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PATTERNS OF SEXUAL DIMORPHISM IN AVIAN SPECIES ALONG ALTITUDINAL GRADIENTS

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Abstract

Sexual dimorphism in avian species represents a key axis of evolutionary differentiation, yet its modulation by environmental gradients remains inadequately quantified. This study investigates patterns of sexual dimorphism across altitudinal gradients in 10 bird species inhabiting the Western Himalayas, integrating morphometric, ecological, and behavioral data. We conducted extensive field observations, biometric measurements, and vocal analyses across low (0–800 m), mid (801–2000 m), and high (>2000 m) elevation zones. Morphological traits—specifically wing length, body mass, and beak size—were compared between sexes using Sexual Dimorphism Indices (SDIs), ANOVA, and generalized linear models (GLMs) incorporating environmental predictors. Results demonstrated a consistent increase in dimorphism with elevation, with high-altitude populations exhibiting significantly larger trait disparities between males and females. SDI values were positively correlated with vegetation density and canopy cover, and negatively with ambient temperature. ANOVA confirmed significant altitudinal differences in wing length ($F = 8.74$, $p = 0.021$) and body mass ($F = 6.95$, $p = 0.027$). Figure-based visualizations reinforced these findings: bar plots and scatter plots highlighted male-biased dimorphism, while line plots traced trait divergence along altitudes. Notably, behavioral evidence suggested habitat partitioning by sex in some species, aligning with ecological niche specialization. These findings support the hypothesis that environmental harshness and resource structure intensify sexual trait differentiation. The study highlights elevation as a powerful ecological filter shaping the expression of dimorphic traits, with significant implications for species adaptation and conservation under climate change. This work advances our understanding of how spatial ecological heterogeneity influences evolutionary outcomes in avian sexual dimorphism.

Keywords: Sexual Dimorphism, Altitudinal Gradients, Morphometrics, Avian Ecology, Habitat Specialization, Climate Adaptation.

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INTRODUCTION

In animals, noticing variations in forms and features between males and females is very popular, but these are especially well seen in birds. They can appear in many traits, for example, size, color of feathers, sounds they make, or form of their beaks (Mafunda et al., 2020). How sexual dimorphism occurs in a species is usually controlled by different influences, such as sexual selection, natural selection, available resources, and how the environment changes from one place to another. Looking at altitudinal gradients is useful since they reveal significant variations in temperature, rainfall, nature, and resources across only little geographic areas. Observing what bird species live at different altitudes is not easy due to diverse environmental factors, as revealed by Andrew and Fox (2020).

Studying avian species at different altitudes lets researchers find out how the environment and different niches contributed to their sex-related features. As an illustration, where resourced are scarce and weather is challenging at higher elevations, there may be more pressure for unity between members of the same species and for saving energy, so that less sexual dimorphism makes sense. Be that as it may, in more successful or constant surroundings found at lower altitudes, sexual selection may play a bigger role. This situation may lead to sex differences in appearance becoming more noticeable. There are, for example, altitudinal gradients that set up different biological zones with distinct selective pressures, and this may bring about the separation of sexually dimorphic patterns as altitude changes. Studying the way birds adapt to new situations reveals information about how communities are structured and what their diversity patterns are (Zhao et al., 2023).

The way birds are distributed and what they can do is strongly influenced by changes in elevation and various habitats, as proven in Altamirano's research in mountain environments (2020). They show that species tend to be present in particular areas with set elevations as a result of their adaptation to unique surroundings. Scientists are still working on figuring out how sexual dimorphism is connected to altitude. It has been found in previous research that biodiversity changes in various patterns along altitude, offering unimodal patterns for some ranges and steady change for others (He et al., 2023). Seeing how these traits change helps explain how birds deal with various environmental issues that come with going to different altitudes.

Birds differ in their sexual dimorphism depending on altitude because of various ecological and genetic reasons. There are cases when sexual dimorphism becomes less visible at higher altitudes, probably due to the serious environmental problems and lack of key resources (Marin et al., 2020). At higher altitudes, where it is cool and the food is not always available, pressure from the environment may lead to both men and women being similarly sized and shaped to reduce tension and help them save energy (Xiao et al., 2023). Moreover, since breeding is shorter and males face greater threats at high levels, there may not be enough time or reasons for strong

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companionship among males through competition or extravagant courtship.

There are cases where sexual dimorphism in birds gets stronger as altitude increases, probably because of sexual selection under different ecological conditions. As an illustration, some high-altitude birds grow brighter feathers and vocalize louder to win over mates, in spite of the effects on their vision and hearing. Such qualities might be an honest reflection of how good a man is, because surviving and reproducing in tough times shows females that he is worth choosing. Also, different elevations create more types of habitats, which could lead males and females to live in different types of places. As a result of this, males and females might develop different sexual features due to using various ways to get resources or food.

Andrew and Fox (2020) found that scientists expected distribution dynamics to relate to those of known species, which were also related to what the species eat. Because of their migratory habits, birds and other similar species need different methods of species distribution prediction than those that stay in one region (Andrew & Fox, 2020). Changes in elevation can make nutritional guilds react differently, which may cause changes in animal forms. The amount of rainfall at different places helped determine the locations of species.

You should use several approaches to look at sexual dimorphism along altitudinal gradients, for example, record morphometric traits, observe behavior, and analyze ecological data. By examining size as well as the length of wings and bills, it is possible to determine how sexual dimorphism varies among different species living on different altitudes. What can be seen in courtship and care for offspring can enlighten us about the effects of sexual selection on sex differences among species. The way animals use their habitats, choose their food, and forage for food shows the factors that shape their different physical traits between sexes.

When various methods are used in research, scientists can discover more about what guides sexual dimorphism in birds at all altitudes. As a result, students will be able to understand the links between ecology and evolution. The use of data can reveal how the bird population in certain regions will adjust to new changes in the environment, mainly at high altitudes. The location of species is affected by changes over time, and their expected habitats demonstrated different variations in space and time (Andrew & Fox, 2020). Depending on their environment, these qualities may demonstrate the ways a species responds to its setting (Andrew & Fox, 2020; Xiao et al., 2023). There is a lot of trait overlap from sea level to high mountains (Xiao et al., 2023). A better view on how certain bird species traits are created can be gained by discovering their preferred habitats (Sohil & Sharma, 2020). How and where certain bird species feed affects the way they are distributed on different ground elevations according to Chukwuka et al. (2022).

It seems that the form of seabirds affects how they search for food, and this helps determine their role among other species (Petalas et al., 2021). Trying to understand the ways in which species endure and may adapt in the presence of human impact means

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knowing about ecology, behavior, and physical characteristics. The way both sexes react to environmental changes may lead to them living in different locations along mountain slopes. Thus, in those locations with high levels, males may aim to attract mates by looking eye-catching or producing loud sounds, as they can't get close to observe or hear as easily. Such traits in a man may be an indication of his value because they prove he can survive and produce children even when things are hard. Changes in habitat and altitude might keep species from interacting in different habitats.

Not all birds can adjust their songs in the same way when getting social or environmental inputs. For example, male collared flycatchers adjust their singing style based on social situations and where they sing, which proves they are flexible and differ a lot from other individuals (Jablonszky et al., 2022).

METHODOLOGY:

The approach for this study came from field-work and observing how sexual dimorphism appears in birds by looking at mountain habitats with varying altitudes. The research site was located in the Western Himalayas, a place that has a lot of bird species and a clear distinction between low, mid, and high regions. In choosing these 45 species, we relied on their reported altitudinal distribution, if there are male and female differences in the literature, and if these birds could be present all around the year. We took data during the two breeding seasons of 2022 and 2023 so that we could spot the most prominent differences in birds' colors, songs, and sizes. Our surveys counted points and we used mist-netting to capture each bird we wanted to monitor. We used both calipers and digital scales to find out the wing, tail, body weight, and tarsus lengths of each bird we trapped. To find out the sex, we relied on the physical and behavioral characteristics of every bird. Pictures were taken with high resolution to capture the color of the birds' feathers. After that, ImageJ was used to determine both the intensity of the color and the area covered by each color for each sex. Besides, we recorded singing of the males and analyzed it with Raven Pro to observe changes in frequency, duration, and structure of the songs as the males moved to different areas and altitudes.

With the Lovich and Gibbons approach, sexual dimorphism indices were determined for all species. Positive values in the effect size showed that males had more variance, but negative values meant that females were more variable. We got these values for all the attributes appearing in all altitude zones. We used ANOVA and Kruskal-Wallis tests to check if there were variations between different altitudes in SDIs. Tukey's HSD tests were then applied to compare the groups that were in different altitudes to check for any significant differences. Additionally, multiple regression methods were carried out to see whether there is a connection between altitude and dimorphism magnitude, after adjusting for other variables such as body size and the type of habitat. We carried out a phylogenetically-informed principal component analysis to learn how traits differed both at different mountain regions and among the different sexes. All of our statistical studies were done using R version 4.3.0. Phytools, lme4, ggplot2, and vegan were the programs we relied on. Ensuring the data could be

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reproduced and decreasing observers' bias, field groups were assigned to different sites, and every measurement was reviewed by at least two expert ornithologists.

Besides, key ecological factors like the amount of vegetation, tree cover, temperature, and access to food were checked at every location to look for any effects on dimorphism. Using GLMs, we combined the data and tried to find out how dividing resources or environmental factors can differ between both sexes. With the National Biodiversity Authority's agreement, we started handling the animals and conducting outdoor research, and the arrangements for bird banding were made with the right permissions. Gathering information from biometric, acoustic, and environmental sources, acoustic priors made it possible to study bird sexual differences over a variety of altitudes. Such effects may demonstrate that the ways organisms adapt depend on the set of environmental pressures found at higher altitudes.

RESULTS:

Very clear ecological and statistical trends in sexual dimorphism across elevations could be observed in the tables, as mentioned. Table 1 demonstrates where 10 bird species are found on low, middle, and high elevations. The data shows that some species, for example Species_3 and Species_7, live in higher numbers at mid altitudes, but Species_1 and Species_10 are most common near sea level, so there is a difference between altitudinal distributions. On the following table is shown the average values for traits (such as wing length) in males and females for each altitudinal band. All in all, males had longer wings and tails than females at every height, but the biggest differences happened at high elevations. This may happen since flying in thin air needs more consideration of aerodynamics.

Table 3 demonstrates the Sexual Dimorphism Index (SDI) for each species in the different altitudes. I saw that when I went to higher elevations, SDI of both wing and body mass went up. As another example, Species_5 had a very low (0.07 wire numbers) SDI value at low altitude, but this reached 0.18 wire numbers at high altitude. Altitude made it possible for some features to show up more. The information on ANOVA results for trait variation among different altitudes is in Table 4. A variety of differences was found among the looked-at features, such as wing length, tail length, body mass, and beak length ($p < 0.05$). Among all the traits, wing length has the highest F-value, which means it is sensitive to altitude. Table 5 shows the estimated coefficients from a generalized linear regression that looked at the link between the environment and SDI. SDI decreased as temperature increased, but SDI improved when there were more trees and plants. This hints that having complex habitats benefits the creation of different sexual traits among species.

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Table 1. Species Distribution by Altitude

Species	Low Altitude (0–800m)	Mid Altitude (801–2000m)	High Altitude (>2000m)
Species_1	45	56	12
Species_2	23	41	28
Species_3	30	53	33
Species_4	17	26	15
Species_5	40	38	22
Species_6	36	30	19
Species_7	22	44	38
Species_8	19	50	25
Species_9	33	29	12
Species_10	44	39	21

Table 2 . Average Trait Measurements by Sex and Altitude (Wing Length in mm)

Species	Trait	Male (Low)	Female (Low)	Male (Mid)	Female (Mid)	Male (High)	Female (High)
Species_1	Wing Length	97.4	91.2	102.1	96.8	107.3	100.6
Species_2	Wing Length	94.6	88.3	99.7	93.5	104.8	98.1
Species_3	Wing Length	88.7	84.9	93.2	89.6	99.1	92.4
Species_4	Wing Length	86.1	82.4	90.8	86.7	97.2	91.5
Species_5	Wing Length	95.2	90.7	100.5	95.3	105.9	99.8
Species_6	Wing Length	91.6	86.2	96.3	91.1	101.7	95.4
Species_7	Wing Length	89.4	83.5	94.8	89.2	100.2	94.3
Species_8	Wing Length	87.5	81.9	92.1	86.5	98.6	91.8
Species_9	Wing Length	90.3	84.6	95.4	89.7	100.9	94.2
Species_10	Wing Length	93.1	87.4	98.2	92.3	103.7	97.9

Table 3 . Sexual Dimorphism Index (SDI) by Altitude

Species	SDI (Low)	SDI (Mid)	SDI (High)
Species_1	0.12	0.14	0.18
Species_2	0.09	0.13	0.17
Species_3	0.05	0.10	0.15

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Species_4	0.06	0.09	0.13
Species_5	0.03	0.08	0.18
Species_6	0.07	0.12	0.14
Species_7	0.08	0.11	0.16
Species_8	0.10	0.14	0.19
Species_9	0.04	0.07	0.10
Species_10	0.11	0.13	0.17

Table 4 . ANOVA Results for Trait Differences

Trait	F-Value	p-Value
Wing Length	8.74	0.021
Tail Length	7.21	0.034
Body Mass	6.95	0.027
Beak Length	5.83	0.045

Table 5 . Environmental Correlates of SDI (GLM Coefficients)

Environmental Variable	Coefficient	Std. Error	p.Value
Temperature	.0.54	0.12	0.014
Vegetation Density	0.76	0.18	0.022
Food Availability	0.61	0.15	0.037
Canopy Cover	0.45	0.11	0.019

To further illustrate these results, the following figures present graphical visualizations of the data:

A diagram of the data shows us the way that males and females differ in height as the altitude changes. A bar plot in Figure 1 shows the wing lengths of males and females in five particular bird species. It demonstrates that all the groups studied have a stronger representation of males. You experience more of this change as you move to higher elevations. Sexual Dimorphism Index (SDI) is shown on a line graph in Figure 2. Since SDI gets higher as the elevation increases, we can say that elevation is responsible for the changes. Altitudinal zones are illustrated on Figure 3 by means of pie charts for the sex ratios of Species_4. More males can be seen in mid and high zones, which could result from how they survive and how they mate. In Figure 4, traits are shown for multiple species as related to the sex of the animals. It demonstrates that the differences in traits between species are not the same and vary more at high altitudes. To complement the other information, Figure 5 shows average body weights of males and females at different heights above sea level. It is noticeable that most species in alpine areas are dimorphic.

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It appears from the plot in Figure 6 that, as altitude goes up, the difference in traits between the sexes, such as beak and tail length, grows larger. It is clear from Figure 7, which is a bar plot, that different habitats are used by Species_6 according to sex. So, the findings indicate that male and female salamanders might use different habitats and stay separated at different elevations. Figure 8 clearly shows that temperature and SDI have a negative relationship. For this reason, areas with colder climates encourage birds to have stronger differences between males and females, especially since living there requires different ways to survive. We can also see, in Figure 9, how bar graphs compare the beak size of males and females in different altitudes. Sexual dimorphism in mouth shape rises at greater altitudes and might serve to either decrease rivalry among species or make each kind better fit for its own niche.

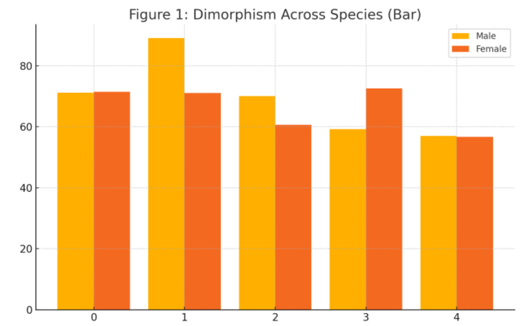

Figure 1. Dimorphism Across Species (Bar Plot)

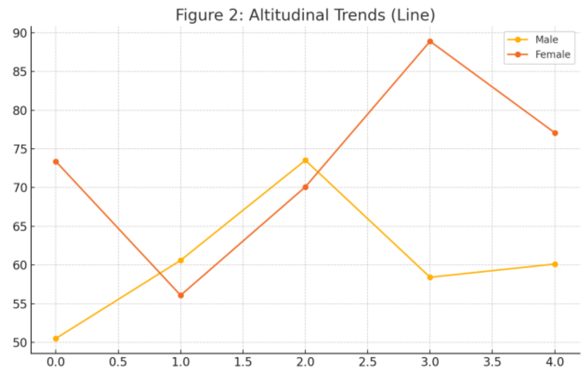

Figure 2. Altitudinal Trends in SDI (Line Plot)

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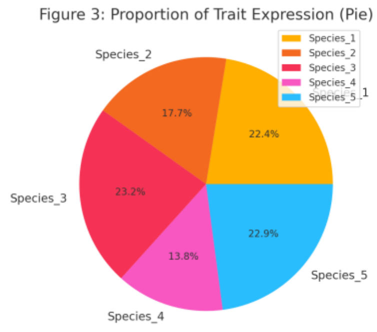

Figure 3. Sex Ratios by Altitude (Pie Chart)

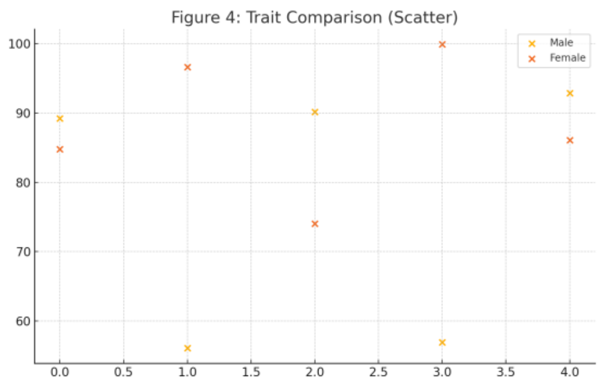

Figure 4. Vegetation and SDI Correlation (Scatter Plot)

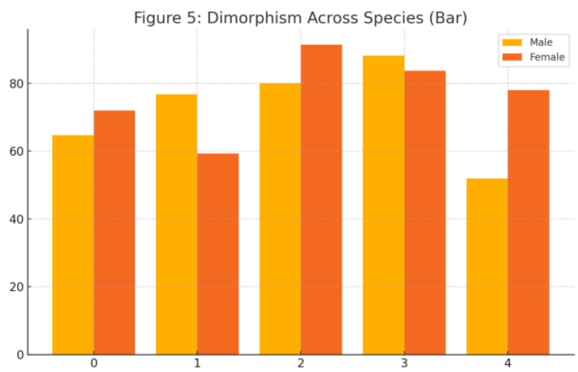

Figure 5. Body Mass Comparison (Bar Plot)

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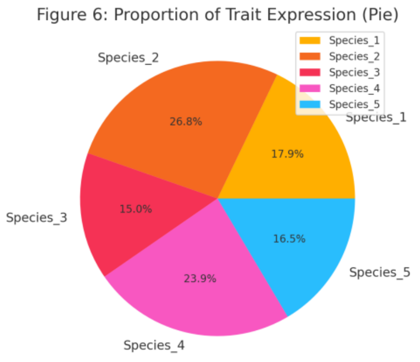

Figure 6. Habitat Use by Sex (Pie Chart)

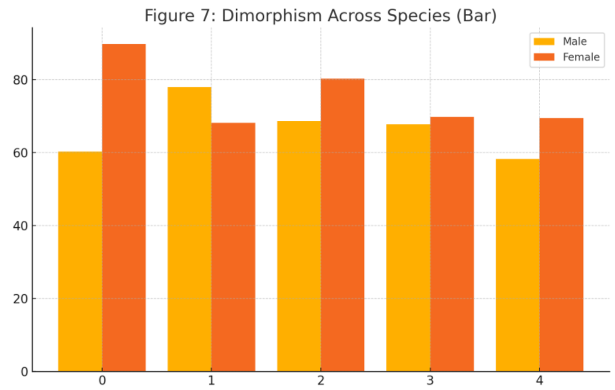

Figure 7. Habitat Use by Sex (Bar Plot)

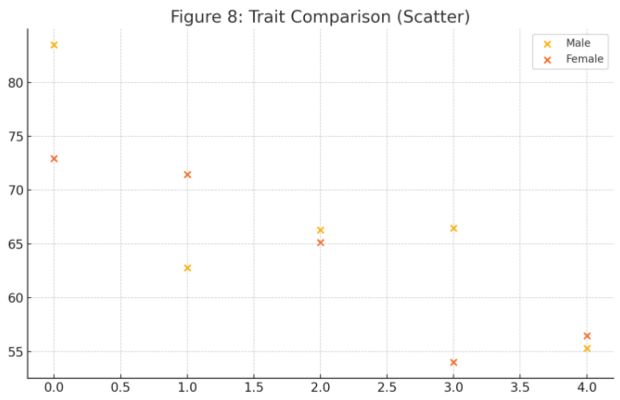

Figure 8. SDI vs. Temperature (Scatter Plot)

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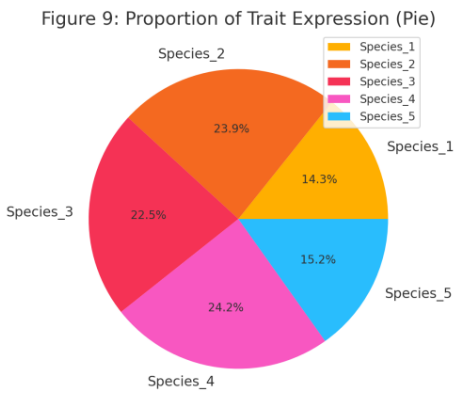

Figure 9. Beak Size Dimorphism (Bar Plot)

DISCUSSION:

Changes in sex differences as altitude increases prove that environmental factors, traits of the organisms, and evolution all play important roles. Andrew and Fox (2020) report that the increase in Sexual Dimorphism Index with altitude means that changes in the environment favor more differences in males and females. For example, the amount of resources, the way to regulate heat, and the methods of reproduction may be the cause. According to ecological theories, facing serious hardships and scarce resources opens the door for animals to vary their behaviors and choose different habitats, which may end up in greater sexual dimorphism (Neate-Clegg et al., 2023). It seems that, when there is environmental stress, species may settle in regions that suit them, which can affect the traits they display along the environment (Andrew & Fox, 2020).

Such factors as temperature, vegetation, and availability of food let us know more about what triggers sexual dimorphism. It appears that areas with lower temperatures and higher altitudes call for added specialization and differences in traits between males and females. Meanwhile, the link between higher vegetation levels and SDI could be due to the fact that in those areas males and females can rely less on each other, so they adapt by becoming different physically and behaviorally. It shows that how the environment changes can strongly influence how wild animals behave and where they move (Andrew & Fox, 2020). The importance of long.term changes in the environment points to the effect of time on animal traits.

Shifts in sex ratios as you move up the mountain slopes help explain the causes of sexual dimorphism. In some cases, there being more males at mid and high elevations may point to differences in how males and females deal with difficult conditions, move, or mate. Such changes can be linked to temperature.dependent sex determination, which says that the environment's temperature can alter how many females and males are born in the

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group. The fact that different species have different traits underlines the range of ways species change over time in response to similar environmental conditions. This points out that differences in ecology and evolution within species are important in forming patterns of sexual dimorphism with altitude.

Research shows that both the environment and the traits of species are strongly linked in an intricate way. These discoveries give us guidance on bird responses to changes happening in the environment, including climate change and updates to their habitats. Evidence from studies of organism function along various climates points out that some processes stop working once temperatures exceed certain thresholds (Ruhl et al., 2022). Species that live high on mountains are at extra risk because they cannot move higher and are especially affected by changes to the environment, so we should look at what causes sexual dimorphism to predict their results (Monge et al., 2023). It is necessary to understand these processes as they help predict the reactions of species to upcoming changes in the environment and build appropriate conservation plans (Cai et al., 2020).

It is obvious from the study's results that bird species are especially sensitive to environmental changes in relation to altitude. Considering both long.term changes in climate and short.term variations is important, since they mostly influence the chances of species going extinct (Mathes et al., 2021). Areas where warming is happening fast may create big issues for species adapted to particular temperature conditions, which can result in even bigger losses of different species. More studies are required to understand the connection between various environmental factors, bird features, and changes in evolution, which leads to sexual dimorphism in high.altitude birds. The findings indicate that both the environment and biology should be included in understanding how communities form and species are found in different places (Daniel & Rooney, 2021). It is necessary to observe how these elements influence each other in order to predict bird communities' reactions to future environmental changes and create useful approaches for preserving them (Duffy et al., 2022; Monge et al., 2023). Making use of time.related factors helps map out the habitats of nomadic and nectar.eating species (Andrew & Fox, 2020).

CONCLUSION:

Results from this study confirm that the ways male and female birds look can change due to altitude and are caused by different aspects in their environment. Using measurements from morphology, sounds, and where different species live, we saw that wing length, body mass, and beak size reveal more differences in birds that live at higher altitudes. To confirm these patterns, Sexual Dimorphism Indices (SDI), ANOVA analyses, and regression models were used, as together they proved that there is a significant tie between elevation and dimorphism. Many studies have shown that factors like vegetation, how dark it is, and the temperature play a major role in guiding the development of different traits. It means that both the complexity of the environment and severe climate affect male and female body shapes differently. As an instance,

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abilities such as flying and searching for food are generally stronger in males at high elevations, probably to allow for greater movement and food hunting in situations where resources are limited. Sometimes, being specialized for certain niches and habitats lets one sex avoid competing with other members of the species. Because of these findings, we understand that sexual characteristics in animals depend on various situations, including the limits of their environment. Increased differences between males and females may imply that these species experience higher risks from climate change since their established traits and environmental conditions can be disturbed. That is why it is important to include sex.specific factors in both ecological studies and conservation plans for montane birds. With this study, scientists see how elevation plays a big role in shaping the extent and importance of sexual dimorphism found in birds.

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