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Bird diversity and density across elevation gradients in Hyrcanian forests: Unraveling ecological patterns, mechanisms, and conservation strategies

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ABSTRACT
Understanding diversity patterns along elevation gradients is critical for conservation. This study examined bird diversity and density in relation to environmental variables across elevation gradients in the Saadabad-Naharkhoran forest, a subregion of Iran's Hyrcanian forests. Birds and environmental variables were recorded within a 25-meter radius at 62 sampling points during autumn and winter 2017–2018. Density was estimated using DISTANCE 6.0, and diversity patterns were analyzed using Canonical Correspondence Analysis (CCA) in CANOCO 4.5. Results revealed distinct bird communities across two elevation classes. Species such as the Coal Tit, Great Tit, and Blackbird were associated with the first elevation class and correlated with variables like shrub cover, temperature, and leaf litter percentage. In contrast, species such as the Tree creeper, Great Spotted Woodpecker, and Nuthatch were associated with the second elevation class and correlated with humidity, canopy cover, and large-diameter trees. These findings highlight the significant influence of elevation gradients and habitat structure on bird community composition. The results underscore the importance of preserving old-growth forest structures and maintaining habitat mosaics to support biodiversity. This study provides valuable insights for sustainable forest management in the Hyrcanian forests, emphasizing the need to balance harvesting practices with conservation efforts.

Keywords: Conservation - Elevation gradients - Habitat structure - Hyrcanian forests - Species distribution.
Article type: Research Article.

INTRODUCTION
The Hyrcanian forests of northern Iran, a UNESCO World Heritage Site, represent one of the last remnants of temperate deciduous forests globally (UNESCO 2019). Stretching along the southern coast of the Caspian Sea and the northern slopes of the Alborz Mountains, these forests cover approximately 1.84 million hectares and are renowned for their exceptional biodiversity, including numerous endemic species of flora and fauna (Akhani *et al.* 2010; Siadati *et al.* 2010). The Hyrcanian forests are not only a biodiversity hotspot but also a critical carbon sink, playing a vital role in mitigating climate change (Hosseini *et al.* 2012; Watson *et al.* 2018). However, this unique ecological region faces significant threats from human activities, such as urban expansion, unsustainable logging, agricultural encroachment, and infrastructure development, which jeopardize its ecological integrity (Akhani *et al.* 2010; Siadati *et al.* 2010). These challenges underscore the urgent need for effective conservation strategies to preserve the Hyrcanian forests and their biodiversity. In ecological research, understanding the relationship between species and their habitats is crucial for conservation planning and ecosystem management

(Morrison *et al.* 1998; Fahrig 2003). Birds, due to their high mobility and sensitivity to environmental changes, serve as excellent indicators of habitat quality and ecosystem health (Marchetti 2004; Gregory *et al.* 2005). Their distribution and abundance are influenced by both vegetation structure and elevation gradients, which shape resource availability, microclimatic conditions, and habitat heterogeneity (Seoane *et al.* 2004; Jankowski *et al.* 2009). While vegetation directly provides essential resources such as food, shelter, and nesting sites, elevation indirectly affects bird communities by altering vegetation composition and structure (Stevens, 1992; McCain & Grytnes 2010). For example, at higher elevations, reduced temperatures and increased environmental variability often lead to distinct bird assemblages, reflecting changes in forest structure and resource availability (Herzog *et al.* 2011; Jankowski *et al.* 2013). Consequently, integrating elevation and vegetation variables can enhance our understanding of bird-habitat relationships and improve predictive models (Seoane *et al.* 2004; Jankowski *et al.* 2013). Despite the ecological significance of the Hyrcanian forests, few studies have explored the relationship between bird communities and habitat variables across elevation gradients in this region (Ghadiri Khanposhtani *et al.* 2012; Shariati Najafabadi & Kaboli 2012). Most existing research has focused on lowland areas, leaving a gap in our understanding of how bird communities respond to elevation-driven changes in habitat structure (Shariati Najafabadi *et al.* 2011). This study was conducted in the Saadabad-Naharkhoran forest, located in the eastern part of the Hyrcanian forests. It aimed to investigate the density and diversity of bird communities across two elevation classes; to determine the relationship between bird species and habitat variables at different elevations. The findings of this study will provide valuable insights for the conservation and sustainable management of the Hyrcanian forests, contributing to the broader understanding of bird-habitat relationships in temperate deciduous forests globally. By identifying key habitat variables that influence bird communities, this research will inform targeted conservation strategies to mitigate the impacts of human activities and climate change on these ecologically significant forests.

MATERIALS AND METHODS

Study area

We conducted our study in the Saadabad-Naharkhoran forest, located in the southwest of Gorgan, Iran. This area is part of the Hyrcanian forests, a UNESCO World Heritage Site known for its unique biodiversity and ecological significance (UNESCO, 2019). The study area covers approximately 4,232 hectares and is situated within the geographical coordinates of 54°22' to 54°29' E longitude and 36°43' to 36°50' N latitude. The elevation ranges from 150 to 1,300 meters above sea level, with an average elevation of 400–500 meters. The elevation gradient was divided into two classes (0–400 m and 400–700 m) for analysis, based on a documented shift in forest structure and dominant tree species composition within the Hyrcanian region, which corresponds to changes in temperature, humidity, and resource availability for avian communities (Shariati Najafabadi & Kaboli 2012; Ghadiri Khanposhtani *et al.* 2012a). The terrain is characterized by an average slope of less than 30%, although some areas exhibit slopes of up to 80% (Fig. 1).

Bird sampling

Bird sampling was conducted using the point-count method within circular plots. Each plot had a radius of 25 meters, and observations were made from the center of the plot to minimize the risk of double-counting individuals (Watson *et al.* 2004). Plots were spaced 200 meters apart to ensure spatial independence (Antongiovanni & Metzger 2005). Each sampling session lasted 15 minutes, during which all birds observed or heard within the plot were recorded (Marsden *et al.* 2001). Species identification was aided by 8 × 30 binoculars, and only birds observed within the plot boundaries were included in the data. Bird calls were used solely for locating individuals and not for species identification unless visually confirmed. Field surveys were conducted during daylight hours, from sunrise to 11:00 AM, under suitable weather conditions (i.e., no heavy rain, fog, or strong winds). Data collection took place between September 2017 and March 2018, covering the non-breeding season to capture seasonal bird diversity. A total of 62 plots were sampled, with 31 plots allocated to each of two elevation classes: 0–400 and 400–700 meters. Plots were selected using a systematic random sampling approach to ensure representative coverage of the study area.

Sampling

Recording environmental factors

We recorded twenty environmental factors known to influence bird habitat selection. These factors were measured within a 25-meter radius from the center of each plot (Castelletta *et al.* 2005). The environmental variables included in this study are as follows:

Microclimatic factors: Temperature (TM) and humidity (HU).
Vegetation structure: Canopy cover (CC), number of strata (ST), grass cover (GC), shrub cover (SHR), and leaf litter characteristics (leaf litter depth [LLD] and leaf litter percentage [LLP]).
Topographic features: Rock cover (ROC).
Tree characteristics: Number of trees with DBH of 12–20 cm (NT20), 20–50 cm (NT50), 50–100 cm (NT100), and 100–300 cm (NT300), as well as the average DBH of trees (DBH).
Coarse woody debris: Average height of snags (SHIG), average height of logs (LHIG), average DBH of snags (SDBH), average DBH of logs (LDBH), decay degree of snags (SDD), and decay degree of logs (LDD).
These factors were selected based on their documented importance in shaping bird habitat preferences and community composition in forest ecosystems (e.g., Waterhouse *et al.* 2003; Smith *et al.* 2020).

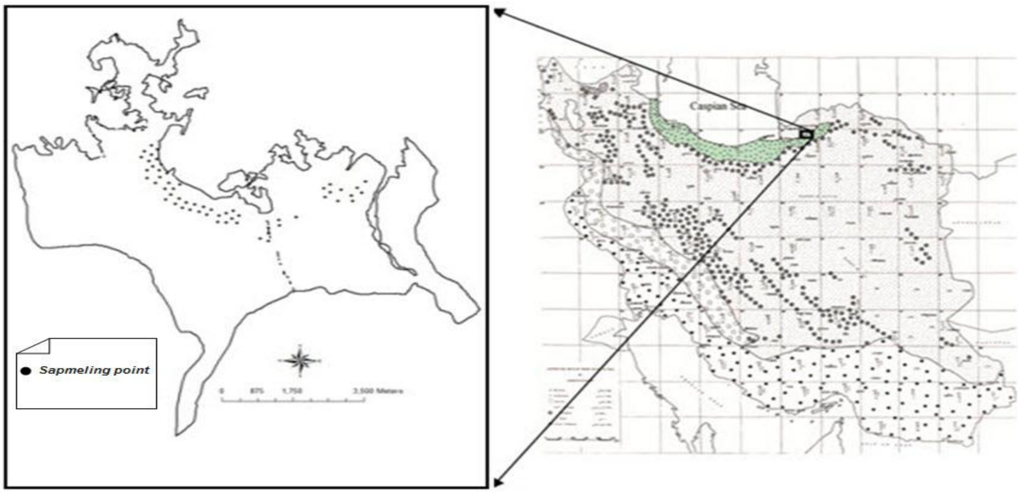


Fig. 1. Map showing the location of Saadabad-Naharkhoran forest in Iran.

Data analysis

To assess the normality of the data, we used the Kolmogorov–Smirnov test. For analyzing bird community diversity, we employed the Canoco 4.5 software package (Ter Braak & Šmilauer, 2018). To visualize the variation in species diversity in response to environmental factors, we generated bi-plot graphs that included environmental factors and isolines of species diversity indices based on the species present in the study area. Additionally, we analyzed the relationship between bird species abundance and environmental factors. Before applying the Unimodal Ordination Method, we conducted a Detrended Canonical Correspondence Analysis (DCCA). The significance of the Canonical Correspondence Analysis (CCA**)** was tested using the Monte Carlo permutation method (Jangman *et al.* 1992). To explain the relationship between bird species distribution and environmental factors, we applied Redundancy Analysis (RDA) and CCA for the autumn and winter seasons respectively. Furthermore, to identify indicator species and determine the most influential environmental variables affecting bird species distribution, we used RDA **(**for autumn**)** and CCA (for winter) with a forward selection process.
Bird species density was estimated using the DISTANCE 6 software (Buckland *et al.* 2001). We evaluated five models as key functions, which included:
Half-normal + Cosine
Half-normal + Hermite
Uniform + Cosine
Uniform + Polynomial
Hazard-rate + Cosine
The final model was selected based on the Akaike Information Criterion (AIC). The reported density values are presented as the mean ± standard error (SE).

RESULTS

Density estimates

During the study, a total of 677 individual birds were observed and recorded across 62 sampling plots. These observations comprised 20 different bird species in the region (see Appendix 1 for the complete list of species).

Autumn

The density of 11 bird species was estimated across different elevation classes during the autumn season **(**Table 1). Other bird species were excluded from the density estimation due to insufficient observation data. This exclusion was necessary to ensure the accuracy and reliability of the density estimates, as low sample sizes can lead to biased results (Buckland *et al.* 2001).

Table 1. Density estimates (individuals per ha, mean ± standard error) for 11 bird species in relation to different elevation classes during the autumn season.

Species	Elevation 1	Elevation 2	Total	Model
Blue Tit (*Parus caeruleus)*	3.688 ± 0.25	3.29 ± 0.1	3.49 ± 0.14	Uniform Cosine
Blackbird (*Turdus merula)*	2.3 ± 0.13	2.95 ± 13	2.62 ± 0.09	Uniform Cosine
Coal Tit (*Parus ater)*	7.68 ± 1.36	7.33 ± 1.33	7.51 ± 1.32	Hazard/Cosine
Chaffinch (*Fringilla coelebs)*	3.49 ± 0.28	7.95 ± 1.1	5.72 ± 0.57	Uniform Hermite
Great Spotted Woodpecker *(Dendrocopos major)*	1.15 ± 0.05	2.62 ± 0.96	3.688 ± 0.55	Uniform Cosine
Great Tit (*Parus major)*	4.92 ± 0.3	2.46 ± 0.17	3.69 ± 0.17	Uniform Hermite
Long Tiled Tit *(Aegithalos caudatus)*	12.21 ± 15.01	0.00	6.11 ± 7.5	Hazard Cosine
Nuthatch (*Sitta europaea)*	1.16 ± 0.03	2.71 ± 0.15	1.94 ± 0.08	Uniform Cosine
Robin (*Erithacus rubecula)*	6.15 ± 1.23	4.53 ± 0.99	5.34 ± 1.12	Uniform Cosine
Treecreeper (*Certhia familiaris)*	0.25 ± 0.00	0.77 ± 0.02	0.51 ± 0.01	Uniform Cosine
Wren *(Troglodytes troglodytes)*	0.21 ± 0.00	0.84 ± 0.02	0.53 ± 0.01	Uniform Cosine

Density patterns across elevation classes

Based on our results, different bird species exhibited distinct density patterns across the two elevation classes in the study area (Table 1). Among the 11 species analyzed for density, the highest total densities were observed for the Long-tailed Tit (*A. caudatus*; 6.11 ± 7.5 individuals ha^{-1}), Chaffinch (*F. coelebs*; 5.72 ± 0.57 individuals ha^{-1}), and Coal Tit (*P. ater*; 7.51 ± 1.32 individuals ha^{-1}). In contrast, the lowest densities were recorded for the Nuthatch (*S. europaea*; 1.94 ± 0.08 individuals ha^{-1}), Wren (*T. troglodytes*; 0.53 ± 0.01 individuals ha^{-1}), and Treecreeper (*C. familiaris*; 0.51 ± 0.01 individuals ha^{-1}; Table 1).

The results indicate that bird species can be categorized into distinct groups based on their responses to the elevation gradient:

Group 1: Species such as the Chaffinch, Great Spotted Woodpecker (*D. major*), Nuthatch, Treecreeper, and Wren showed higher densities in the second elevation class compared to the first elevation class.

Group 2: Species such as the Great Tit (*P. major*), Long-tailed Tit, and Blue Tit (*C. caeruleus*) exhibited higher densities in the first elevation class compared to the second one (Table 1).

These patterns suggest that elevation gradients play a significant role in shaping bird species distribution and density, likely due to variations in habitat structure, microclimate, and resource availability across the elevation classes (Waterhouse *et al.* 2003; Smith *et al.* 2020).

Density estimates in winter

The density of 13 bird species was estimated across different elevation classes during the winter season (Table 2). Among the species analyzed, the highest total densities were recorded for the Chaffinch (*F. coelebs*; 8.44 ± 0.24 individuals ha^{-1}), Great Tit (*P. major*; 6.64 ± 0.55 individuals ha^{-1}), and Coal Tit (*P. ater*; 5.44 ± 1.46 individuals ha^{-1}). In contrast, the lowest densities were observed for the Jay (*G. glandarius*; 0.26 ± 0.01 individuals ha^{-1}), Wren (*T. troglodytes*; 0.67 ± 0.02 individuals ha^{-1}), and Lesser Spotted Woodpecker (*D. minor*; 0.42 ± 0.01 individuals ha^{-1}; Table 2).

Based on the results, the studied bird species can be categorized into distinct groups according to their responses to the elevation gradient:

Group 1: Species such as the Chaffinch, Great Spotted Woodpecker (*D. major*), Lesser Spotted Woodpecker, and Coal Tit exhibited higher densities in the second elevation class compared to the first one.

Group 2: Species such as the Great Tit, Wren, Jay, and Blackbird (*T. merula*) showed higher densities in the first elevation class compared to the second one (Table 2).

These findings highlight the influence of elevation gradients on bird species distribution during the winter season, likely due to variations in habitat structure, microclimate, and resource availability across the elevation classes (Waterhouse *et al.* 2003; Smith *et al.* 2020).

Table 2. Density estimates (individuals per ha, mean ± standard error) for 13 species in relation to different elevation classes in winter season.

Species	Elevation 1	Elevation 2	Total	Model
Blue Tit (*Parus caeruleus)*	4.27 ± 0.22	4.81 ± 0.21	4.54 ± 0.15	Uniform/Hermite
Blackbird (*Turdus merula)*	1.96 ± 0.13	1.06 ± 0.04	1.51 ± 0.06	Uniform/Cosine
Coal Tit (*Parus ater)*	4.08 ± 1.06	6.8 ± 1.9	5.44 ± 1.46	Uniform/Cosine
Chaffinch (*Fringilla coelebs)*	5.43 ± 0.35	11.45 ± 0.3	8.44 ± 0.24	Uniform/Cosine
Great Spotted Woodpecker *(Dendrocopos major)*	0.89 ± 0.02	3.03 ± 0.09	1.96 ± 0.05	Uniform/Hermite
Great Tit (*Parus major)*	8.08 ± 0.72	5.19 ± 0.47	6.64 ± 0.55	Hazard/Cosine
Jay (*Garrulus glandarius)*	0.53 ± 0.03	0.00	0.26 ± 0.01	Uniform/Hermite
Lesser Spotted Woodpecker *(Dendrocopos minor)*	0.00	0.84 ± 0.02	0.42 ± 0.01	Uniform/Cosine
Long Tailed Tit *(Aegithalos caudatus)*	2.49 ± 0.16	3.2 ± 0.26	2.85 ± 0.15	Uniform/Cosine
Nuthatch (*Sitta europaea)*	1.06 ± 0.04	1.42 ± 0.05	1.24 ± 0.03	Uniform/Cosine
Robin (*Erithacus rubecula)*	0.58 ± 0.03	0.77 ± 0.02	0.67 ± 0.02	Uniform/Cosine
Treecreeper (*Certhia familiaris)*	0.00	3.8 ± 0.11	1.9 ± 0.06	Uniform/Cosine
Wren (*Troglodytes troglodytes)*	1.06 ± 0.06	0.89 ± 0.04	0.98 ± 0.04	Uniform/Hermite

Bird community analysis

Autumn

A strong relationship was observed between environmental variables and the abundance of understory avian species. The overall ordination of species along environmental gradients was statistically significant (p = 0.02, Monte Carlo simulations with 999 permutations). The first two axes of the Redundancy Analysis (RDA) explained 50.1% variation in species data that could be attributed to environmental variables. Specifically, the first two axes accounted for 31.7% of the total variation, representing 15.9% of the variation in understory bird species. The species-environment correlations for the first two axes were 0.7 and 0.66, respectively.

As illustrated in Fig. 2, the RDA analysis divided the bird species into two main groups:

Group 1: Species such as the Coal Tit (*P. ater*), Great Tit (*P. major*), Blue Tit (*C. caeruleus*), Long-tailed Tit (*A. caudatus*), Sombre Tit (*Poecile lugubris*), Tawny Owl (*Strix aluco*), Green Woodpecker (*P. viridis*), Song Thrush (*Turdus philomelos*), and Blackbird (*T. merula*) showed positive responses to the first elevation class. These species were strongly correlated with environmental variables such as the number of trees with a DBH of 12–20 cm, temperature, shrub cover, rock cover, log height, stratum, and leaf litter percentage.

Group 2: Species such as the Treecreeper (*C. familiaris*), Great Spotted Woodpecker (*D. major*), Lesser Spotted Woodpecker (*D. minor*), Wren (*T. troglodytes*), and Nuthatch (*S. europaea*) exhibited positive responses to the second elevation class. These species were positively correlated with environmental variables such as humidity, canopy cover, number of trees with a DBH of 50–100 cm, number of trees with a DBH of 100–300 cm, and ground cover.

These results highlight the importance of environmental factors, such as vegetation structure and microclimate, in shaping bird community composition across different elevation classes during the autumn season (Waterhouse *et al.* 2003; Smith *et al.* 2020).

Environmental variables and species diversity

According to Fig. 3, the Redundancy Analysis (RDA) divided the environmental variables into two main groups, each playing a distinct role in shaping species diversity. The numerical values of all diversity indicators, including the Simpson Evenness Index, Shannon-Wiener Diversity Index, and number of dominant species (N2), were lower in the first elevation class compared to the second one.

In the first elevation class, environmental variables such as shrub cover, temperature, stratum, and rock cover showed a positive correlation with lower diversity values, suggesting that these factors may contribute to a less diverse bird community in this elevation range.

In contrast, in the second elevation class, variables such as moisture, ground cover, number of trees with a DBH of 100–300 cm, and number of trees with a DBH of 50–100 cm exhibited a positive correlation with higher diversity values. These findings indicate that these environmental factors support a more diverse bird community in the second elevation class.

These results underscore the importance of environmental variables, such as vegetation structure and microclimate, in influencing bird species diversity across different elevation classes (Waterhouse *et al.* 2003; Smith *et al.* 2020).

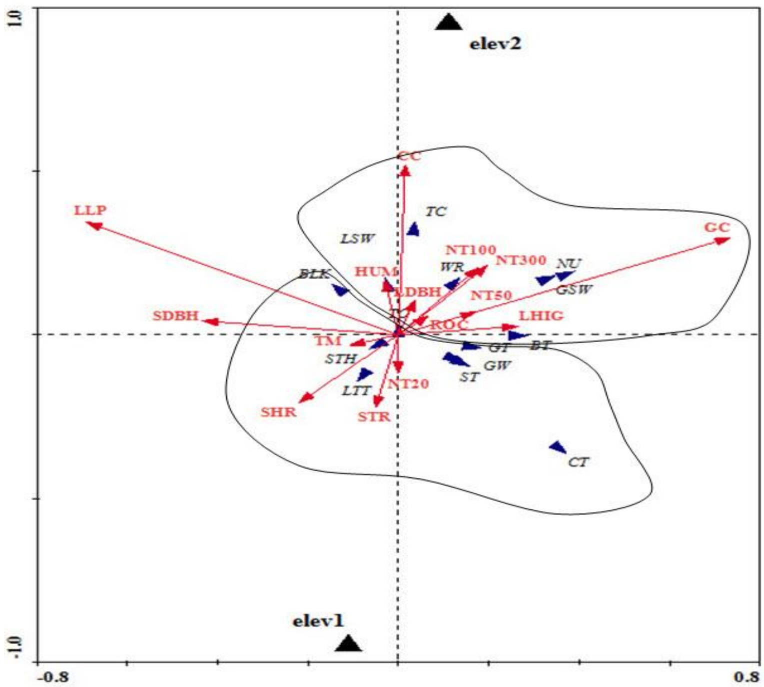


Fig. 2. Ordination diagram of the first two axes of RDA for insectivorous birds and the most important environmental variables in Saadabad-Naharkhoran forest. Bird species: BT: Blue Tit, TC: Tree creeper, WR: Wren, GSW: Great Spotted Woodpecker, NU: Nuthatch, CT: Coal Tit, BLK: Blackbird, GW: Green Woodpecker, ST: Sombre Tit, STH: Song Thrush, LSW: Lesser Spotted Woodpecker, LTT: Long Tiled Tit, TO: Tawny Owl. environmental variables: TEM: temperature, CC: canopy cover, STR: number of stratum, LLP: leaf litter percentage, SHR: shrub cover, NT20: number of tree with dbh of 12-20 cm, NT50: number of trees with dbh of 20-50NT100: number of trees with dbh of 50-100 cm, NT300: number of trees with dbh100-300 cm, LDBH: log dbh, LHIG: log height, SDBH: snag dbh, ROC: rock cover, HUM: humidity, GC: ground cover.

Winter

The results indicated that the overall ordination of species along environmental gradients was statistically significant (p = 0.01, Monte Carlo simulations with 999 permutations). The first two axes of the Redundancy Analysis (RDA) explained 41.7% of the variation in species data that could be attributed to environmental variables. Specifically, the first two axes accounted for 29.9% of the total variation, representing 14.5% of the variation in understory bird species. The species-environment correlations for the first two axes were 0.81 and 0.72, respectively.

These findings highlight the significant influence of environmental factors on bird species distribution during the winter season, with the first two axes capturing a substantial portion of the variation in species data. The strong species-environment correlations further emphasize the importance of environmental variables, such as vegetation structure and microclimate, in shaping bird community composition across different elevation classes (Waterhouse *et al.* 2003; Smith *et al.* 2020).

Species grouping based on CCA analysis

As shown in Fig. 4, the Canonical Correspondence Analysis (CCA) divided bird species into two main groups based on their responses to environmental variables:

Group 1: Species such as the Great Tit (*P. major*), Long-tailed Tit (*A. caudatus*), Blue Tit (*C. caeruleus*), Chaffinch (*F. coelebs*), Jay (*G. glandarius*), and Blackbird (*T. merula*) exhibited positive responses to the first elevation class. These species were strongly correlated with environmental variables such as temperature, shrub cover, stratum, leaf litter percentage, and the number of trees with a DBH of 12–20 cm.

Group 2: Species such as the Nuthatch (*S. europaea*), Lesser Spotted Woodpecker (*D. minor*), Great Spotted Woodpecker (*D. major*), Wren (*T. troglodytes*), Green Woodpecker (*P. viridis*), Treecreeper (*C. familiaris*), Coal Tit (*P. ater*), and Robin (*E. rubecula*) showed positive responses to the second elevation class. These species were positively correlated with environmental variables such as humidity, number of trees with a DBH of 50–100 cm, number of trees with a DBH of 100–300 cm, and ground cover.

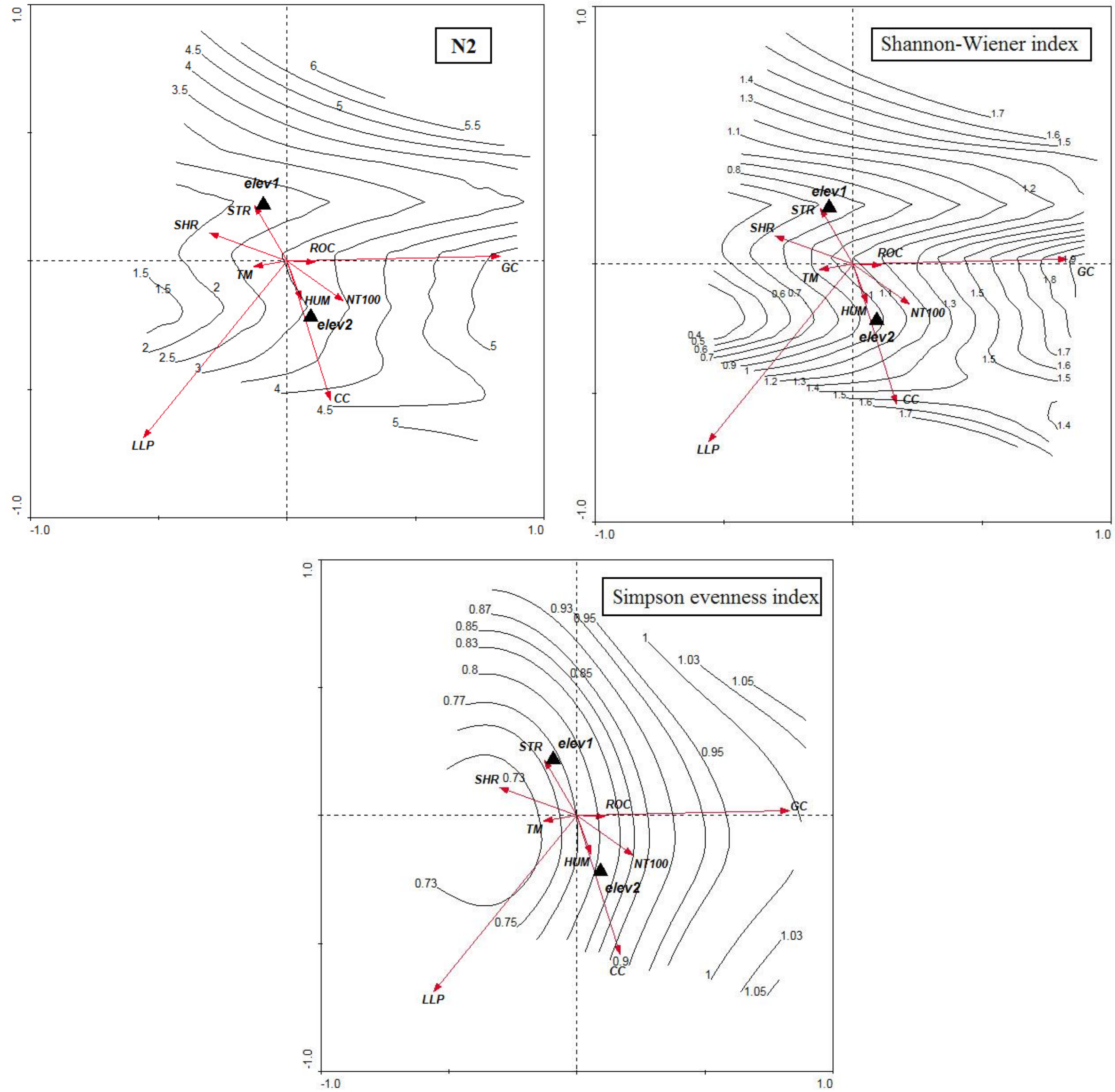


Fig. 3. The isolines of bird species diversity of samples with the most important environmental variables, plotted in the RDA ordination diagram in Saadabad-Naharkhoran forest. N2 diversity index, Shannon-Wiener diversity index and Simpson evenness index.

Environmental variables and species diversity

According to Fig. 5, the CCA analysis divided environmental variables into two main groups that influenced species diversity. The Simpson Evenness Index, Shannon-Wiener Diversity Index, and Number of Dominant Species (N2) showed little difference in diversity values between the two elevation classes.

The highest diversity values were positively correlated with habitat variables such as the number of trees with a DBH of 100–300 cm, number of trees with a DBH of 50–100 cm, humidity, ground cover, and rock cover.

The lowest diversity values were positively correlated with variables such as temperature, leaf litter depth, shrub cover, and canopy cover. Additionally, the highest evenness values were positively correlated with ground cover, rock cover, number of trees with a DBH of 100–300 cm, and leaf litter percentage. In contrast, the lowest evenness values were associated with the number of trees with a DBH of 20–50 cm, humidity, and temperature.

These results highlight the complex interplay between environmental variables and bird species diversity, emphasizing the importance of habitat structure and microclimate in shaping bird communities across different elevation classes (Waterhouse *et al.* 2003; Smith *et al.* 2020).

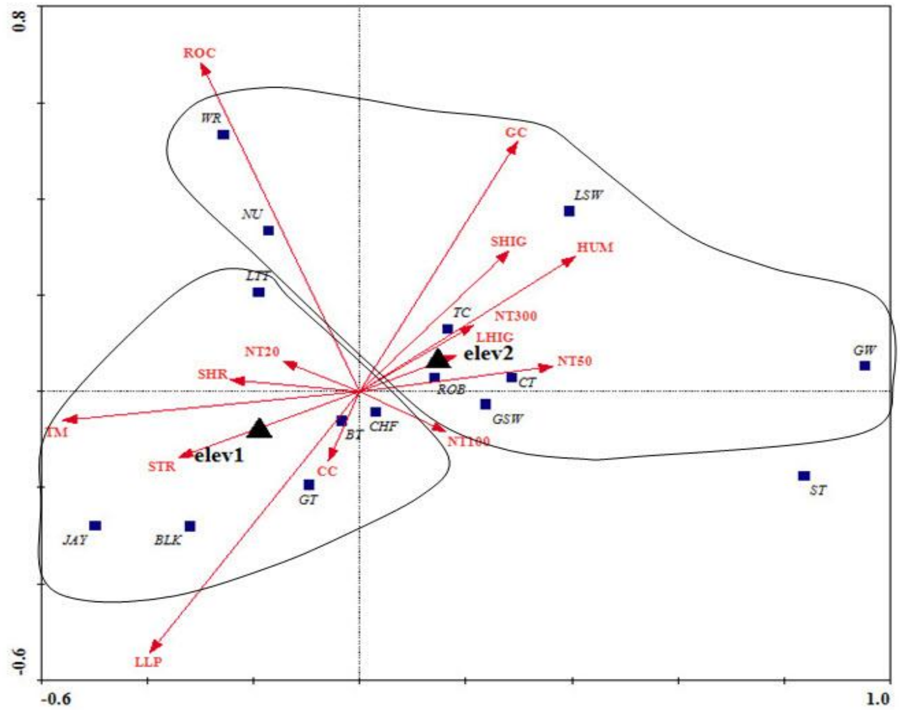
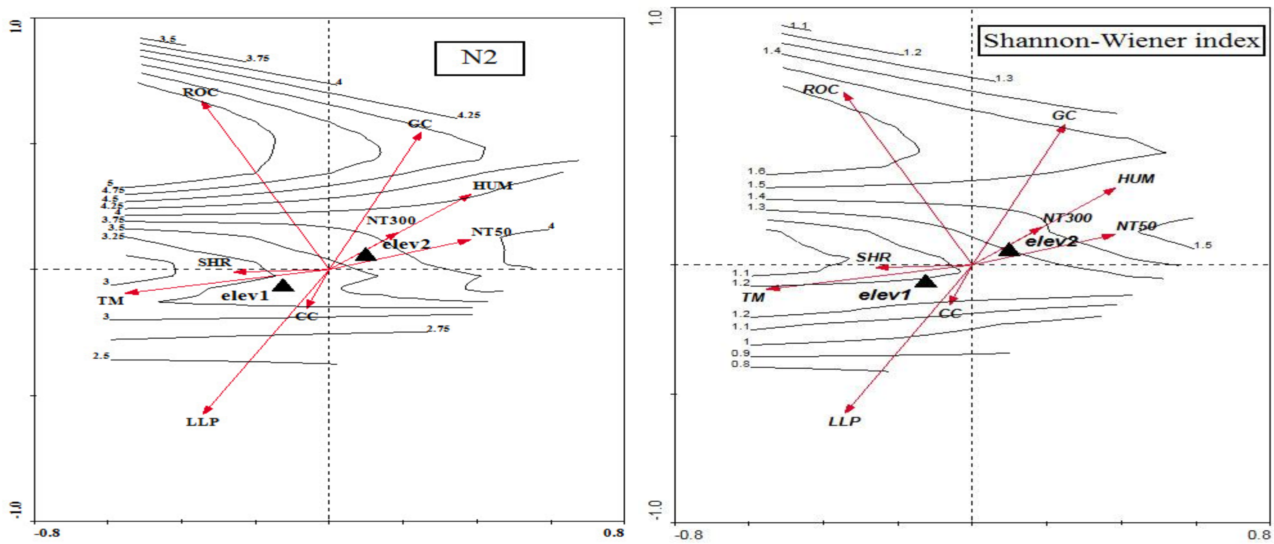


Fig. 4. Ordination diagram of the first two axes of CCA for insectivorous birds and the most important environmental variables in Saadabad-Naharkhoran forest. Bird species: BT: Blue Tit, TC: Treecreeper, WR: Wren, GSW: Great Spotted Woodpecker, NU: Nuthatch, CT: Coal Tit, CHF: Chaffinch, BLK: Blackbird, ROB: Robin, GW: Green Woodpecker, LSW: Lesser Spotted Woodpecker, LTT: Long Tiled Tit, JAY: Jay, ST: Sombre Tit. Environmental variables: TEM: temperature, CC: canopy cover, STR: stratum, LLP: leaf litter percentage, SHR: shrub cover, NT20: number of tree with dbh of 12-20 cm, NT50: number of trees with dbh of 20-50cm,NT100: number of trees with dbh of 50-100 cm, NT300: number of trees with dbh of100-300 cm, LHIG: log height, , HUM: humidity, GC: ground cover, ROC: rock cover.



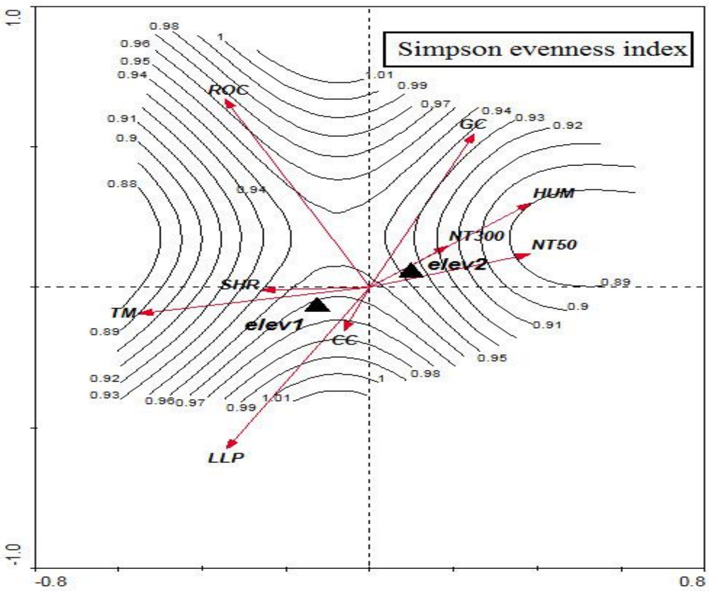


Fig. 5. The isolines of bird species diversity of samples with the most important environmental variables, plotted in the CCA ordination diagram in Saadabad-Naharkhoran forest. N2 diversity index, Shannon-Wiener diversity index and Simpson evenness index.

DISCUSSION

Overview of findings

The primary objective of this study was to evaluate changes in bird communities along an elevation gradient and to explore the relationship between bird species and habitat variables in the Hyrcanian forests of Iran. Our findings revealed significant variations in bird density and community composition across different elevation classes, consistent with previous studies (Shariati Najafabadi & Kaboli 2012). Additionally, we observed a strong relationship between bird species and habitat structures, aligning with similar research (Shochat *et al.* 2001; Laiolo 2002; Díaz 2006; Ghadiri Khanposhtani *et al.* 2012a, b).

Bird community composition and elevation gradient

Bird species in the study area were categorized into two distinct groups based on their habitat preferences and responses to elevation gradients:

Group 1: Species associated with early successional stages, such as the Great Tit (*P. major*), Blue Tit (*C. caeruleus*), Blackbird (*T. merula*), Robin (*E. rubecula*), and Chaffinch (*F. coelebs*), were more abundant in the first elevation class. These species showed a strong preference for habitats with sparse vegetation, high light availability, and significant shrub cover (Villard *et al.* 2007; Ghadiri Khanposhtani *et al.* 2012a). The expansion of shrubs and lower-story trees in these areas provides critical resources for this group (Canham, 1985; Ghadiri Khanposhtani *et al.* 2012a).

Group 2: Species associated with late successional stages, such as the Great Spotted Woodpecker (*D. major*), Lesser Spotted Woodpecker (*D. minor*), Treecreeper (*C. familiaris*), and Nuthatch (*S. europaea*), were more abundant in the second elevation class. These species preferred dense vegetation, high canopy cover, and large-diameter trees, which provide essential resources such as food and nesting sites (Nadkarni & Matelson 1989; Sillett 1994; Ghadiri Khanposhtani *et al.* 2012b). The presence of invertebrates, which thrive in humid environments, further supports the abundance of these species in higher elevations (Zanette *et al.* 2000). It is worth noting that for some species, such as the Long-tailed Tit (*A. caudatus*), the density estimate was associated with a relatively large standard error (Table 1). This likely reflects a clumped distribution pattern and/or a lower number of detections, leading to less statistical precision for this particular species, despite its observed presence across the gradient.

Habitat variables and species diversity

Forest structure variables, such as canopy cover, tree diameter at breast height (DBH), and the presence of snags and logs, were identified as critical factors influencing bird species richness and diversity (Doyon *et al.* 2005;

Vergara & Schlatter 2006). Our analysis revealed a strong relationship between habitat variables and the bird community diversity. Higher diversity and evenness values were associated with habitats characterized by large-diameter trees, dead trees, ground cover, and high humidity. In contrast, lower diversity values were linked to variables such as temperature, shrub cover, and rock cover. These findings are consistent with previous studies highlighting the importance of habitat structure in shaping bird communities (Waterhouse *et al.* 2003; Ghadiri Khanposhtani *et al.* 2012 a,b; Shariati & Kaboli 2014).

Implications for forest management

The results of this study underscore the importance of preserving old-growth forest structures, such as large-diameter trees, snags, and logs, for maintaining bird diversity in the Hyrcanian forests. Conservation efforts should focus on protecting these critical habitat components, particularly in the Saadabad-Naharkhoran forest, to support bird populations that depend on them (Newton 1994; Berg *et al.* 1994). Forest managers can use these findings to inform sustainable harvesting practices, ensuring that elevation-specific habitat requirements are considered in management plans. For example, maintaining a mosaic of early and late successional habitats across elevation gradients can help support diverse bird communities.

CONCLUSION

In conclusion, this study highlights the significant role of elevation gradients and habitat structure in shaping bird communities in the Hyrcanian forests. Our findings provide specific guidance for conservation: (i) preserving large trees and deadwood in higher elevations to support late-successional species; (ii) maintaining a mosaic of shrub-rich patches in lower elevations for early-successional birds; and (iii) adopting elevation-sensitive logging practices that mimic natural disturbance regimes. By integrating such habitat-based strategies into forest management plans, we can develop more effective approaches to safeguard the unique avian biodiversity of these ecosystems. Future research should explore the long-term impacts of these management practices on bird communities and investigate the potential effects of climate change on elevation-dependent species distributions.

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Appendix 1: The number of independent insectivorous bird species in Saadabad-Naharkhoran forest

Scientific name	Common name
Turdus merula	Blackbird
Parus caeruleus	Blue Tit
Corvus corone	Carrion Crow
Fringilla coelebs	Chaffinch
Parus ater	Coal Tit
Dendrocopos major	Great Spotted Woodpecker
Parus major	Great Tit
Picus viridis	Green Woodpecker
Garrulus glandarius	Jay
Dendrocopos minor	Lesser Spotted Woodpecker
Aegithalos caudatus	Lon Tiled Tit
Sitta europaea	Nuthatch
Erithacus rubecula	Robin
Parus lugubris	Sombre Tit
Turdus philomelos	Song Thrush
Strix aluco	Tawny Owl
Certhiafamiliaris	Treecreeper
Troglodytes troglodytes	Wren
Pernis apivorus	European Honey Buzzard
Accipiter brevipes	Levant Sparrow hawk