Biological Adaptations Assessed by Morphological Changes within *Zonotrichia* Taxa: A Focus on Climate Change Impacts

Martha L. Gomez Mateo

ABSTRACT

Delving into the evolutionary diversification process occurring within a species in response to climate change unveils how organisms are adapting and evolving. In this study, I employed a comparative approach to examine the White-crowned Sparrow *(Zonotrichia leucophrys)* and three of its subspecies *(nuttalli*, *gambelii*, and *pugetensis)* in relation to the Golden-crowned Sparrow *(Zonotrichia atricapilla).* I measured bill surface area, wing length, and tarsus length to analyze the differences between a bird species with multiple subspecies and one without subspecies to observe whether there is evidence of adaptation to climate change through time. I measured a total of 473 skin study samples from around the Bay area of California using the taxa's study skins gathered from museums over a span of 137 years. Using statistical analysis, significant morphological changes were discovered in the *gambelii* subspecies of the White-crowned Sparrow and the Golden-crowned Sparrow, consistent with predicted responses to climate change. In the *gambelii* subspecies, there was an increase in bill surface area and a decrease in wing length. Furthermore, the Golden-crowned Sparrows exhibited a decreased wing length over time. The findings of this study provide insight into the adaptive responses of bird species to environmental influences, particularly climate change, emphasizing the importance of Allen's and Bergmann's rules in avian morphology. By investigating the variables that drive changes in avian morphology, researchers gain a deeper understanding of the intricate relationships between organisms and their environments to preserve biodiversity and support more sustainable conservation methods.

KEYWORDS

evolution, museum collections, environmental changes, Arctic, Allen's and Bergmann's rules

INTRODUCTION

The continuous rise in human populations and technological advances have drastically altered the environment through urbanization, pollution, habitat destruction, and climate change (Benham and Bowie 2021). Since these human alterations are occurring at a fast pace, many organisms are struggling to adjust to the constantly changing environment. This fast rate of change has contributed to declines in organism populations and increased their risk of extinction (Bird et al. 2020). To evade extinction organisms can shift their distributions through migration to follow ecological niches spatially, or persist by adapting physiologically, morphologically, or behaviorally to new conditions in current places (Aitken et al. 2008; Rowe et al. 2015; Benham & Bowie 2021). Morphological adaptation is a pivotal response to ensure the survival of a population as morphology has been observed to closely follow shifts in environmental factors (Tattersall et al. 2017). Therefore, as morphological change occurs through time due to the environmental factors affecting them, it can be used to measure the adaptation responses in an ecological timescale (Friedman et al. 2019) and make predictions on how species will react to ongoing global change. Furthermore, understanding the effects of human activity on various species and ecosystems is critical for conservation efforts to be effective in maintaining and conserving our natural world.

Natural history museum specimens serve as important indicators of environmental change (Schmitt et al. 2018) and by studying these collections, we can learn more about how species evolved and adapted to changes in their environment. Museum collections provide an unparalleled opportunity for researchers to study and evaluate morphological changes among species across long time periods. Collections provide spatial and temporal specimen series that allow us to quantify the morphological and other functional changes various species have undergone (MacLean et al. 2019). Additionally, changes in organisms can be attributed to phenotypic plasticity or local adaptation (heritable change), and both strategies can improve survival in a changing climate. It may be difficult to discern between several pathways and determine which is responsible for the observed phenotypic alterations depending on how the data or models are linked with phenotypic measures (MacLean et al. 2019). While most of the research done with museum specimens has been conducted to demonstrate phenotypic, genetic, and life-history characteristics throughout time, they also serve as historical occurrence records to enhance studies of urban evolution (Shultz et al. 2021). Through them, we can increase the spatial sampling, but more importantly, it can increase the temporal sampling making it easier to assess the morphological changes over the past decade or century (Ryding et al. 2021). Therefore, comparing multiple morphological changes through time and throughout species is made possible through the study of museum collections.

An effective way to comprehend these relationships and, as a result, forecast ecological responses to environmental change, is to evaluate patterns in morphological variation both between and within species. Natural experiments can be used to study modem evolution through spatial patterns of morphology, physiology, life history, and behavior (Cardilini et al. 2016). One way to approach this understanding of animal adaptation is through ecological theory (Cardilini et al. 2016). The ecological theory sets the framework for understanding how ecological processes such as competition, predation, and mutualism shape communities and ecosystems (Youngflesh et al. 2022). According to ecological theory, organisms' sizes and shapes should vary across latitude and elevation, especially for avian species (Youngflesh et al. 2022). Two major adaptation rules known as Bergmann's and Allen's rules explain how size and shape change in response to environmental challenges. According to Allen's rule, endothermic organisms of the same species or genus living in cold surroundings have shorter appendages, such as ears and limbs, than endothermic organisms living in warmer conditions, which have longer limbs and appendages (Ryding et al. 2021). This is because shorter appendages help limit heat loss and conserve body heat in cold situations (Symonds and Tattersall 2010). Bergmann's rule asserts that among endothermic creatures of the same or closely related species, populations and species with bigger body sizes are found in colder habitats, whereas those with smaller body sizes are found in warmer climates (Ryding et al. 2021). This is because bigger organisms have larger bodies and hence produce more body heat. Geographical variation can lead to morphological changes in organisms, particularly in warmer regions where individuals tend to be smaller (Weeks et al. 2020). Additionally, endotherms' appendages may alter in relation to their bodies, changing the overall shape of the body as a result of their adaptation to rising temperatures (Ryding et al. 2021). While Bergmann's rule is the principle linking external temperature and the ratio of body surface to weight in warm-blooded animals, anthropogenic climate change may quicken the process of reduced body size in a manner that is temporally analogous to geographic patterns (Teplitsky and Millien 2014).

Specifically, bill surface area, body size, and wings have been shown to change the most in response to climate change. (Youngflesh et al. 2022), found strong spatial and temporal trends in average body size in more recent years throughout equatorial latitudes. Out of 105 North American Bird species measured over 30 years (1989-2018), 80 showed avian body size decreased over time. (Friedman et al. 2019) found an association between bill shape and size with both climate and foraging behavior. The increase in bill size with increased summer temperature in birds was also previously shown in (Greenberg et al. 2012), and (Danner and Greenberg 2015). Likewise, (Bosse et al. 2017) found that while examining the spatial-temporal variation between the museum samples of great tits *(Parus major)* in the United Kingdom and mainland Europe, the UK population had considerably longer bills as well. While most of the research done with museum specimens has been conducted to demonstrate consistent temporal changes among different species, few researchers have studied temporal morphological changes across different populations of the same species. Additionally, while there have been a fair number of studies looking at the temporal change in a single species from a single place, few studies actually look at how different populations of the same species may be changing. Since anthropogenic change is not uniform across different geographic regions, different populations of the same species are subject to different pressures. Furthermore, it's possible that some populations have lower genetic diversity than others and lack the genetic variation to adapt (Benham and Bowie 2021). Comparing various populations could be useful for comprehending how differing life histories or other factors might affect alterations in response to environmental stressors. This can show how a species is resilient and adaptable to environmental change.

This study aims to observe if there has been any morphological change through different subspecies populations within the same species. Our species of interest are the White-crowned Sparrow *(Zonotrichia leucophrys)* and the Golden-crowned Sparrow *(Zonotrichia atricapilla).* White-crowned Sparrows are known to have five subspecies which are *Z. l. gambelii,* Z. 1. *leucophrys*, *Z. l. oriantha, Z. l. pugetensis,* and *Z. l. nuttalli.* Hereafter, the studied *Zonotrichia leucophrys* species are referred to as White-crowned Sparrows, *gambelii,* leucophrys, oriantha, *pugetensis,* and *nuttalli.* The *Zonotrichia atricapilla* is referred to as the Golden-crowned Sparrow. Each of the Zonotrichia taxa ranges differently across North America through either breeding or wintering ranges. The White-crowned Sparrow has a wide breeding range from Alaska across the Taiga zone of Canada to Newfoundland, and across the Pacific coast along the major mountain ranges. The only subspecies that makes an exception for a wide breeding or wintering range is the *nuttalli* subspecies as it is non-migratory and only ever found along the Pacific coast mountain ranges in California. The Golden-crowned Sparrow breeds in western Canada and Alaska and winters in central coastal California, USA (Seavy et al.,2012). Golden-crowned Sparrow has no subspecies. Comparing a bird species with subspecies to one without subspecies can give information about the factors that contribute to subspecies' development and adaptation. By comparing subspecies, researchers can identify specific ecological or environmental factors that may be causing divergence within a species. For this reason, the White-crowned Sparrow is an appropriate candidate to compare with its close relative the Golden-crowned Sparrow because they have similar breeding and wintering ranges. The Bay Area is a great place to investigate how changes in the climate affect birds' morphology as the Bay Area has experienced significant climate change and massive urbanization during the last century. As a result, multiple species have gone under climatic stress. We may compare morphological traits in the birds that co-occur in the winter in the Bay Area, such as the *gambelii, pugetensis,* and *nuttalli* subspecies of the White-crowned Sparrow and the Golden-crowned Sparrow, to observe any morphological change through time. This comparison could provide vital insights into their morphological variation across the different migratory and resident populations of subspecies. The study of morphological changes in bird species can provide valuable information on how birds adapt to their surroundings. Understanding morphological variation within a species is important because various subspecies may have different adaptations to local environments.

The strength of this research lies in comparing the different morphological adaptations that have occurred through time among the White-crowned Sparrow subspecies and Golden-crowned Sparrow species to provide valuable insights into the evolution and adaptation of these avian species. This aimed to provide researchers with a better understanding of how various environmental variables may influence change over time in different populations. In this study, I made standard measurements on the subspecies of White-crowned Sparrow and Golden-crowned Sparrow species from the collection of the Museum of Vertebrates and California Academy of Sciences across a 137-year period to understand whether these birds also exhibit morphological change and whether it is similar to what has been observed in resident species. The morphological features I measured included bill surface area, wing length, and tarsus length. The residential subspecies of interest I measured were *nuttalli*, while the migratory subspecies I measured were *gambelii*, *pugetensis*, and the Golden-crowned Sparrow. Firstly, observations were made to determine if there were any morphological changes over time within *Zonotrichia* taxa following Allen's and Bergmann's rules. If Bergmann's rule held true, a decrease in sparrow body size was expected to be observed as they adapt to warmer conditions over time. If Allen's rule held true for the *Zonotrichia* taxa bill surface area, changes were expected to be observed as these species adapt to different temperatures over time. From these observations, I anticipated that this research would have produced one of three possible outcomes: (1) both residential and migratory *Zonotrichia* taxa show morphological change, (2) only either residential or migratory subspecies show morphological change over time, or (3) neither residential nor migratory subspecies show change. Based on the results of the outcome, my main question became; Has the *Zonotrichia* taxa exhibited morphological change throughout different populations? Due to morphological changes being exhibited within the same species in other studies (Weeks et al. 2020), I predicted that there would be morphological changes within the different *Zonotrichia* species and subspecies populations. I then asked the following questions to assess further my research: (a) Does morphology vary significantly through time within any of the *Zonotrichia* taxa populations? (b) Which environmental factors can most effectively account for morphological variation among *Zonotrichia* taxa populations?

METHODS

Data collection of museum skin samples

I measured a total of 338 White-crowned Sparrows *(Zonotrichia leucophrys)*, and 135 Golden-crowned Sparrows *(Zonotrichia atricapilla)* study skin specimens from the Museum of Vertebrate Zoology at the University of California, Berkeley, and the California Academy of Sciences in San Francisco, CA, to understand the morphological trait differences in each population (Table 1). The museums provided the skin study samples to measure, and a data set from VertNet was downloaded to obtain the catalog number of each bird to find the locality of the specimens in the museum. According to their website, VertNet is a collaborative NSF-funded project that makes biodiversity data freely available on the internet (VertNet, 2022.). It comprises hundreds of biological collections sharing biodiversity data.

Table 1. Sample size of *Zonotrichia* taxa measured. There were a total of 473 specimens measured from museum skin studies sampled over the past 137 years.

	Historic (pre-1975)		**Modem (post-1975)**			
Zonotrachia Taxa	**male**	**female**	**male**	**female**	unknown sex	Total adults
Nuttalli	91	57	14	18	5	185
Gambelii	32	23	11	5	7	78
Pugetensis	**41**	21	3	5	5	75
Golden-crowned	58	32	19	20	6	135

Species of interest

Out of the five White-crowned Sparrow subspecies, I only measured three of them. The three subspecies of interest I measured are *nuttalli, gambelii,* and *pugetensis.* Additionally, I measured skin samples from the Golden-crowned Sparrow species. The three subspecies of White-crowned Sparrow along with the Golden-crowned Sparrow species were sampled between a 137-year time period between the years 1883 and 2020. There are both female and male birds included in the data set. The *Zonotrichia* taxa have a wide geographical range that spans from the residential *nuttalli* subspecies in the Bay Area to the migratory Golden-crowned Sparrow species, *gambelii* and *pugetensis* subspecies, which breed in western North America before migrating to the Bay Area during winter. The skin study samples from the museums vary across the nine counties in the bay area; Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma (Figure 1).

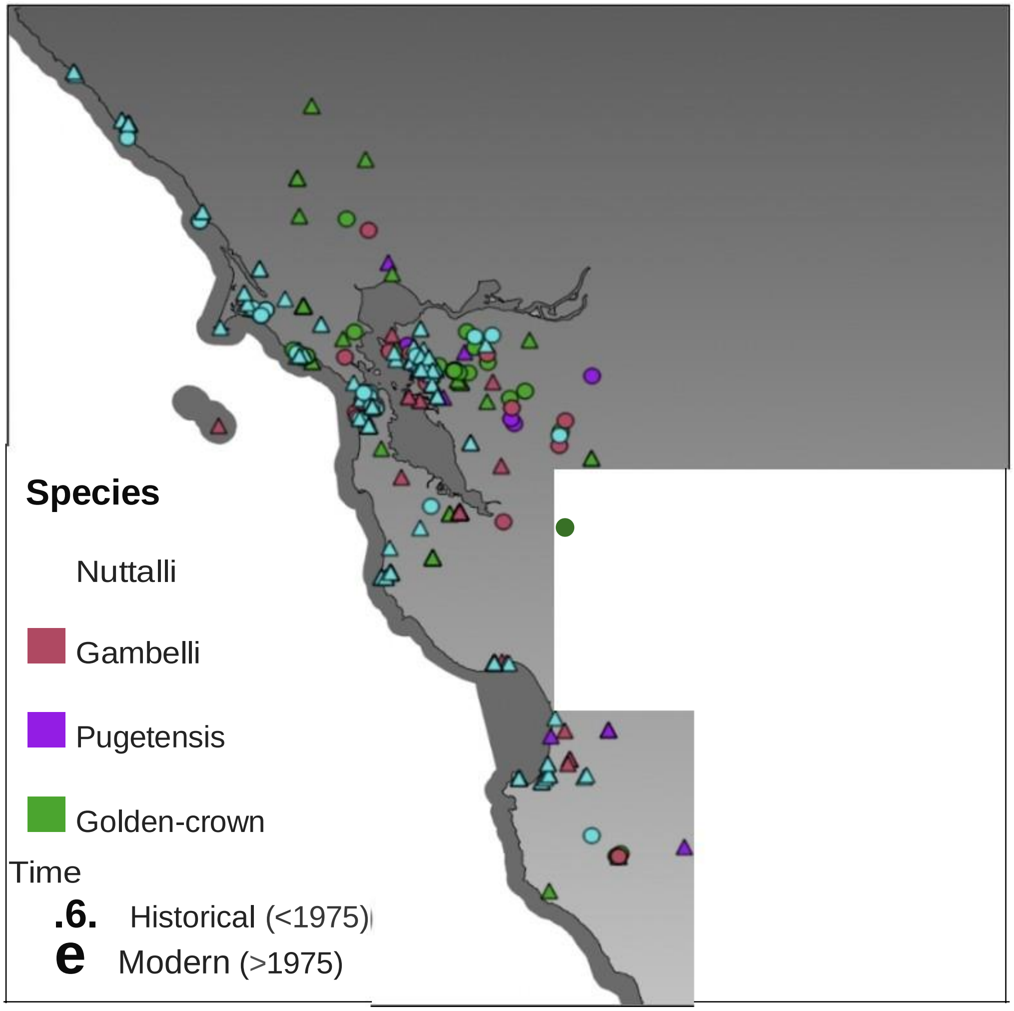

Figure 1. Museum Specimen Distribution Across The Bay. A distribution map illustrating several wintering bird migration patterns across time through California, created using QGIS software. For each sample location, a single dot in the appropriate color is used as a stand-in. There is a historical (prior-1975) triangle stand-in and a circle stand-in shape for modern(post-1975). The figure depicts each subspecies' geographic range and gives context for the time patterns of data gathering.

Data selection

The data set only includes the immature and adult stages of the wintering migratory White-crowned subspecies, *gambelii* and *pugetensis*, residential *nuttalli* subspecies, and Golden-crowned species over time (Figure 2). None of the subspecies have been shown to migrate in a juvenile stage. I aged birds based on plumage. Pyle's (1997) "Identification Guide to

North American Birds: Columbidae to Ploceidae" contains extensive details on various bird species' identification, behavior, and ecology. I used this information to differentiate a juvenile bird from an adult or immature bird. In the immature stages, the crown has brown and cream head stripes that transition to black-and-white stripes in adult White-crowned Sparrows, and the crown transitions to black stripes with a bright-yellow crown for adult Golden-crowned Sparrows (Pyle 1997).

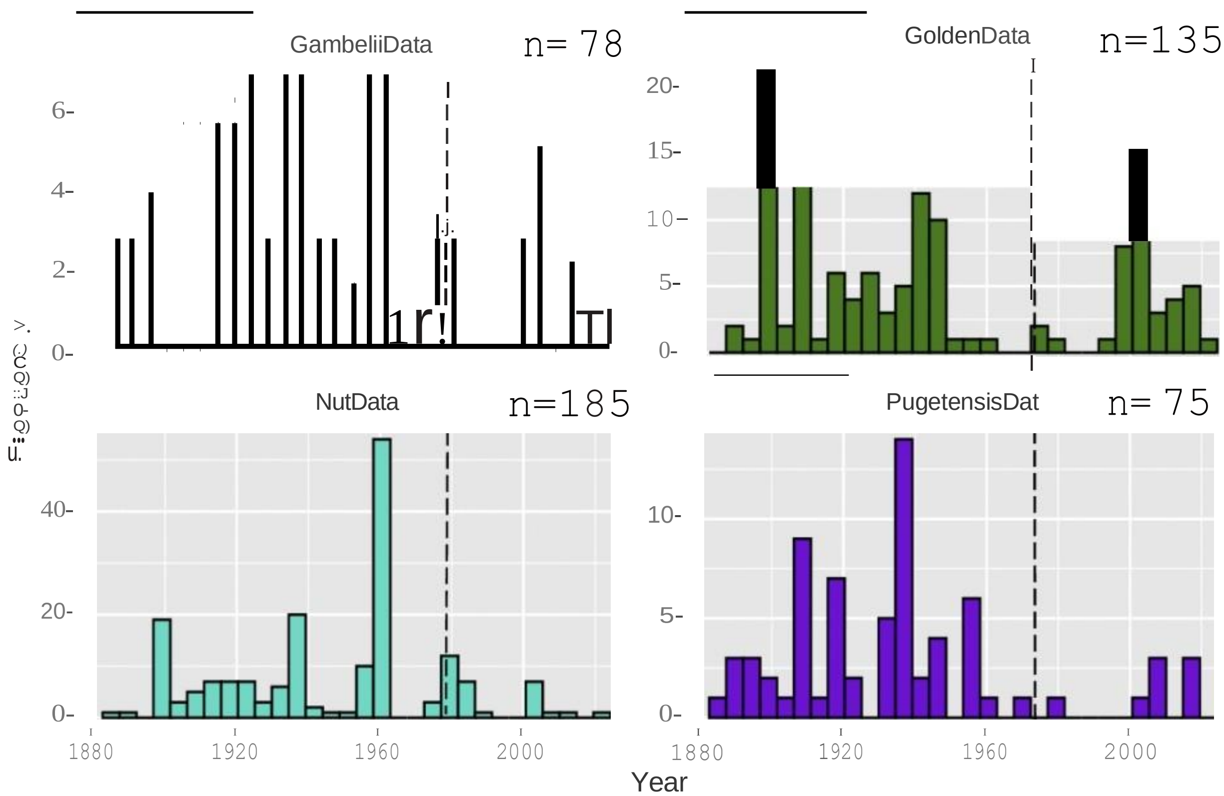

Figure 2. Distribution of Years by Sampling Dataset With 1975 borderline. The histograms in the figure reflect the frequency of specimens collected across time, with the dashed line representing historical specimens obtained prior to and after 1975. The histograms represent the temporal patterns in data collection for each subspecies and demonstrate how the sampling effort has changed over time. When Figures 2 and 3 are combined, they provide critical insights into the studies of these subspecies and help us comprehend their distribution and ecology.

Measurements

The morphological traits I measured were; bill length, bill depth, bill width, wing length, and tarsus length. Similar to previous studies (Weeks et al. 2020; Friedman et al. 2019), the morphological traits I measured have been shown to change the most over time and space. The bills of each subspecies were measured from the anterior part of the nares to obtain the bill length. To calculate the bill surface area, I used a formula that has frequently been used to calculate the total bill surface area in birds (LaBarbera et al., 2017) which is Bill surface area= ((bill width + bill depth)/4)*bill length*n. The mathematical formula for the surface area of the near elliptical cone was discovered to be a better predictor of size variation in bill surface area based on different measurements of length, depth, and width, in comparison to the linear measurement of bill length alone (Subasinghe et al., 2021). The length of the wing cord was measured from the bend in the wing to the tip of the longest primary feather. Additionally, I used the wing length as a proxy for body size as a prior study discovered that wing length is consistently the strongest predictor of estimated lean mass (size) and the most reproducible, providing the best general measure of body size within species of passerines (Gosler et al., 1998). The length of the tarsus was measured from the intertarsal joint to the first metatarsal.

All measurements were taken with digital clippers that have 0.01mm precision. I took the measurement of each morphological trait; bird length, bill depth, bill length, wing length, and tarsus length three times and then averaged the three to obtain a better measurement result and find an average value. These averages were taken as the final measurement.

Data analysis

I observed the temporal change in three morphological traits-bill surface area, tarsus length, and wing length-to examine the morphological change over time. All statistical analyses were carried out using R-Studio version R-4.3.0 and the findings were recorded and converted to assist further analysis in checking for a change in morphological traits over time. To maintain data quality, missing sex identification, locality, bill length, depth, width, tarsus length, or wing length measurements were removed prior to analysis. Each morphological trait in each of the *Zonotrichia* taxa was tested using statistical models to see how this species of bird have changed morphologically over time.

I used the 'aov' function in R to run analysis of variance (ANOVA) tests to examine group variation and estimate the statistical significance of differences between groups. I used ANOVA tests to compare the mean values of each morphological trait among the three White-crowned subspecies and Golden-crowned species to determine if the differences in the temporal changes across the species are statistically significant. Overall, this method enabled us to identify and quantify morphological changes in the three crowned bird species throughout time, offering insights into their adaptive responses to environmental changes.

RESULTS

Specimen data

I measured a total of 473 skin study samples from around the Bay area using the species occurrence data gathered from MVZ and CAS through VertNet. I excluded a total of 26 skin study samples from these data that had missing values or were thought to beoutliers. Of the total museum skin study data samples dispersed throughout the Bay area, 26 omit data made up ~5.5% of the data. After removing these 26 samples n=178 *nuttalli,* n=7l *gambelii,* n=70 *pugetensis,* and n=l28 Golden-crowned remained, for a total of 447 skin study samples. I used box plots to compare the measurements of the different *Zonotrichia* taxa to visually display their data distribution, with the resulting measurement differences depicted in Figure 3 via transformed box plots.

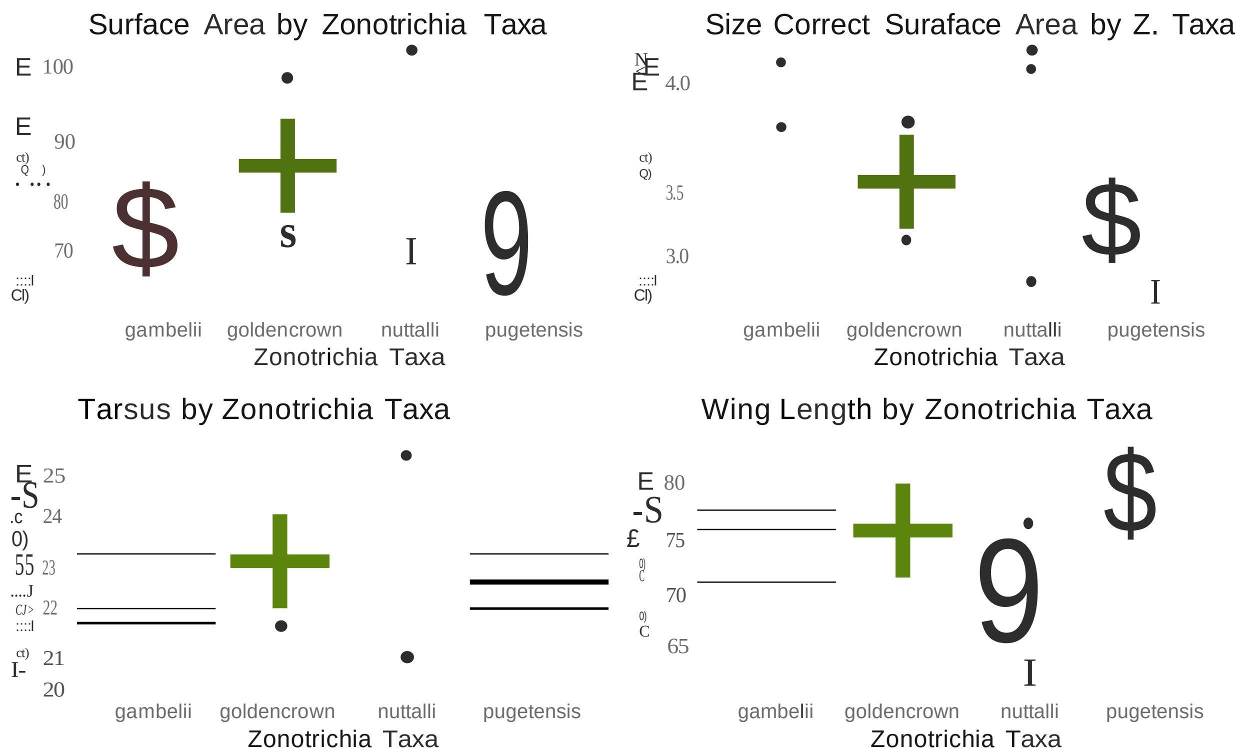

Figure 3. Differences of Distribution for Morphological Traits. This figure depicts four different box plots that measure the differences in morphological traits across species. The whiskers extending from the box show the range of the data, with outliers plotted as individual points. Size range in avian species' morphological traits can be seen mainly in surface area and wing length.

Even after accounting for surface area, morphological traits revealed that the Golden-crowned and *nuttalli* species had the largest bills, and tarsus as seen in Figure 3. The *gambelii* and Golden-crowned Sparrows had the longest wing length measurements. These findings show that the morphological features of these species differ greatly, which could have implications for their adaptation and survival in their respective environments.

Spatial and Temporal Patterns of Morphological Change

Bill surface area changes

I performed a linear regression analysis to compare morphological features (bill surface area, tarsus length, and wing length change over time across the study specimens. After performing a linear regression analysis on the bill surface area of each and all the taxa measured, the *gambelii* subspecies' bill surface area had the only increase over time when compared to the other species (Figure 4). This surface area-dependent value was discovered to be significantly related to only the independent factor of year.

I used the "aov" function to test for a significant link between the bill surface area variable and the year and sex variables, as well as their interaction across the *Zonotrichia* species of interest. The results revealed a statistically significant association between the *gambelii* subspecies bill surface area and year *(p*= 0.019) (Table 2). This demonstrates evidence of fluctuation in the bill surface area of the *gambelii* subspecies throughout time.

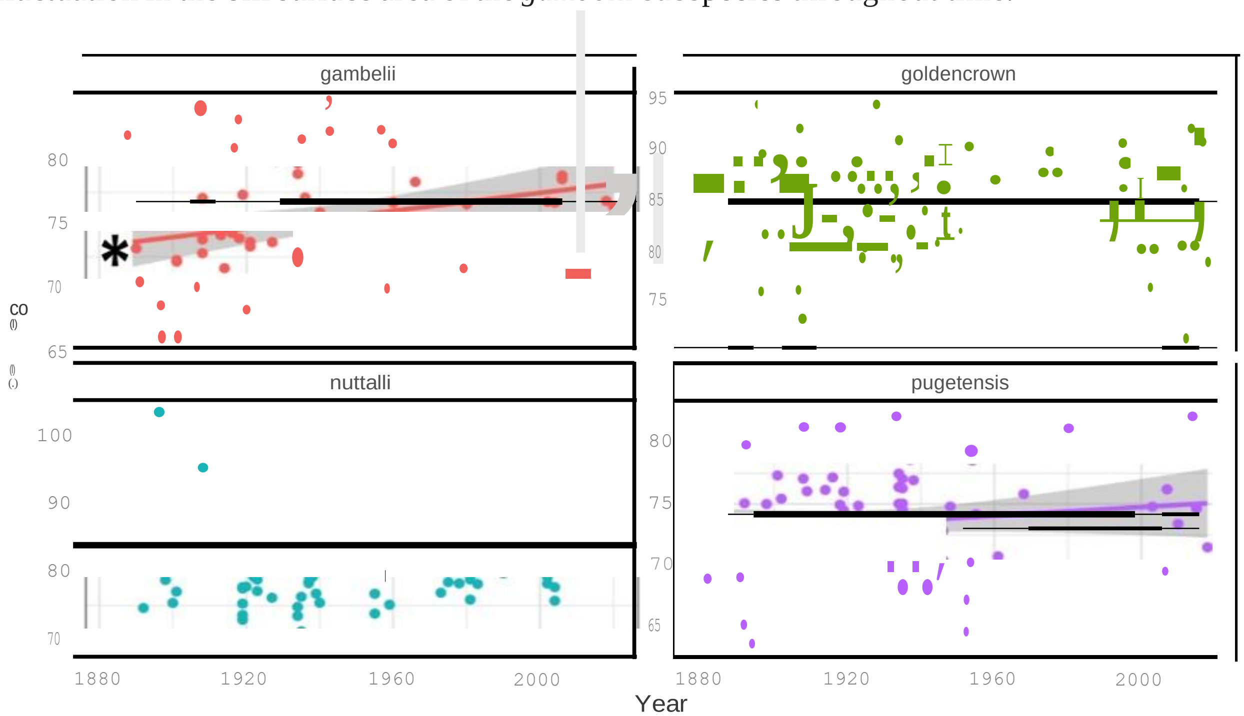

Figure 4. ***Zonotrichia* Taxa's Bill Surface Area Through Time** For the four *Zonotrichia* study species, Figure 4 shows a linear regression model of the bill surface area (mm"2) across time. In comparison to the other three study species, the *gambelii* subspecies' bill surface area has significantly increased over time (p=0.0190). The surface area measurement is represented by the y-axis, while time is represented by the x-axis.

Table 2. ANOVA model results. Association between the surface area variable and the year and sex variables, as well as their interaction. Significant results are in bold with a significance level ofp < 0.05.

Zonotrichia Taxa	Year	Sex	Year"Sex
Nuttalli	0.696	**< 0.01**	0.471
Gambelli	**0.019**	0.0923	0.353
Pugetensis	0.271	0.588	0.253
Golden-crowned	0.6796	**0.00514**	**0.148**

Wing and tarsus length change through time

Wing length was employed as a proxy for body size as it is commonly used as a body size corrector. The linear regression model of wing length over time for the four *Zonotrichia* research species is shown in Figure 5. For two of the examined species, *gambelii*, and Golden-crowned, the model revealed a statistically significant negative correlation between wing length and year, showing that the wing lengths of both populations had declined over time (Figure 5). When compared to the other species in the study, these two species showed the only significant variation in wing length over time.

An analysis of variance (ANOVA) was performed in R using the "aov" function to investigate the association between wing length, sex, and year, as well as the interaction between the two. The significance level chosen for this study is $p < 0.05$. The ANOVA results demonstrated that both year and sex had a statistically significant decreasing effect on wing length in the *gambelii* subspecies (p=0.005) and Golden-crowned species (p=0.026). The effect of sex on wing length was slo statistically significant in *gambelii* (p=0.0006), and Golden-crowned (p<0.01) The interaction between year and sex, on the other hand, was not statistically significant in any taxa, indicating that the effect of sex on wing length did not change with time (Table 3). These findings suggest that wing length in these species has significantly decreased over time, with *gambelii* and Golden-crowned species exhibiting the longest wing length among the studied species (Figure 3).

There were no significant differences in tarsus length between subspecies or time periods studied. The White-crowned sparrow's *pugetensis* and *nuttalli* subspecies, in particular, showed no appreciable changes in their bill surface area, tarsus length, or wing length over the course of the research. These findings imply that some anatomical characteristics may be relatively stable throughout time within a species, possibly as a result of the absence of selection or environmental constraints.

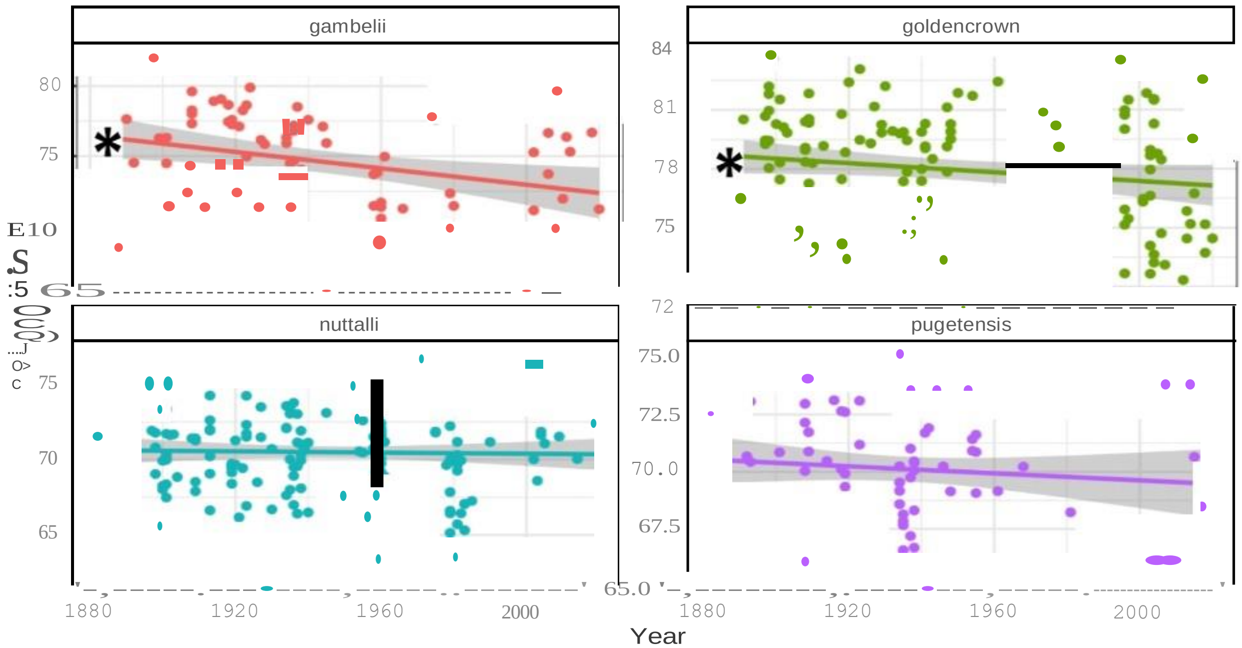

Figure 5. Linear Regression of *Zonotrichia* Taxa's Wing Length Through Time The linear regression model of wing length over time for the four *Zonotrichia* research species is shown in Figure 5. The millimeters of wing length is represented on the y-axis, and time is represented on the x-axis. The wing length trend is particularly obvious for *gambelii*, which has consistently displayed a considerable decline. certain results imply that in certain bird species, wing length may be a helpful indicator of evolutionary changes.

Table 3. Statistical Results of Regression Analyses Comparing Change In Wing Length Over Time. Significant results are in bold.

Zonotrichia Taxa	Year	Sex	Year""Sex
Nuttalli	0.763	<0.01	0.12
Gambelli	0.004711	0.000598	0.0705931
Pugetensis	0.321423	0.000152	0.827841
Golden-crowned	0.0257	<0.01	0.519

DISCUSSION

In recent years, avian morphology has grown in importance as a field of study. This is owing, in part, to the fact that changes in avian morphology can provide useful insights into the ecological and evolutionary processes that create the natural world. Understanding these processes is essential for predicting how bird populations will react to environmental changes and creating successful conservation policies. One key focus of my research has been on the *Zonotrichia* tax.a, a group of avian taxa found across North America. Measuring and comparing the morphological features of three subspecies of the White-crowned Sparrow *(Zonotrichia leucophrys)* - *nuttalli, gambelii,* and *pugetensis* - and species of the Golden-crowned Sparrow *(Zonotrichia atricapilla)* - helped gain a better understanding of of the environmental factors influencing subspecies' evolution and diversification. Through the measurement and comparison of three distinct physical traits of various *Zonotrichia* taxa over time, this research has yielded valuable insights into the factors responsible for changes in bird morphology. The investigation of three key morphological features - bill surface area, tarsus length, and wing length - was chosen due to their relevance in avian adaptation (Weeks et al. 2020; Friedman et al. 2019). The study's results are significant as they reveal the importance of accounting for within-species variation when analyzing avian morphology. Some studies suggest that climate change may be a significant driver of these morphological changes in *Zonotrichia* populations.

Morphological observed changes in *Zonotrichia* Taxa

Prior to conducting this study, I hypothesized that each species' morphological traits would differ based on Allen's and Bergmann's rules. The observed increase in bill surface area in the *gambelii* subspecies (Figure 4) supports my hypothesis that birds in rising-temperature environments may develop longer bills to assist in heat dissipation. This finding supports and is consistent with Allen's rule, which states that animals in warmer climates develop longer extremities (Symonds and Tattersall 2010). A longer bill in a hotter environment can help bird species dissipate heat in hot weather (Greenberg et al. 2012). A study of 214 bird species found convincing evidence in favor of Allen's rule by demonstrating that birds in colder climates have shorter bills than those in warmer areas, indicating that bill length helps regulate body temperature (Symonds and Tattersall 2010). The study also showed that bird bills are more sensitive to temperature changes than other body parts (Symonds and Tattersall 2010). My findings align with previous research on the California Savannah Sparrow's subspecies, which also found an increase in the bill surface area in only one of the four subspecies in response to a warming environment (Benham and Bowie 2021). This increase in appendage size in a warm climate confirms Allen's rule, according to the study conducted by Benham and Bowie in 2021. The morphological change in bill surface area, in particular, in the *gambelii* subspecies, indicates the potential impact of environmental factors on the evolution of bird features.

Additionally, the reduction in wing length found in *gambelii* and the Golden-crowned Sparrows (Figure 5) supports my second hypothesis that wing length will decrease over time as the species adapt to increasing climate temperatures. This finding is compatible with Bergmann's rule, which argues that animals in warmer areas have lower body sizes to dissipate heat better. Concurrently, wing length is often used as a proxy of overall body size in birds (Gosier et al., 1998). Therefore, a decrease in wing length may suggest that the overall body size has decreased due to rising temperatures (Weeks et al. 2020). This is consistent with studies suggesting that North American birds are shrinking over time, a pattern linked to climate variations. Controlling for latitude and elevation, 80 out of 105 bird species were recently discovered to have decreased their body size over the past 30 years (Youngflesh et al. 2022). The study also found that temperature fluctuations affect avian body size, with warmer temperatures resulting in smaller birds. This is consistent with my findings that shorter wing lengths help avian species adapt to warmer temperatures over time. Another recent study discovered there were consistent reductions in body size across various species during the study period (Weeks et al. 2020). These reductions were due to increasing summer temperatures, which were predicted to cause these reductions over a 40-year period (Weeks et al. 2020).

The results obtained in my study suggest that changes in morphology, as reflected by variations in wing length, occur throughout time in the studied *Zonotrichia* taxa populations. My findings contribute to a better understanding of avian adaptation and the impact of environmental influences on species morphology. They emphasize the significance of addressing within-species variation when studying morphological features. We learned about the mechanisms governing subspecies' evolution and diversification by examining the White-crowned Sparrow subspecies and comparing them to the Golden-crowned Sparrow species.

Impacts on Morphology Due to Climate

My study's findings show that *Zonotrichia* populations are capable of adapting and changing over time. Understanding the environmental elements that may be influencing these adaptive responses is vital. I discovered that species that breed closer to the Arctic, such as *gambelii* and Golden-crowned, were more likely to exhibit a gradual reduction in wing length as a result of warming Arctic temperatures. Among the studied *Zonotrichia* taxa, the *gambelii*, and Golden-crowned Sparrow migrate the farthest from their breeding grounds. Despite having the longest overall wing length among the *Zonotrichia* taxa measured (Figure 3), the *gambelii* and Golden-crowned species are displaying a decline in wing length over time (Figure 5). Their larger wing length transition to smaller wing size among the *Zonotrichia* taxa studied could be an adaptation to sustain their extended movement. Given the known decline in Arctic regions due to rising temperatures, the observed decrease in wing length in the *gambelii* subspecies of the White-crowned Sparrow and Golden-crowned Sparrow species over time is of special concern.

Recent research performed by Rantanen et al. (2022) revealed an accelerating warming trend in the Arctic, which coincides with the breeding grounds of the *gambelii* subspecies and Golden-crowned species that exhibited the most morphological change in my study. Over the past 43 years, the Arctic region's pace of warming has been increasing at four times the rate of global increases (Rantanen et al. 2022). According to climate model simulations, the reported four-fold increase in warming rates over the past years is evident (Rantanen et al. 2022). These simulations provide valuable insights into how the climate is changing and indicate the need for effective. measures to mitigate the impact of climate change. This shows a possible relationship between observed morphological alterations and changing Arctic conditions. Bergmann's rule, which states that animals in warmer climates typically have smaller body sizes to enhance heat dissipation (Ryding et al. 2021), is supported by this through the wing size reduction shown in my study. Allen's rule, on the other hand, correlates with the rise in the *gambelii* bill size as a result of the Arctic increase in global temperatures. According to Allen's rule, animals in warmer climates typically have longer extremities, e.g., bills, to help dissipate heat, whereas those in colder climates typically have shorter extremities to help conserve heat (Ryding et al. 2021). Therefore, as a means of dissipating excess heat, birds may grow larger bills as a result of rising climate temperatures.

The findings in this study demonstrate the close connection between bird morphology and environmental factors. Scientists have identified a number of important factors that affect how avian morphology is changing, including climate change. In order to survive, birds may have to adapt to new conditions as temperatures rise and weather patterns become more unpredictable.

LIMITATIONS AND FUTURE DIRECTIONS

Understanding the development of bird features and the possible effects of environmental changes on species morphology is significantly impacted by these findings. This study has limitations that should be discussed. For starters, the study focused primarily on skin samples from wintering birds in the Bay area, limiting the findings' generalizability to this specific region. Second, the use of museum specimens made a direct assessment of true body size impossible, necessitating the use of wing length as a proxy. Third, a larger sample size would have helped boost the statistical power and dependability of the results. Finally, the limited availability of climate data for *gambelii* and Golden-crowned Sparrow breeding distributions in Alaska and western Canada prevented the investigation of the potential influence of breeding sites on observed trends. Future studies should seek to address these limitations by broadening the investigation to cover a broader range of locales and populations, with a particular focus on the Golden-crowned Sparrow's understudied breeding grounds (Seavy et al.,2012). All things considered, a more comprehensive understanding of the factors influencing the features and behaviors of these avian species would result from such an approach.

To begin with, it would be advantageous to broaden the study's geographical focus beyond the Bay area in order to develop a deeper understanding of wintering bird behaviors and features in various geographic areas. Examining new wintering locations, recording a range of environmental factors, and documenting population changes may all be necessary. Second, future research could use cutting-edge methods like digital imaging or 3D scanning to collect exact measurements in order to increase the precision of body size estimates (Ryding et al. 2021). The statistical power would also be improved and more subtle patterns would be shown by working with other researchers and expanding the sample size through data collection operations. Focusing on the breeding grounds of *gambelii* and Golden-crowned Sparrows in Alaska and western Canada through fieldwork, direct observations, and specimen collecting will be beneficial to understand the function of breeding grounds better. Last but not least, collecting thorough meteorological data would help in assessing the study's results.

BROADER IMPLICATIONS

Ultimately, measunng museum avian species provide valuable insights into the evolutionary history and ecological dynamics of these birds. Out of 447 skin study samples of Bay Area wintering *Zonotrichia* taxa, I found a significant positive relationship in bill surface area in the *gambelii* subspecies in accordance with Allen's Rule. Additionally, I found a significant decrease in wing length size in the *gambelii* subspecies and Golden-crowned species. Notably, *gambelii* and Golden-crowned taxa have the furthest north breeding ranges and furthest wintering migration patterns in contrast to *nuttalli* and *pugetensis* which showed no change throughout this study. Although this study was limited to an association with the environmental factors contributing to this morphological change, it is important to note that there is strong evidence that it can be correlated to the rising warming temperatures in the Arctic. These discoveries may have implications for understanding how climatic changes affect bird morphology, such as rising temperatures and decreasing Arctic habitats, which is critical for creating successful conservation efforts. The observed morphological change presented in this study shows us that some subspecies are responding to the altering climate.

These discoveries highlight how environmental factors play a significant role in the development and variety of subspecies within a species. Birds adapt to changing environmental conditions, such as temperature increases or the absence of habitats, which can affect their morphology and adaptations. It's crucial to understand the processes that create and maintain biodiversity in avian populations. We can better foresee and prevent the possible implications of ongoing environmental changes on bird species by incorporating environmental considerations into conservation programs.

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