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RESEARCH ARTICLE

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Protecting alpine biodiversity in the Middle East from climate change: Implications for high-elevation birds

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Abstract

Aims: The Middle East, located in the arid belt of the Earth, is home to a diverse range of biodiversity, with its mountain ecosystems being the most important centres of species diversity and endemism. In this study, the impact of climate change on alpine bird species in the Middle East was assessed across five mountain systems: Alborz–Kopet-Dagh, Caucasus–Pontic, Levant–Taurus, Sarawat–Hijaz and Zagros–Central Iran.

Location: Middle East.

Methods: Using species distribution models (SDMs), 38 native alpine bird species were analysed under different climate change scenarios. We also identified future multispecies in situ and ex situ climate refugia and assessed the efficiency of the current protected areas (PAs) system in protecting them.

Results: The results indicated that, on average, habitat suitability for these species is projected to decline by 36.83% (2050, SSP2-4.5) to 60.10% (2070, SSP5-8.5) with an upward range shift. Based on stacking range change of the species, Levant–Taurus, Zagros–Central Iran and Alborz–Kopet–Dagh mountain ranges will experience the highest amount of habitat loss, respectively, with Caucasus–Pontic being least affected. The gap analysis showed that the existing PAs system covers only 13% and 10% of the in situ and ex situ climatic refugia, respectively.

Conclusions: Our findings underscore the significance of mountainous regions in the Middle East for the persistence of alpine bird species and the urgent need to prioritize climate refugia in transboundary and participatory conservation plans. It is crucial to prevent habitat degradation and alteration resulting from human activities in these areas to ensure the persistence of alpine species and their habitats.

KEYWORDS
climate refugia, gap analysis, mountain PAs, SDMs, upward range shift

1 | INTRODUCTION

Mountains, shaped by tectonic and volcanic processes, are inherently dynamic and prone to rapid changes over short time periods (Rahbek et al., 2019). Due to their diverse microclimates and complex topography, mountains generally support high biodiversity and endemism, with up to half of the global biodiversity hotspots located in these regions (Antonelli et al., 2018; Noroozi et al., 2018). Mountain regions, characterized by rapid climate differentiation along altitudinal gradients, are particularly vulnerable to climate change impacts (Dullinger et al., 2012; Parmesan, 2006). However, the global impacts of climate change are not expected to be homogenous. The arid and semi-arid environments of the Middle East are among the most vulnerable regions globally to global warming (Bayram & Öztürk, 2021). Unlike other regions anticipating future climate change impacts, the Eastern Mediterranean and Middle East are already experiencing irreversible threats from desertification and global warming at an alarming pace (Haktanir et al., 2004; Zittis et al., 2022). Despite the warming and drier climate, the Middle East harbours substantial biological diversity due to remarkable topographic, temperature and precipitation gradients (Noroozi et al., 2018; Şekercioğlu et al., 2011). The Middle East is globally unique as the transition zone between three Old World zoogeographic realms, including Palearctic, Afrotropical and Oriental (Holt et al., 2013). Vast mountain systems of the Middle East, like those in Caucasus and Irano-Anatolian, host rich biodiversity, aligning with three global biodiversity hotspots. Also, notable plant endemism occurs in mountainous areas of the region, including Taurus, Alborz, Zagros and Sarawat-Hejaz mountains, emphasizing their ecological significance (Al-Namazi et al., 2021; Noroozi et al., 2019).

The Middle East is home to more than 850 species and subspecies of birds, with many resident species confined to isolated mountainous habitats (Porter & Aspinall, 2013). Although suitable microclimate and distance from human-dominated areas enrich mountainous areas as the most important centres of species richness and endemism (Antonelli et al., 2018; Fjeldså et al., 2012), the species inhabiting these areas are very sensitive to climate changes (Brambilla et al., 2022; Dullinger et al., 2012). According to Parmesan (2006), species living in polar regions and mountainous habitats might experience the highest risk of extinction due to climate change-induced range contraction. On a global scale, the current acceleration of temperature puts one in six species at risk of extinction (Urban, 2015). Similarly, previous researches show that alpine birds have lost a large part of their current distribution range and will witness a high risk of extinction in the near future (Freeman et al., 2018; Lehikoinen et al., 2019; Sekercioglu et al., 2008). However, the vulnerability of birds to climate change is not adequately captured in IUCN assessments where 83% of them are not described as threatened in the Red List (Foden et al., 2013).

The impact of environmental changes, particularly climate change, poses a significant threat to alpine species, necessitating conservation strategies that explicitly consider the adverse effects and integrate them into landscape management and conservation planning (Groves et al., 2012; Lehikoinen et al., 2019). Although some species suffer from climate change-induced range loss, especially those with limited dispersal abilities, others could potentially benefit from colonizing new habitats that offer suitable climatic conditions in the future (Brambilla et al., 2022). In order to increase the likelihood of successful long-term conservation planning, it is crucial to prioritize the effectiveness of existing protected areas (PAs) as a first step (Ahmadi et al., 2020; Mi et al., 2023). This can be accomplished by developing both in situ and ex situ conservation-oriented systems (Pritchard et al., 2012). Temporally speaking, these in situ and ex situ systems could be interpreted as resistant and resilient climate refugia, respectively (Hannah, 2011; Yang et al., 2022), which are of important role in climate change adaptive conservation efforts (Mi et al., 2023; Morecroft et al., 2012). To achieve this goal, the initial step involves the identification of in situ and ex situ climate refugia (Brambilla et al., 2022; Keppel et al., 2012). While the former refers to areas that are presently occupied and are predicted to remain suitable for future survival, the later are areas currently unoccupied but expected to become suitable with changing environmental conditions (Keppel et al., 2012). In the current era of human impact on the environment, PAs are essential for safeguarding biodiversity and avoiding climate-driven extinctions (Bosso et al., 2024; Brambilla et al., 2022). In many instances, PAs are linked to a reduced rate of climate change negative impacts (Lehikoinen et al., 2021), and the projected extent of species range loss within PAs is lower compared to areas outside their boundaries (Mi et al., 2023). Nonetheless, their fixed boundaries and locations may limit their effectiveness in conserving species that are experiencing significant and sudden shifts in their distributions as a result of rapidly changing climate conditions (Regos et al., 2016), and adapting to this dynamic scenario may require additional management strategies. In the face of such a changing scenario, it becomes imperative to identify the geographical patterns of species' range shifts caused by climate change (Hoffmann et al., 2019; Malakoutikhah et al., 2018) and design PAs accordingly.

Species distribution models (SDMs) are operational tools providing the conservationist with the ability to predict suitable range of the species in both current and future environmental conditions (Guisan et al., 2013; Zurell et al., 2020). SDMs, namely, mechanistic and correlative, are now widely used in the field of ecosystem management, and have been considered as powerful tools in biogeography conservation (Buonincontri et al., 2023; Guisan et al., 2017; Shabani et al., 2016). Despite their assumptions and uncertainties, SDMs remain an important tool for predicting future habitat suitability of species (Franklin, 2023; Shabani et al., 2019; Zurell et al., 2020). So far, SDMs have been used in several studies to assess the risk of species extinction in the future due to climate change (Ahmadi et al., 2019; Fordham et al., 2012). Notwithstanding, the scientific literature has rarely explored the regionalization of extinction risk among species and compared the vulnerability of different centres of biodiversity to climate change. Considering the isolation of the mountainous environments of the Middle East, their biological importance as centres of species richness and endemism, and

the region's high vulnerability to global warming, this study aims to assess the impacts of climate change on alpine birds in the Middle East and identify in situ and ex situ climate refugia. We hypothesize that alpine birds will be negatively impacted by climate change, and that various mountainous regions in the region, which serve as important refugia for these species, will be differentially affected. Additionally, we will assess the efficiency of protected areas (PAs) in providing long-term protection for alpine birds across five Middle Eastern mountainous regions. We utilized SDMs, coupled with geographic information systems (GIS), in order to evaluate the potential alterations in the habitat of 38 resident alpine birds under two IPCC6 shared socioeconomic pathways (SSPs) from the current time to 2050 and 2070. We used resident alpine birds as functioning indicators to compare vulnerability of Middle Eastern mountainous environments to global warming. The study's importance stems from comparing different alpine ecosystems of the Middle East regionally regarding climate change and evaluating the effectiveness of protected areas in a less studied but significant ecoregion of the world.

2 | MATERIALS AND METHODS

2.1 | Species data

To select target species, we first reviewed two bird guide books; Birds of the Middle East (Porter & Aspinall, 2013) and Collins Bird Guide (Svensson, 2010). Given their habitat description and proposed range maps, we filtered 38 alpine birds that are resident or breeding in the Middle East's alpine habitats (see Table S1). We checked species' scientific names with the Integrated Taxonomic Information System (ITIS) using the 'taxize' package (Chamberlain & Szöcs, 2013) in R environment. The data of the species occurrence points were obtained from the GBIF data set using the 'rgbif' package. This platform contains exact occurrence points from a wide variety of taxa. Data of the birds species, compared to other groups, are more complete in this data set because (i) 50% of occurrence records on GBIF are collected by citizen scientists using public platforms, such as eBird and iNaturalist, and (ii) birds are one of the most popular groups in citizen science.

GBIF allows accessing a huge amount of georeferenced species distribution records, but many observations include coordinate uncertainties, duplicated records or ambiguous centroids. Hence, it is necessary to perform comprehensive pre-processing and filtering procedures to make them ready for the SDM approach. To this end, first we set a pre-download constraints to the GBIF downloading process to filter out observation duplicates, observations without coordinates, absence records, observations with equal latitude and longitude, observations identified as having corrupted coordinates, observations older than 1990, coordinates with less than four decimals and removal of raster centroid data sets (Zizka et al., 2019). In total, the original observational data set obtained from the GBIF included 267,978 observations (GBIF, 2022). We further filtered out occurrence points with a minimum distance between them to 5 km. Specifically, we spatially filtered clumping records to reduce the negative impacts of their spatial autocorrelation (SAC) since it may inflate model accuracy or mislead parameter estimate during SDM analysis (Dormann et al., 2007). It is worth mentioning that there is no rule of thumb for selecting the minimum distance between presence points to reduce SAC. Moreover, in SDM approaches, it would be naïve to consider a distance between presence points to which the spatial autocorrelation (SAC) is zero, as many species, particularly range-restricted alpine ones, exhibit clustered distribution patterns. To balance the requirement of having an adequate number of points for modelling and reducing the spatial autocorrelation (SAC), we carefully selected the minimum distance based on similar studies on alpine species (Lorestani et al., 2022; Malakoutikhah et al., 2018). For each species, we also downloaded shapefile of its range map from the Birdlife International. We then visually screened occurrence points in the ArcMap desktop and removed those occurring outside of resident and/or breeding areas considering Birdlife International range maps plus proposed range maps depicted in the Birds of the Middle East filed guide. The initial data set of birds' occurrence points was ranged from 153 records for Philby's Partridge to 36,680 records for Black Redstart. The final data set used for the SDM analysis was ranged from 38 records for Caucasian snowcock to 1993 records for northern wheatear (Table S1). Since the correlative SDM methods require data of both presence and absence or background locations, we randomly selected 10,000 background points within the study area and merged it with the species' presence data for the SDM analysis.

2.2 | Climatic variables

We obtained 19 bioclimatic data layers from WorldClim (version 2.1), at a spatial resolution of 2.5 min, for both the baseline of the near-current (1970–2000) period, as well as for two future time periods: 2040–2060 (representing 2050) and 2060–2080 (representing 2070) (Fick & Hijmans, 2017). For the future, we used two shared socio-economic pathway scenarios developed for the Coupled Model Intercomparison Project Phase 6 (CMIP6): SSP2-4.5 and SSP5-8.5. These scenarios represent a moderate and upper boundary of climate change outcomes, allowing us to explore a range of future climate possibilities. For future climate projections, we focused on five different global circulation models (GCMs), including ACCESS-CM2, CNRM-CM6-1, IPSL-CM6A-LR, MIROC6 and MPI-ESM1-2-LR. Using different GCMs allows researchers to account for the inherent uncertainties and limitations in climate modelling, providing a more comprehensive and robust assessment of potential future climatic conditions suitable for a species. While there is no direct comparison of the performance of these GCMs specifically in the study area, they have been widely used in previous studies on climate change projections for Iran and the Eastern Mediterranean region (Logothetis et al., 2023; Lorestani et al., 2022; Shahsavarzadeh et al., 2023). For each species, the final ensemble of habitat suitability was calculated based on averaging GCMs' climatic suitability

over two SSP scenarios. To ensure that the predictive models are ecologically insightful and statistically sound, we selected variables based on their ecological relevance and variance inflation factor (VIF) values (Bradie & Leung, 2017). We extracted the values of 19 climatic variables at 10,000 background points within the study area and computed the VIF of the variables using the 'usdm' package (Naimi, 2015). In a stepwise procedure, we selected variables with VIF < 6. By doing so, seven climatic variables were selected for the SDM analysis including mean annual temperature (bio1), isothermality (bio3), mean temperature of wettest quarter (bio8), mean temperature of driest quarter (bio9), precipitation of wettest month (bio13), precipitation of driest month (bio14) and precipitation seasonality (bio15).

2.3 | SDM analysis

To model distribution of 38 alpine birds, we focused on two simple regression-based methods, including generalized linear model (GLM) and flexible discrimination analysis (FDA), and three complex machine learning ones, including generalized boosting model (GBM), random forest (RF) and maximum entropy (MaxEnt). By doing so, we were interested in using advantages of extrapolative methods, that is, simple models, and interpolative ones, that is, complex models, in our SDM analysis (Ahmadi et al., 2023; Merow et al., 2014). GLM and FDA had no specific parameters during model fitting. For MaxEnt, we chose default settings, including all feature classes, a regularization multiplier of 1 and a maximum iteration of 500. For RF and GBM, we allowed 1000 number of trees and a train fraction of 0.8 for GBM. A cross-validation with 10 replications was applied to generate training and test data sets. In this method, presence and background records were randomly split into 10 folds, training models were fitted with excluding each fold in turn and the excluded folds were used to test the performance of the training models. We used the area under the curve (AUC) of the receiver operating characteristic (ROC) plot and the true skill statistic (TSS) to test the predictive performance of models. AUC is a threshold-independent index that varies from 0.5 to 1; values close to 0.5 indicating a random predictive discrimination; and values close to 1 showing perfect discrimination. TSS as a measure of classification accuracy is calculated as (sensitivity + specificity) −1 and ranges from −1 to +1. TSS scores close to +1 indicates perfect classification accuracy and those close to −1 shows agreement worse than chance. To take into account the uncertainty related to each model (Araújo & New, 2007), for each species, an ensemble of models was created based on a TSS-weighted mean across five initial SDMs. After performing the current model, we projected the predicted potential distribution model into the future climatic scenarios. We adopted two procedures to assess relative importance of the explanatory variables on the habitat suitability of the species. We assessed the extent to which the inclusion of each variable enhances the model's performance, relative to the exclusion of that variable by employing a cross-validation technique. In an alternative technique, we used a randomization process that assesses the association between predicted values and predictions when the target variable is randomly permuted. The prediction is anticipated to be more affected by the permutation if the variable has a high contribution to the model, resulting in a lower correlation (Thuiller et al., 2009). All the SDM analyses were implemented using 'sdm' package (Naimi & Araújo, 2016) in R environment. To quantify changes in each alpine bird's distribution, we compared the current and future suitable habitats and calculated the percentage of range loss and range gain for two SSP scenarios and for 2050 and 2070. To identify suitable habitats, we converted continuous ensemble models of each species into binary presence/absence maps considering a threshold where sum of sensitivity plus specificity was maximum, as recommended by Liu et al. (2013). The percentage of range loss and range gain was calculated considering number of pixels remaining suitable in current and future projections (stable), number of pixels that are currently not occupied but predicted to be in the future (habitat gain) and number of pixels that are suitable in the current but predicted to be non-suitable in the future (habitat loss). We also calculated the mean elevation above sea level for all bird species extracted from their presence points, and considering an elevation threshold of 1500 m.a.s.l., categorized them into two groups—semi-alpine birds (elevation <1500 m) and alpine birds (elevation >1500 m). We then compared magnitude of habitat loss and habitat gain between these two functional groups based on a *t*-test analysis with Bonferroni-adjusted *p*-value. Finally to assess the altitudinal range shift in the alpine birds' suitable habitats, we calculated mean of elevation of predicted suitable patches for the current and future climate change scenarios.

2.4 | Climatic refugia and efficiency of PAs

We identified in situ and ex situ refugia based on comparing suitable habitats predicted for the current and future climate change scenarios. To this end, we followed the procedure suggested by Morelli et al. (2020) in which climate refugia are considered as areas that probably will retain, that is, in situ refugium, or attain, that is, ex situ refugium, suitable climate conditions for target species. Accordingly, we recognized two different types of climate refugia for each species (Brambilla et al., 2017; Morelli et al., 2020): (i) Type 1 indicating suitable habitats identified for a species under current and all future climate change models, and (ii) Type 2 depicting the important habitats of ex situ refugia where climate condition is not currently suitable for a species, but will be suitable under future climate change scenarios. While Type 1 refugia are of utmost importance to improve population resistance, Type 2 refugia are key habitats promoting resilience, that is, areas that could be considered in future introduction re-introduction programmes (Beaumont et al., 2019; Keppel et al., 2012). Finally, to assess the efficiency of the current PAs network, we recognized all Type 1 refugia for at least three species (Brambilla et al., 2022) and refugia Type 2 for more than one species (Beaumont et al., 2019). We considered these areas as multi-species and persistent refugia that play a key role for implementing

priority setting conservation measures for alpine birds. We then computed the spatial overlap between those refugia and the current network of PAs. The latter was obtained by merging the shapefile of Key Biodiversity Areas (KBAs available on https://www.keybiodiversityareas.org/) and PAs recorded in the IUCN's World Database on Protected Areas (WDPA available on http://protectedplanet.net/) for all countries of the study area.

3 | RESULTS

The SDM of alpine birds showed a range of good to excellent predictive performances. The Chukar partridge had the lowest AUC and TSS scores, 0.84 and 0.65, respectively, while the Yemen thrush had the highest AUC and TSS scores, 0.93 and 0.92, respectively (Table S1). Comparing the predictive performance of five SDM methods over 38 alpine birds (Figure 1) indicated that, on average, RF had the highest predictive performance (AUC = 0.94, TSS = 0.90), followed by MaxEnt (AUC = 0.90, TSS = 0.76) and GBM (AUC = 0.88, TSS = 0.72).

After generating binary presence/absence maps, the extent of climatically suitable patches for current time was calculated as an index of the species niche breadth. The results revealed that Philby's partridge (24,034 km^2) and Chukar partridge (1,385,992 km^2) had the lowest and greatest niche breadth, respectively (Table S2). Generally, among five mountain ranges of the Middle East, the alpine birds of Sarawat and Hijaz mountains, in southern Arabian Peninsula, showed the lowest niche breadth. For each species, we also calculated relative importance of the climatic variables in its climatic model (see Table S2). We found that, on average, temperature-related variables had the higher contribution to the climatic suitability of the alpine birds compared to precipitation ones where annual mean temperature had the highest relative importance (Table 1).

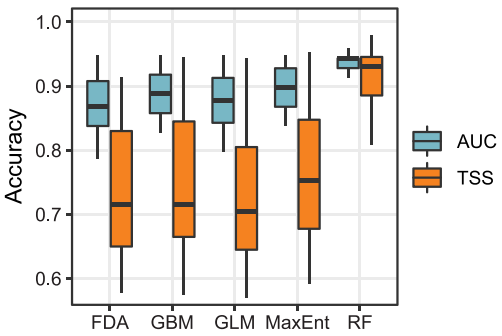

FIGURE 1 Mean AUC and TSS of initial SDM methods over 38 alpine birds.

Projecting the current SDM of the species to future climate change scenarios indicated that all alpine birds will probably experience a continuous pattern of range contraction from current time to 2050 and 2070. Figure 2 illustrates predicted suitable habitats of three alpine birds, including *Alectoris melanocephala*, *Emberiza cia* and *Irania gutturalis*, for current and future climatic scenarios. In the Supporting Information, we present the predicted suitable habitats and the estimated range shift of all alpine birds. Our findings suggested that range contraction will increase over time (current, 2050 and 2070) and under the more severe emissions scenarios, that is, SSP2-4.5 to SSP5-8.5 (Figure 3). On average, habitat loss of the species increases from 36.83% (2050, SSP2-4.5) to 60.10% (2070, SSP5-8.5) while habitat gain was only 4.60% for 2050 SSP2-4.5, and 5.60% for 2070 SSP5-8.5 (Figure 3). We also observed a consistent pattern of range shift towards higher areas from 1600 m.a.s.l. in the current time to 1782 m.a.s.l. under 2070 SSP5-8.5 scenario, as shown in Figure 3. When comparing species habitat loss and habitat gain (Table S3), the greatest habitat loss was calculated for *Eremophila alpestris* (84.74%), *Pyrrhocorax graculus* (83.28%) and *Crithagra rothschildi* (81.03%), all under 2070 SSP5-8.5 scenario. The lowest habitat loss was obtained for *Alectoris Chukar* (12.22%), *Tachymarptis melba* (12.85%) and *Emberiza cineracea* (13.91%) all under 2050 SSP2-4.5 scenario. Overall, our results revealed that, by 2070 and under the SSP5-8.5 scenario, 30 of 38 Middle Eastern alpine birds will lose more than 50% of their current suitable habitats. Maximum habitat gain was calculated for *Anthus similis* (19.57%), *Sitta tephronota* (19.48%) and *Oenanthe melanura* (14.38%). For 13 alpine birds, including all alpine birds of the Sarawat and Hijaz mountains in southern Arabian Peninsula, habitat gain was zero. When comparing average habitat gain and habitat loss values across five main mountain ranges (Figure 3), the greatest habitat loss was calculated for Levant–Taurus (78.01%), Zagros–Central Iran (76.21%), and Alborz–Kopet-Dagh (75.64%), all under 2070 SSP5-8.5 scenario. Our results revealed that the greatest unchanged habitat suitability will occur in Caucasus–Pontic Mountains, and accordingly, alpine birds in this region will experience the lowest habitat loss (Figure 4).

TABLE 1 Mean and standard error (SE) of the relative importance of the climatic variables in the habitat suitability of 38 alpine birds.

	Permutation correlation		AUC of test	
	Mean	SE	Mean	SE
Bio1	0.36	0.04	0.15	0.02
Bio3	0.14	0.02	0.04	0.01
Bio8	0.21	0.01	0.06	0.01
Bio9	0.25	0.02	0.06	0.01
Bio13	0.18	0.02	0.05	0.01
Bio14	0.19	0.02	0.03	0.01
Bio15	0.13	0.01	0.03	0.01

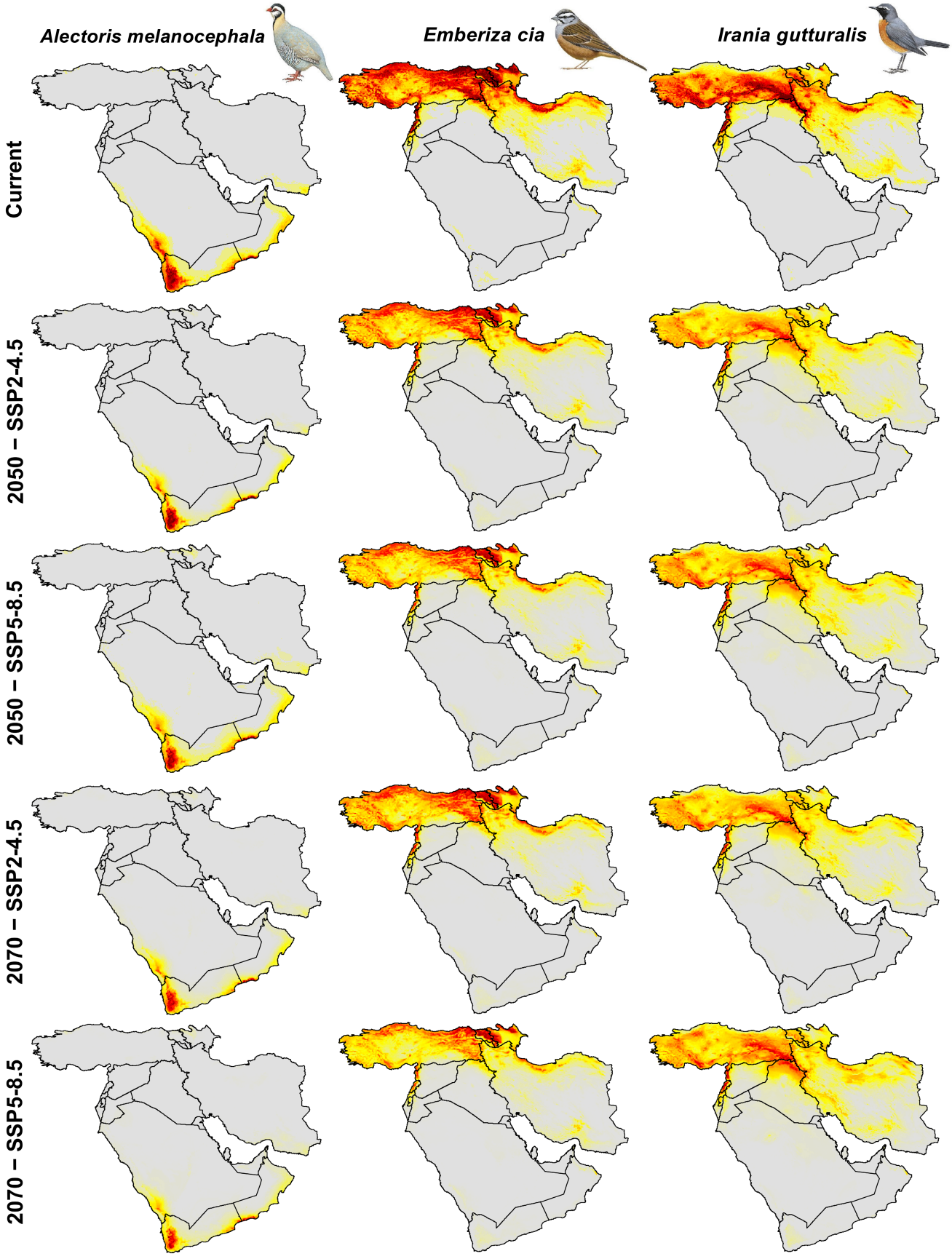

FIGURE 2 Predicted suitable habitats of the current and future climate change scenarios of three alpine birds.

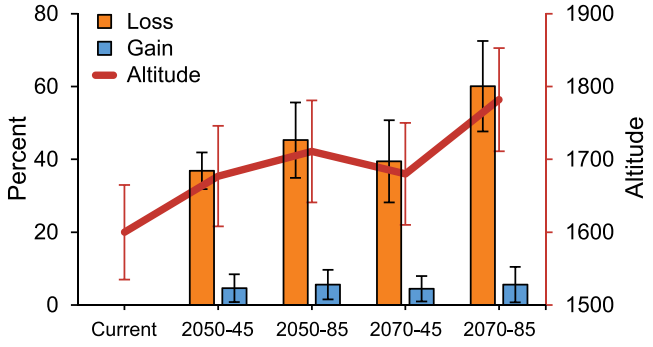

FIGURE 3 Mean and standard deviation of habitat loss, habitat gain and altitude of 38 alpine birds' suitable habitats for current, 2050 SSP2-4.5 (2050–45), 2050 SSP5-8.5 (2050–85), 2070 SSP2-4.5 (2070–45) and 2070 SSP5-8.5 (2070–85).

The comparison of range shifts between semi-alpine and alpine bird species revealed that both groups will probably experience greater habitat loss than habitat gain (Figure 5). Interestingly, the *t*-test analysis revealed that the habitat loss for alpine birds was significantly greater than for semi-alpine birds (p-value <0.05) under all climate change scenarios. In contrast, habitat gain for semi-alpine species was greater than for alpine birds; however, this difference was only statistically significant (p-value <0.05) under the SSP2-4.52070 climate change scenario (Figure 5).

Species-specific comparisons of climate refugia indicated that, for all species, the extent of climate refugia will decline by the time and from moderate to severe climate change scenarios (see Table S4). Among the studied species, *A. chukar*, *Oenanthe xanthoprymna*, *Tetraogallus caspius* and *S. tephronota* were identified as top

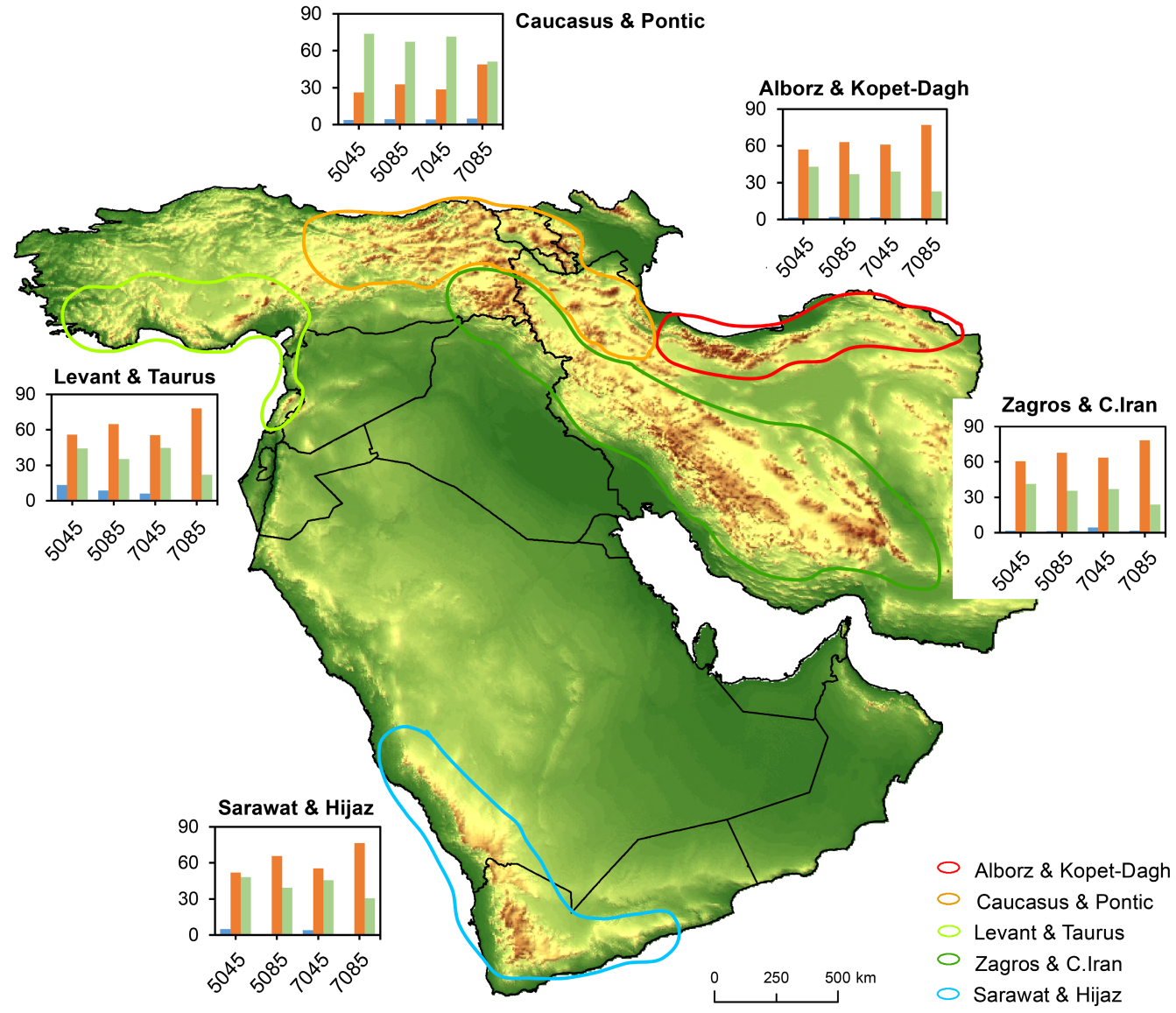

FIGURE 4 Mean of habitat gain (blue), habitat loss (orange) and unchanged habitats (green) of 38 alpine birds across five Middle Eastern mountainous regions under future climate change scenarios: 2050 SSP2-4.5 (5045), 2050 SSP5-8.5 (5085), 2070 SSP2-4.5 (7045) and 2070 SSP5-8.5 (7085).

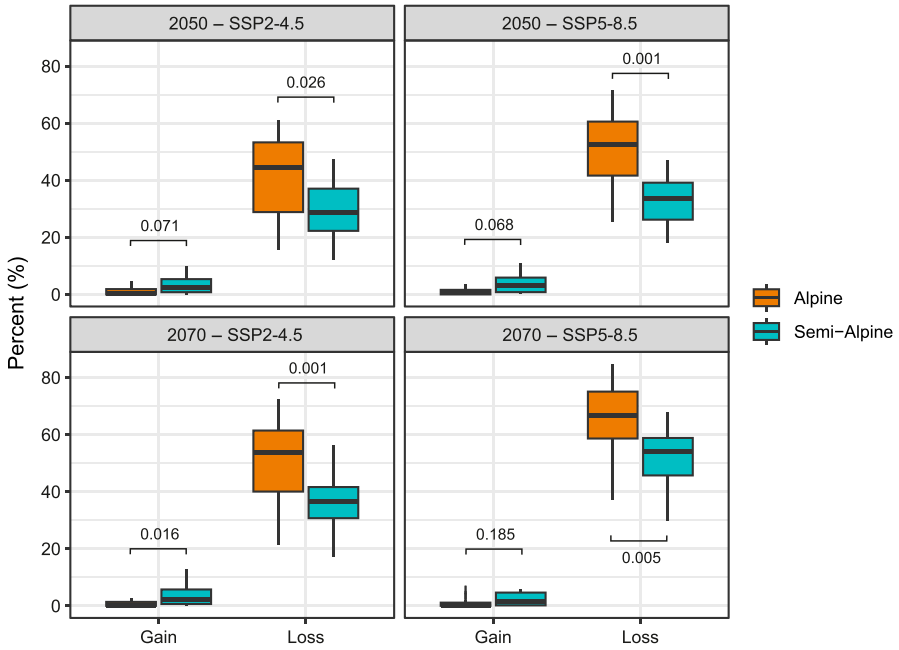

FIGURE 5 Habitat loss and gain for alpine and semi-alpine birds. A *t*-test was used to compare the significance of habitat loss and gain between alpine and semi-alpine birds. Bonferroni-adjusted *p*-values are indicated above and below the boxplots.

TABLE 2 Results of the gap analysis of the Middle East's PAs network in supporting Type 1 refugia and Type 2 refugia different climate change scenarios by 2050 and 2070. Area values are in km^2.

	Refuge type 1				Refuge type 2			
	Area	Percent	Protected	Percent	Area	Percent	Protected	Percent
2050—SSP2-4.5	625,432	10.19	80,117	12.81	45,790	0.75	3786	8.27
2050—SSP5-8.5	550,237	8.97	72,466	13.17	43,022	0.70	4022	9.35
2070—SSP2-4.5	613,611	10.00	78,726	12.83	43,471	0.71	3808	8.76
2070—SSP5-8.5	379,419	6.18	51,980	13.70	33,071	0.54	4133	12.50
Average	542,175	9	70,822	13	41,339	1	3937	10

four species with the greatest unchanged suitability from current to all climate change scenarios, for example, Type 1 refugia. *S. tephronota*, *Sylvia buryi*, *T. caspius* and *Prunella collaris* obtained the greatest extent of climate Type 2 refugia (Table S4). The results of the gap analysis indicated that while Type 1 refugia encompass, on average, 9% of the region only 13% of their total extent will be potentially covered by the current network of PAs (Table 2 and Figure 6). This pattern was notably different for Type 2 refugia where their extent covers only 1% of the region but 10% of it will be covered by the current network of PAs. We also found that, while by the time and from moderate to severe climate change scenarios, the extent of Type 1 refugia and Type 2 refugia will decrease the conservation coverage of the PAs will slightly increase (Table 2 and Figure 6).

4 | DISCUSSION

In the past decades, there has been a decrease in species richness in mountain ranges (Lehikoinen et al., 2019; Pauli et al., 2012). In this case, climate refugia are crucial for species survival, particularly those that are sensitive to climate change, as they provide conservation opportunities for long-term persistence (Brambilla et al., 2022; Morelli et al., 2020). This study focuses on identifying the most significant climate refugia for 38 native Alpine bird species in the Middle East using a combination of spatially explicit SDMs and future climate change scenarios. Our choice to focus on these particular species and their vulnerable arid habitat was motivated by several reasons. Alpine birds are crucial representatives of high-elevation biodiversity, and they are currently facing a decline in habitat and increased extinction rates due to environmental change (Foden et al., 2013; Lehikoinen et al., 2019). Moreover, alpine habitats act as sky islands and play a critical role in long-term species persistence, particularly concerning climate change.

4.1 | Birds range shift

Our results represent an ongoing major range contraction of endemic alpine birds from current to 2050 and 2070, in particular, due to the increase in temperature, which was the most influencing drivers of environmental suitability for most of the target species. To our knowledge, our study is the first attempt to assess the impact

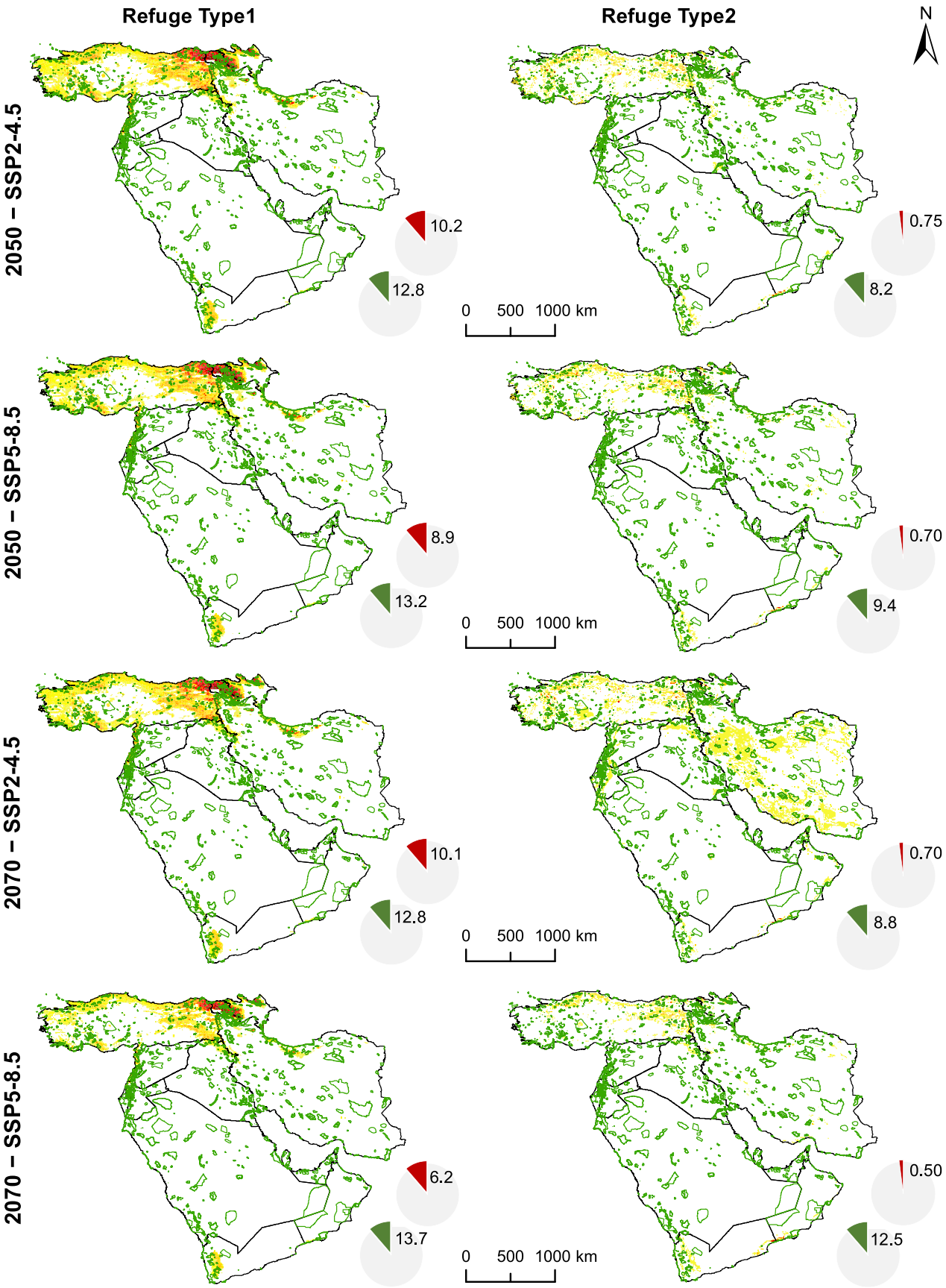

FIGURE 6 Distribution of the climate refugia and PAs of the region in future climate scenarios. Pie charts and values indicate proportion of climate refugia from whole region (red) and those covered by the PAs (green).

of climate change on Middle Eastern alpine birds. However, our estimation of species' range contraction is higher than in other regions, especially in comparison to Europe where species composition is similar to our region. For example, while Brambilla et al. (2022) and de Gabriel Hernando et al. (2021) reported an average of 24% and 36% range contraction of *M. nivalis* and 26% and 35% for *P. collaris* in the European Alpine habitats under the similar climate change scenarios, we projected 54% and 40% range contraction for these species in the Middle Eastern alpine habitats. Similarly, the projected range loss of *P. graculus* in our study was greater than that of European Alpine, 26% versus 16% obtained by de Gabriel Hernando et al. (2021). A few studies that modelled the impact of climate change on other taxonomic groups inhabiting alpine habitats in the Middle East have generally identified patterns of range loss. Ahmadi et al. (2019) predicted, on average, 79% range contraction for mountain vipers with possible extinctions in the alpine regions of eastern Mediterranean. Similar patterns of range contraction were projected for the amphibians of the Near and Middle East (Niknaddaf et al., 2023; Vaissi, 2021) due to future climate warming. In addition to climate change-driven range shift, it is also argued that elevated temperatures increase physiological stress (Wingfield et al., 2011) and decrease reproductive success (Dreitz et al., 2012), as well as causing phenological mismatches between food availability and energetic demands (Saalfeld et al., 2019) or raising the competition and predation risk between species (Lurgi et al., 2012).

The predicted climate models demonstrated contraction of suitable areas for most species under climate change, and the general patterns appeared consistent across GCMs. Such a contraction, according to the 'worst scenario' SSP5-8.5, may imply a loss of 81–85% of suitable range for *E. alpestris*, *P. graculus* and *C. rothschildi*, all of which known as specialist alpine birds. Contrarily, we found that changes may be less marked for generalist species such as *A. Chukar*, *T. melba* and *E. cineracea*. This pattern was reflected in comparing alpine and semi-alpine groups where habitat loss of the alpine birds was significantly greater than that of semi-alpine birds. As broadly documented (Chamberlain et al., 2013; Jähnig et al., 2020), semi-alpine species due to broader geographic distribution are exposed to a wider range of environmental conditions across their range compared to alpine species with restricted geographic ranges and more specialized habitat requirements. Such an unfavourable outlook for specialized species towards climate change is coherent with previous studies (Ahmadi et al., 2019; Thuiller et al., 2005). Adaptation to a broad range of climatic conditions throughout a species' distribution is thought to confer a higher tolerance to climate change, in contrast to species with more restricted ranges (Wiens, 2016). Accordingly, there is a linear correlation between niche breadth and the percentage of stable habitat (Thuiller et al., 2005), suggesting that species occupying a wider range of climatic conditions are more likely to be able to withstand the effects of climate change (Devictor et al., 2012; Şekercioğlu et al., 2012).

One of the important findings of this study is that all alpine birds in the Sarawat and Hijaz Mountains are projected to experience no range gain, resulting in the smallest size of Type 2 refugia in the southern Arabian Peninsula. This could be attributed to their marginal position on the temperature gradient, resulting in the expectation of the lowest proportion of new habitats gained during climate change (Abeli et al., 2018; Thuiller et al., 2005). The Sarawat and Hijaz Mountain range, with peaks over 3000 m high, influences local climate by retaining rainy clouds from winter winds in the northwest and catching the tail of the southwest monsoon in summer, resulting in high precipitation (Patlakas et al., 2019). The region's microclimatic zones, determined by topography, winds and proximity to the sea, allow for the development of rich biodiversity and high rates of endemism in a such a low-latitude bioregion (Al-Namazi et al., 2021). As suggested by Abeli et al. (2018), the persistence of cold-adapted species in low-latitude refugia may possess a combination of alleles that promote resilience to the challenges posed by a warmer climate. However, the isolated geographic position and increasing pressures due to land use change, especially in terms of man-made agricultural terraces in high-elevated areas, highlight the necessity to implement long-term management plans in this biodiversity hotspot.

Overall, between-mountains comparison revealed Levant–Taurus, Zagros–Central Iran and Alborz–Kopet-Dagh as most threated areas losing greatest extent of climatic suitability in the near future. All of this high-elevated regions have long been recognized as substantial centres of species richness and endemism due to their important functioning as palaeontological refugia in the past, particularly during Plio-Pleistocene climatic oscillations (Ahmadi et al., 2018; Médail & Diadema, 2009; Rajaei Sh et al., 2013). Dramatically, a previous study revealed that the significant alteration in the climate of the Middle East pertains to a reduction in rainfall, especially across Eastern Mediterranean, that is, Turkey, Syria (Taurus and Levant), Northern Iraq and western Iran (Zagros) and North and Northeastern Iran (Alborz and Kopet-Dagh) by the end of the century (Evans, 2009). Furthermore, the region is expected to experience a sustained, gradual and relatively intense temperature rise of around 3.5–7°C by the end of the century (Lelieveld et al., 2012). Coupled with climate, the structure of land use and land cover (LULC) in the eastern Mediterranean region is highly dynamic and has been continuously transforming due to a long history of anthropogenic effects and rural dynamics (Ersoy Mirici et al., 2018; Sharifi et al., 2021). The increase in the frequency and intensity of droughts and hot weather conditions, in addition to the lengthening of the dry season, water resource shortage and vegetation cover degradation (Heidarlou et al., 2019; Nouri et al., 2019), will have an impact on the growing season and cropping strategies in the region. More importantly, the impact of climate change and LULC change on biodiversity can be much more severe when they occur in synergy (Marshall et al., 2018; Ostberg et al., 2015). Accordingly, human land use activities, such as deforestation, agricultural expansion and urbanization, lead to habitat fragmentation and degradation, thereby creating novel stressors that further reduce the ability of species to adapt to changing climatic conditions (Brook et al., 2008; Sih et al., 2011).

Furthermore, due to climate change and its indirect impacts, several ecological processes are at risk, including vegetation succession

dynamics in high-elevation areas. In this regard, habitats and species beyond the tree line are particularly susceptible (Malfasi & Cannone, 2020). As a result, increasing temperatures prompt the encroachment of shrubs and trees onto uphill grasslands, often impeded by abiotic limitations that hinder their upward movement (Cannone et al., 2007). To cite an example, Chamberlain et al. (2013) and Jähnig et al. (2020) showed that the distribution of the majority of forest or shrub birds either remains intact or increases, while species inhabiting open habitats at higher elevations may lose their habitats due to the encroachment of newcomers into upper grasslands in European alpine systems. The abandonment of extensive grasslands and pastures in many mountain systems, coupled with agricultural intensification in the remaining ones, is exacerbating the contraction of grasslands which causing negative effects on alpine birds (Jähnig et al., 2020; Scridel et al., 2018).

4.2 | Modelling limitations

Apart from uncertainties associated with biological factors, there are also methodological uncertainties that arise from variations in data sources and statistical techniques employed for niche and climate modelling, such as SDMs, GCMs and emission scenarios (Araújo et al., 2019; Chauvier et al., 2021; Zurell et al., 2020). It is widely argued that different SDMs and GCMs are the major contributor to uncertainty in predicting species range shifts, as noted by various studies (Ahmadi et al., 2023; Shabani et al., 2019; Thuiller et al., 2009). Here, we tailored several methods to take into account SDM uncertainty arisen from different aspects. First, and before the SDM analysis, we used spatial filtering method for each species to relieve spatial bias of the input data. Second, and during the SDM analysis, we used a range of simple regression-based and machine learning methods and integrate them to an ensemble model to use the ability of models' extrapolation and interpolation in finding potential suitable habitats of the species (Merow et al., 2014; Zurell et al., 2020). This also allowed us to take into account model-specific uncertainties raised from their inherent modelling algorithm (Araújo & New, 2007).

However, our predictive models might suffer some levels of uncertainty due to the lack of future predictions for specific variables. Therefore, caution must be exercised when interpreting our future projections. Specifically, species-specific traits such as dispersal ability, phenotypic plasticity, and climatic niche breadth can essentially influence their response to climate change (Jiang et al., 2023; Ma et al., 2021; Sauve et al., 2021). Incorporating species' physiological, ecological, and evolutionary traits, together with predictions of their exposure to climate change, can lead to more precise identification of species at high risk (Fordham et al., 2012; Schleuning et al., 2020). Furthermore, we did not consider potential changes in land use, tree line elevation, or specific macroclimatic variables, which could alter our projections. Despite this, it is doubtful that accounting for future changes in these variables would reduce the predicted range loss and upward shift in the Palaearctic, as the tree line is projected to move upwards (Leonelli et al., 2011), windiness is expected to shift northwards and snowfall is expected to decrease during the present century (Lelieveld et al., 2012). Moreover, long-lived species like the majority of alpine specialists could postpone their responses to climate change, as they can persist in unsuitable habitats while undergoing a decline in population size due to climatic maladaptation (Cotto et al., 2017). In this case, the negative effects of rising macroclimate temperatures on cold-adapted species might be buffered and their movement or extinction delayed in small-scale situations with special microclimates (Maclean et al., 2015; Scherrer & Körner, 2011). Microrefugia in such areas can serve as stepping stones for future range expansions (Hannah et al., 2014); hence, the management of the existing population requires a comprehensive attitude towards current and future scenarios facing conservation-oriented decision-making (Beaumont et al., 2019).

4.3 | Conservation implications

National Red Lists tend to have a lack of representation for species that inhabit alpine regions (Franzén & Molander, 2012). Through providing buffer areas to track suitable habitats, heterogeneous landscape of mountains plays a key role in persistence of alpine species towards climate change (Brambilla et al., 2022; Hannah et al., 2014). In the Middle East, where high-elevation habitats are limited, protecting these species becomes even more important. Nevertheless, according to our research, current network of protected areas is unable to completely prevent habitat quality degradation. Our gap analysis reveals that, under the moderate and severe scenarios of climate change, the current PAs network will cover only 13% of the surface of climate refugia Type 1. This proportion falls below the conservation goals set by the Aichi Targets of COP10 and the Biodiversity Framework of COP15 of the Convention on Biological Diversity (CBD) for 2020 and 2030, respectively, which aim for 17% and 30% of lands under protection (CBD Secretariat, 2020). For climate Type 2 refugia, this pattern differs as these areas will only cover a small fraction of the total area of the region, for example, 0.75% in SSP2-4.52050 to 0.5% in SSP5-8.52070, yet between 8.3% and 12.5% of their extent will be covered by current PAs, respectively. Regos et al. (2016) found a similar pattern where the effectiveness of N2000 for birds' conservation in a Spanish Mediterranean ecosystem is expected to increase in the next decades because the amount of suitable habitats is predicted to decrease less inside than outside this network. For Middle Eastern PAs, the observed pattern can be attributed mainly to the selection of protected areas in the region. These areas are usually confined to mountainous regions where they are not conducive to human development (Ahmadi et al., 2020). Although we used the most up-to-date versions of protected areas available, we recognize that there may be georeferencing errors or uneven accessibility to PAs across countries, which could impact the accuracy of our conservation conclusions.

Altogether, with global warming and the shift of species' habitats towards higher elevations, the role of the current network of

protected areas in the region will become increasingly promising. However, these sky islands may eventually lose their conservation efficiency due to their isolation and lack of habitat connectivity over time. It is also worth mentioning that three of the four near threatened birds in the region, *Lyrurus mlokosiewiczi*, *S. buryi* and *Turdus menachensis* are specialized species belonging to the alpine groups and only one species, *E. cineracea*, inhabits semi-alpine regions with broader availability of environmental requirements. Our gap analysis for these species revealed that *S. buryi* and *T. menachensis*, both found in Sarawat and Hijaz mountains, are exposed to more than 50% habitat loss with no availability of climate refugia Type 2 under any of the future climate change scenarios. For *L. mlokosiewiczi*, while habitat loss was low, 16–38%, there also will be no availability of climate refugia Type 2. This finding again underscores the importance of conserving the current suitable habitats to ensure the long-term persistence of the near threatened species of the region.

Hence, we recommend that well-established conservation strategies must be more engaged with prioritizing ecologically representative, well-connected and equitably governed systems of PAs. Additionally, the degree of altitudinal heterogeneity is a crucial factor that influences the velocity of climate change and affects the vulnerability of PAs to climate change (Malakoutikhah et al., 2018). PAs with higher altitudinal heterogeneity offer more opportunities for their resident species to migrate uphill (Brambilla et al., 2022). However, the majority of the PAs of the regions are relatively small in size, which limits their ability to support upward movements of species over a prolonged period, or even to sustain large enough populations for survival. Therefore, it is necessary to create new protected areas that consider maximizing climate space, abiotic diversity (e.g. geology, soils, hydrology) and structural heterogeneity (e.g. elevation, topography, habitats) to address this issue (Beaumont et al., 2019; Schloss et al., 2011). We recommend prioritizing the conservation of high-elevation species in the Middle East by designating the identified climate refugia as priority areas. The conservation sites of the future should rely on functional landscapes that will likely remain viable over extended periods of time and provide the environmental diversity required for biodiversity to adapt to global change. These issues have national and international significance; thus, limiting global temperature increases and planning for priority setting transboundary conservation measures is essential to sustain alpine biodiversity towards the negative impacts of future climate change.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All data used for modelling species distribution including species occurrence points, background data, climatic variables for current and future (2050 and 2070) and the R code designed to perform the SDM analysis are openly available in Dryad at: https://doi.org/10.5061/dryad.np5hqbzzv

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BIOSKETCH

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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