6	14.4	24.6
	Bio 4	7.7	10.2
	Bio 3	6.6	8.5
	Bio 11	3.3	2.9
	Bio 2	2	0
	Bio 14	0.1	0.1
	Bio 15	0	0.3
M_2_F_LT_060	Bio 13	73.2	73.8
	Bio 6	17.3	18.6
	Bio 3	9.5	7.5
	Bio 15	0	0
M_1_F_PH_060	Bio 13	69.5	71.2
	Bio 6	21.3	21.8
	Bio 3	8.9	6.5
	Bio 15	0.4	0.3

Bio 2 mean diurnal range, *Bio 3* isothermality, *Bio 4* temperature seasonality, *Bio 6* min temperature of the coldest month, *Bio 11* mean temperature of the coldest quarter, *Bio 13* precipitation of wettest month, *Bio 14* precipitation of driest month, *Bio 15* precipitation seasonality

Across these models, the median contributions highlight precipitation during the wettest month (BIO13) and the minimum temperature of the coldest month (BIO6) as the most influential factors (Table 2). Specifically, BIO13's median contribution across the models is approximately 69.5%, indicating a significant reliance on precipitation patterns. Concurrently, BIO6's median contribution is approximately 17.3%, suggesting that colder temperatures during the coldest month are also a significant factor for the species presence.

Ecological niche

It can be seen that the present climatic niche model results are largely compatible with the actual real distribution of the Levaillant's Woodpecker. Nonetheless, the model also includes unoccupied but favorable areas for the species, namely the southern Iberian Peninsula, the Balearic Islands, Sardinia, and a few small foci in northwestern Libya and Cap Bon in Tunisia (Fig. 1).

During the Last Interglacial period, modeling of climatic niche revealed that the Levaillant's Woodpecker had a fragmented and spatially limited distribution. Suitable conditions for its presence seemed to have existed in only southern Portugal, the Strait of Gibraltar, the Atlantic coasts of Morocco, and some coastal forest regions of Algeria and Tunisia. However, during the Last Glacial Maximum, this species revealed a significant predicted expansion with a suitable niche on both shores of the Western Mediterranean basin, including the Maghreb countries. Under mid-Holocene bioclimatic conditions, the prediction showed little difference from the current distribution (Fig. 2).

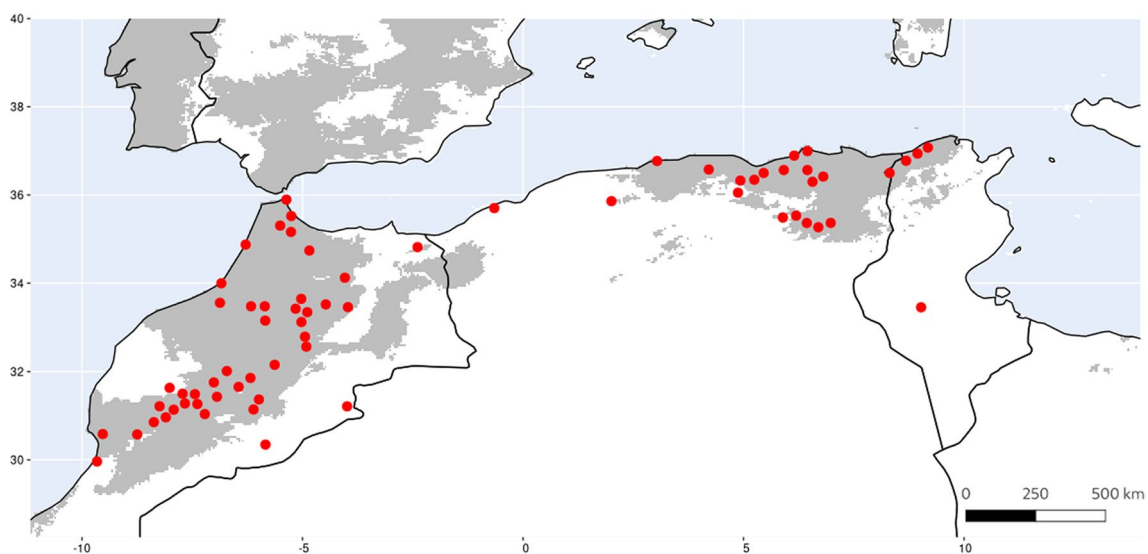
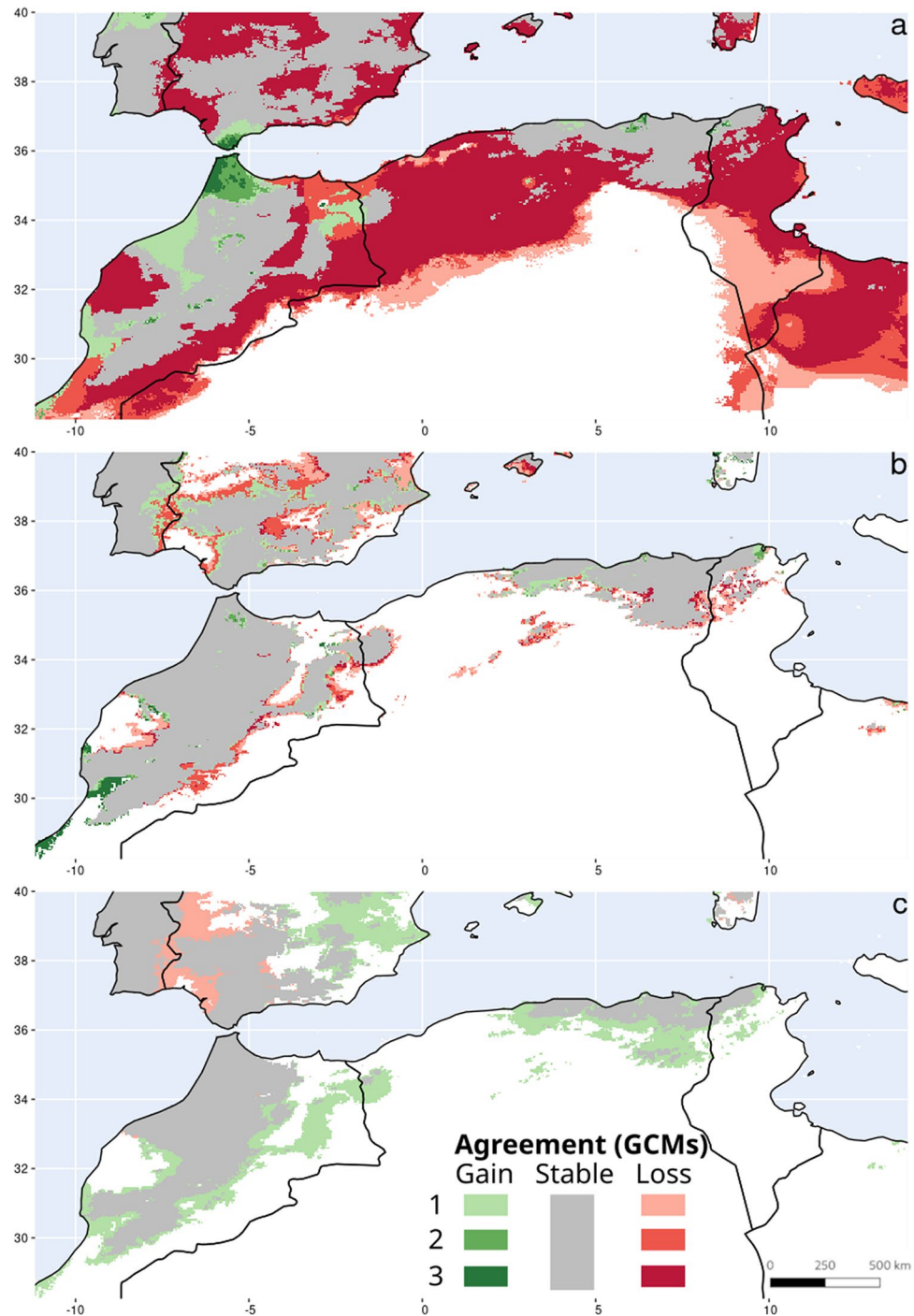


Fig. 1 Occurrence points of Levaillant's Woodpecker used in ecological niche modeling (red points) alongside the delineated suitable areas (gray shaded area)

Fig. 2 Modeled suitable areas for Levaillant's Woodpecker (*Picus vaillantii*) under historical bioclimatic conditions, with **a** the Last Glacial Maximum, **b** the Mid-Holocene, and **c** the Last Interglacial Period. Variations in color denote the level of agreement between general circulation models (GCMs). While the Last Glacial Maximum and Mid-Holocene are based on three GCMs, the Last Interglacial Period is derived from a single GCM



The results of the study of the effect of global warming on the distribution of the Levaillant's Woodpecker by projecting future climatic conditions predicted that the distribution of the species would shrink under all optimistic and pessimistic scenarios. Indeed, in 2050 and then in 2070, according to the RCP 2.6 and RCP 4.5 scenarios, significant losses of ecological niche will occur mainly in

eastern Morocco and northeastern Algeria, central-western Tunisia, Andalusia in Spain, which is an area currently unoccupied by the species. As for the RCP 8.5 pessimist scenario, the suitable surfaces should decrease excessively, and the species will therefore face a decline to the point that its spatial distribution is limited to a few small-disjointed forests, especially at altitude (Fig. 3).

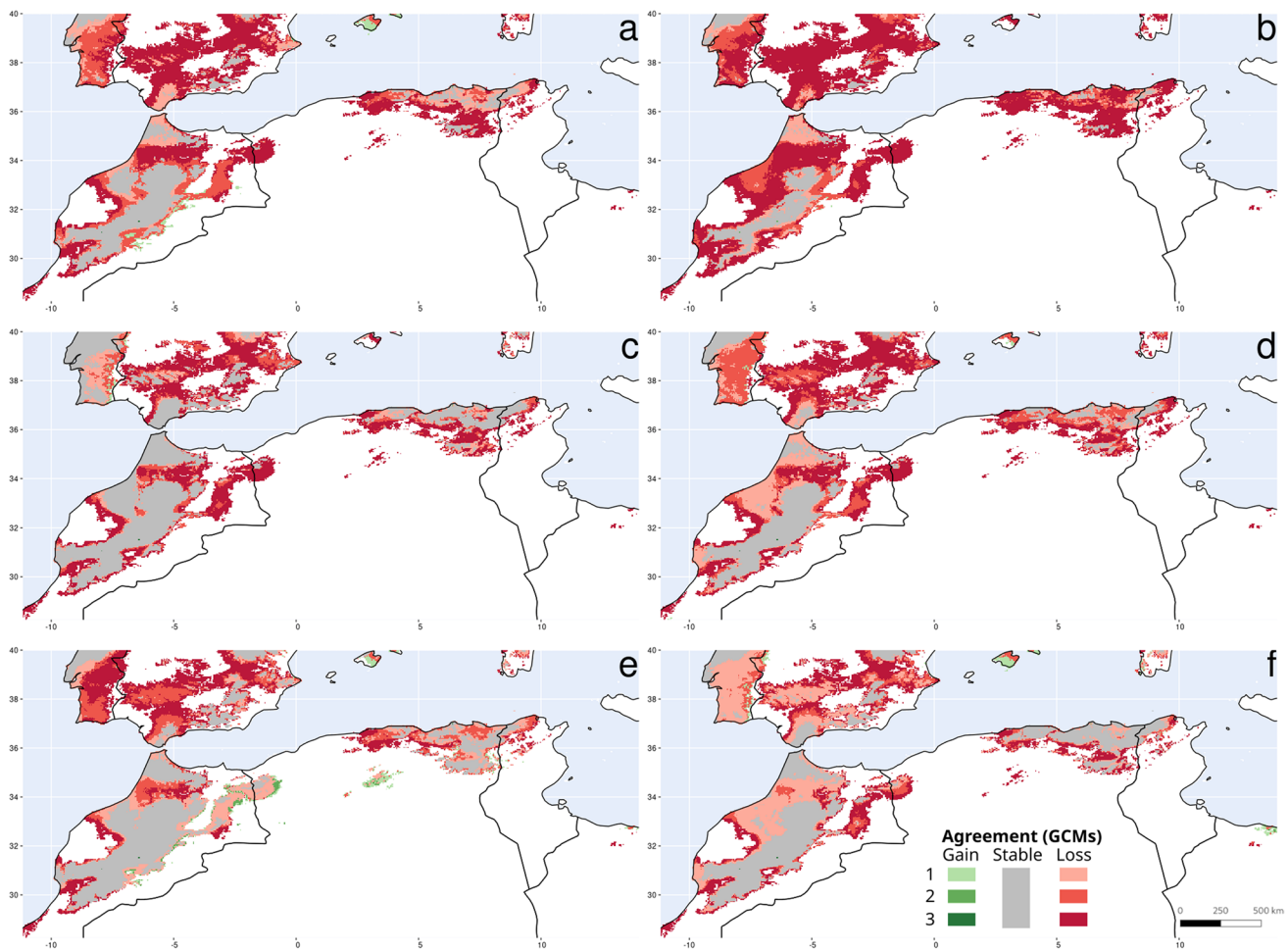


Fig. 3 Projected future distribution of Levallant's Woodpecker (*Picus vaillantii*) for 2050 under RCPs 8.5, 4.5, and 2.6 shown in **a**, **c**, and **e** respectively; and for 2070 under the same RCPs shown in **b**, **d**, and **f**. Three different GCMs were utilized for each time slice and RCP projection

Discussion

With the emergence of phylogeographic studies, many inferences were made about the population changes of temperate zone species, especially during the Late Quaternary, using mitochondrial DNA (Avice 2000; Hewitt 2004). Ecological niche models have made important contributions to understanding genetic diversity and species history. Several ecological niche model studies have produced similar outcomes to genetic studies (Waltari et al. 2007; Gür et al. 2018; Perkaş et al. 2019). For this reason, ecological niche model studies on species in regions where the necessary genetic data for coalescent models are unavailable will both contribute to the understanding of the biogeography of the region and contribute to the determination of target species for future genetic studies. The responses of Levallant's Woodpecker to climate change have been examined in this study. These responses are reflected by the spatiotemporal changes in its distribution area, which constitutes the basic unit of

the biogeography of the species in question (Lomolino et al. 2017).

The ecological niche modeling was highly informative, as evidenced by the high AUC values meeting our criteria, and accurately described suitable habitats that corresponded very well with the environmental conditions found at presence localities recorded for the Levallant's Woodpecker (Sesink Clee et al. 2015). The bioclimatic variables with the greatest contribution to the best model were those related to the coldest and the wettest month (the precipitation of the wettest month and the minimum temperature of the coldest month). This could suggest that this species prefers to excavate its nesting cavities in habitats located in the cold humid bioclimatic stages in high-altitude forests (Badis and Hamdi 2022b). These results imply that the likelihood of Levallant's Woodpecker occupying a given area increases with higher precipitation in the wettest month and lower temperatures during the coldest month. This relationship underscores the species' adaptation to specific climatic

conditions that are potentially vulnerable to the impacts of climate change (Peterson et al. 2011).

As demonstrated by the modeling, the current climatic niche overlaps the known distribution area of the Levaillant's Woodpecker that frequents the high-altitude wooded areas of Morocco, those of northern Algeria, as well as the western regions of Tunisia (Isenmann and Moali 2000; Isenmann et al. 2005). This species appears to have reached equilibrium with the climate (Nogués-Bravo 2009). The availability of a climatically suitable niche that can host the species outside its typical range, especially in Spain, suggests that the distribution of this endemic species may be limited by factors other than climatic. These are mainly biotic factors, in particular the occupation of these areas by genetically related species such as the Iberian Green Woodpecker *Picus viridis sharpei*, vicarious of the Levaillant's Woodpecker, which dominates in the Iberian Peninsula. Furthermore, the model of the current climatic niche shows a probable existence of two distinct mega populations of the Levaillant's Woodpecker, a western population occupying the Moroccan Atlas Mountains and an eastern population inhabiting the mountains of northwestern Tunisia and northern Algeria. This result needs to be improved by phylogeographic analyses of the two populations, to better understand their separation by the mountain ranges of western Algeria.

When the distributional predictions of the species are examined from the present to the past, it is seen that the suitable areas for the species in the mid-Holocene, which took place about 6000 years ago, are quite similar to the present distribution. The increase in precipitation during this period caused the vegetation to expand, giving us a clue that the species' distribution is an accurate reflection of its ideal habitat (Rachmayani et al. 2015).

According to the "expansion–contraction" model for temperate species, the Last Glacial Maximum's climatic conditions led most species to contract their distributions (Hewitt 2004). However, the habitats with suitable climatic conditions for the Levaillant's Woodpecker appear to have increased tremendously in this period. While some models suggest that dominant vegetation cannot achieve such a wide distribution (Ray and Adams 2001), it is predicted that there may be some expansion as related tree species are expected to expand their range. As demonstrated by Ülker et al. (2018), there were highly suitable areas for Pedunculate oak *Quercus robur* in North Africa, although, this tree species does not exist in the region. Furthermore, Bouahmed et al. (2019) reported that Atlas cedar *Cedrus atlantica*, which has limited distribution in North Africa, exhibited an increased suitable niche in the Last Glacial Maximum. It should be noted that cedar and oak trees serve as nesting sites for Levaillant's Woodpecker (Badis and Hamdi 2022a). In addition, Andersen et al. (2019) suggest that Tunisia poses a refugium for the Winter moth *Operophtera brumata*, which

is a defoliator species of oak forest. This provides evidence for a possible suitable habitat for the studied species in this region because it has been recognized that outbreaks of the moths favor the presence of woodpeckers (Showalter and Whitmore 2002). Therefore, it can be inferred that the high predicted distribution range of the Levaillant's Woodpecker during the Last Glacial Maximum is indicative of the significance of the west Mediterranean region as a refugia for the forest avian species.

For a better understanding of the impact of the last glaciation on the examined species, it was essential to assess and understand its geographical range before this era. As a result, research was conducted on the Last Interglacial 130,000 years ago. During this period, the Levaillant's Woodpecker experienced a marked contraction in its predicted distribution. As this species is like all woodpeckers, a forest specialist species (Mikusiński et al. 2001), this contraction of suitable habitat is also highlighted in many studies on forest birds. As like the Krüper Nuthatch *Sitta krueperi*, a cavity nester endemic to Anatolia (Perktaş et al. 2015). Also, the predicted distributional patterns of the Subalpine Warbler *Sylvia cantillans* during the Last Interglacial were extremely restricted (Perktaş et al. 2019). In North Africa, Perktaş et al. (2017) found the same phenomenon in Chaffinches *Fringilla coelebs*. According to Cowie (2007), this pattern of contraction is probably the result of the increase in temperatures and their seasonality during the Last Interglacial. Indeed, the average temperature of this period was high by about 4.5 C° compared to those of today (Felis et al. 2004; Wilcox et al. 2020).

Based on the hypothesized quantities of greenhouse gases set to be released over the coming decades, we have modeled multiple scenarios in order to predict the distribution of the Levaillant's Woodpecker. Starting with the optimistic scenario in which the radiative forcing will not exceed 2.6 watts/m², the suitable climatic niche to host this cavity-nesting species will be affected and there will be minimal habitat losses compared to the present model. Then in the case of a more marked radiative forcing of the RCP 4.5 scenario, the loss of habitats will be more and more serious, and the threats of population decline will begin to appear. Finally, based on the most pessimistic scenario with a radiative forcing reaching 8.5 watts/m², the Levaillant's Woodpecker would have, over the next few decades, only a few habitats of its niche likely to accommodate its populations. These are the high habitats of the Algerian and Moroccan cedar forests as well as the forests of northwestern Tunisia. This escalator effect will allow this species to avoid low-altitude habitats that will be more affected by global warming, which, according to Jetz et al. (2007), will lead to a decrease in the distribution of more than 400 bird species by 2050; this number will reach 900 bird species by 2100. Our result is also supported by Bouahmed et al. (2019) under

the RCP 8.5 scenario on the extinction of the cedar forests, which constitute the main habitat of the Levaiillant's Woodpecker (Badis and Hamdi 2022a). In Algeria, only the high places of the Aurès Mountains remain home to these trees. As stated by Freeman et al. (2018), four high-altitude species endemics to the South American Andes have disappeared during the last three decades. The probable decline of the populations of the Levaiillant's Woodpecker will be the result of both climate change and anthropological pressures on the species' habitats.

The findings suggest that the conservation plans for the Levaiillant's woodpecker should be taken into consideration and implemented as soon as possible, especially in the niche where we are witnessing a loss of habitat. It will also be essential, to preserve the areas that will probably be the only refuges for this species in the coming decades, these are the three chains of the Moroccan Atlas, the Aurès and Babors Mountains in Algeria, as well as the mountains of northwestern Tunisia. Also, it will be interesting to realize capture campaigns involving the two western and eastern populations, in order to study possible morphological and genetic variations.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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