ORIGINAL ARTICLE

USING MORPHOMETRICS TO DETERMINE SEX IN A NEOTROPICAL PASSERINE: THE GRAY-BREASTED WOOD-WREN (*HENICORHINA LEUCOPHRYS*)

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Abstract · Sexual size dimorphism is a widespread pattern among birds, but has remained untested for many Neotropical species. Here we examine sexual differences in a relatively common passerine that is found from Mexico to Bolivia, the Gray-breasted Wood-Wren (*Henicorhina leucophrys*), and provide models to determine the sex of individuals using classical morphometric variables. Measuring 137 museum specimens from five of the 17 recognized subspecies, we describe and test patterns of sexual size dimorphism. Differences between males and females in this sexually monochromatic species were assessed through *t*-tests and Logistic Regression Analyses (LRA). Males were larger than females in most measurements for all taxa. Additionally, using univariate LRA models we correctly classified 83–93% of the males and 70–93% of the females using wing length for *manastarae* and *meridana*, tail length for *tamae* and bill length for *venezuelensis*. All our analyses showed adequate significance and goodness of fit, and models were compared according to their classification percentages and AICc values. We highlight that patterns of sexual dimorphism in this species vary geographically, with some subspecies being more dimorphic than others. To the best of our knowledge, this morphometric research represents the first sex determination assessment for a Neotropical passerine while considering geographic variation, and a first step to describe and understand the patterns of phenotypic variation in this wren species.

Resumen · La morfometría como herramienta de determinación del sexo en un paseriforme Neotropical: el Cucarachero Selvático (*Henicorhina leucophrys*)
El dimorfismo sexual de tamaño es común en las aves; sin embargo, no ha sido estudiado en un gran número de especies Neotropicales. En este trabajo examinamos las diferencias sexuales en un paseriforme de amplia distribución que se distribuye desde México hasta Bolivia, el Cucarachero Selvático (*Henicorhina leucophrys*), y proveemos modelos de determinación del sexo a través del uso de variables morfométricas clásicas. Para describir los patrones de dimorfismo sexual se midieron un total de 137 ejemplares de museo pertenecientes a cinco de las 17 subespecies reconocidas. Evaluamos las diferencias entre machos y hembras de esta especie sexualmente monocromática a través de pruebas *t* y determinamos los patrones de dimorfismo sexual implementando análisis de Regresión Logística. En todos los taxa los machos presentaron valores mayores que las hembras para la mayoría de las variables. Modelos univariados de Regresión Logística clasificaron correctamente entre 83–93% de los machos y 70–93% de las hembras dentro de cada subespecie, usando largo de ala para *manastarae* y *meridana*, largo de cola para *tamae* y largo de pico para *venezuelensis*. Los modelos mostraron efectos significativos y valores de bondad de ajuste adecuados, y fueron comparados a través de sus porcentajes de clasificación y valores de AICc. Mostramos que en esta especie los patrones de dimorfismo sexual varían geográficamente, siendo algunas subespecies más dimórficas que otras. Hasta donde sabemos, este estudio aborda por primera vez la determinación del sexo a través de variables morfométricas en un paseriforme Neotropical, considerando su variación geográfica, y representa un primer paso en la caracterización y el estudio de los patrones fenotípicos de esta especie.

Key words: *Henicorhina leucophrys* · Logistic Regression · Morphometrics · Sexual Dimorphism · Size · Venezuela · Wren

INTRODUCTION

Sexual dimorphism is common among birds, particularly in terms of color and body size (Bennett & Owens 2002). Some species show plumage dichromatism, color differences between sexes that could be apparent to

the unexperienced observer, and others exhibit sexual size dimorphism, in which males and females might be difficult to separate just by observation (Ranta et al. 1994, Bennett & Owens 2002, Covino 2015). Since the ability to discriminate the sex of individuals in a population may be a necessary step to develop demographic, ethological and life history studies (Wheelwright et al. 1994), different morphological and molecular techniques have been implemented to accomplish this issue.

Sex identification techniques might differ in their availability to a researcher. Molecular methods have proved to be quite efficient (Bantock et al. 2008), but could be expensive or inaccessible to laboratories with limited funding in developing countries. Laparotomy, an acceptable and secure procedure (Piper & Wiley 1991), requires specific equipment and training, and could be unnecessary if simpler and less invasive alternatives exist (Fair et al. 2010, Covino 2015). Morphometric methods represent a time efficient and inexpensive procedure to estimate the sex of individuals.

Different analytical approaches have been developed and discussed in relation to morphometric sexing techniques. Discriminant Analysis has been the most commonly used approach to determine sex based on morphometric characters, mainly in temperate and migratory bird species (Dechaume-Moncharmont et al. 2011). However, as this method has rigorous assumptions, like multivariate normality and homogeneity of variance-covariance matrices (Quinn & Keough 2002), other alternatives have been applied, including Logistic Regression Analysis (Jeffrey et al. 1993, Gill & Vonhof 2006, Hallgrimsson et al. 2008, Ellrich et al. 2010). This method could be performed using one or multiple variables depending on sample sizes (Agresti 2007), and it constitutes an excellent alternative for researchers in the Neotropics, a region with an outstanding avian diversity and a large number of monochromatic species (Ridgely & Tudor 1994) that are in need of basic natural history studies for which sex determination methods could greatly contribute to their success.

The Gray-breasted Wood-Wren (*Henicorhina leucophrys*, Troglodytidae) is a widespread sexually monochromatic species that inhabits mountain forests from Mexico to Bolivia, showing considerable geographic variation as reflected in its current taxonomy (17 subspecies), particularly in northwestern South America, where nearly half of its subspecies can be found (Kroodsma & Brewer 2005, Restall et al. 2006). Differences found in molecular, vocal and morphometric characters suggest that diversity in the genus is larger than traditionally recognized (Salaman et al. 2003, Dingle et al. 2006, Dingle et al. 2008, Caro et al. 2013, Aguilar et al. 2014, Pegan et al. 2015, Cadena et al. 2016). Additionally, both sexes of this territorial species are highly vocal (Dingle 2009), which makes identification of individuals' sex challenging if song repertoires are unknown. As such, studies of morphological geographical differentiation,

along with patterns of sexual dimorphism, could greatly contribute to understanding the taxonomy and evolutionary history of the genus *Henicorhina*.

In this study, we aimed to assess sexual size dimorphism in *Henicorhina leucophrys* populations distributed in Venezuela. We implemented models based on museum specimens due to its availability and usefulness for generating data before conducting field studies (e.g., behavioral studies; Gill & Vonhof 2006). We explored patterns of sexual dimorphism in five subspecies: *venezuelensis* (Cordillera de la Costa Central); *meridana* (Cordillera de Mérida); *sanluisensis* (northwestern Sierra de San Luis); *tamae* (Macizo El Tamá), and *manastarae* (Serranía de Perijá), the last two taxa also found in Colombia. In short, we aimed to: 1) determine if mean differences in morphometric characters exist between male and female specimens within these subspecies, and 2) develop models to diagnose their sex.

METHODS

Morphological measurements. We measured 137 *Henicohrina leucophrys* study skins representing all five subspecies from three major Venezuelan museums and collections (Colección Ornitológica Phelps (COP), Museo de Historia Natural La Salle (MHNLS), and Museo de la Estación Biológica Rancho Grande (EBRG)). We assigned sex according to label information or sexed specimens through molecular methods (N = 6, Fernandes et al. 2016), considering only adult birds (i.e., without any sign of yellowish gape flanges). As we just had five adult *sanluisensis* specimens, we did not include this taxon in subsequent statistical analysis. Samples sizes were as follows: *manastarae* (N_F = 19 females, N_M = 13 males), *meridana* (N_F = 12, N_M = 15), *tamae* (N_F = 13, N_M = 21), and *venezuelensis* (N_F = 12, N_M = 27). Mensural characters included three bill measurements taken at the anterior edge of nostrils (length, width, and depth), wing (unflattened chord), tarsus, and tail lengths (Baldwin et al. 1931). We used an Avinet stop-end ruler to measure wing and tail lengths to the nearest 1 mm, and the rest of the variables were measured with a Somet Inox caliper to the nearest 0.05 mm (all study skins were measured by FMS). We assessed measurement error percentages for all morphometric variables with a model II ANOVA (Yezerinac et al. 1992), making three non-consecutive measurements of male individuals from the same geographic area (N = 16).

Data analysis. We tested sexual size dimorphism in each mensural character for each subspecies using *t*-tests (two tails) with sex as a factor. All statistical tests were made in R version 3.2.5 (R Core Team 2016) using RStudio version 0.99.467 (R Studio Team 2015). We tested assumptions of normality (Shapiro-Wilk test) and equality of variances *a priori* (Levene test, car package; Fox & Weisberg 2011). Only one case showed a statistical deviation from normality,

and we took a non-parametric approach (i.e., Mann-Whitney test). These tests were followed by a series of Logistic Regression Analyses (LRA) where sex was a dichotomous variable (Y) dependent on the morphometric descriptor (X), and quantified a specimen's probability of being male, using the expression $P(\text{male}) = 1 / 1 + e^{-(\alpha + \beta X)}$, where α and β are the regression coefficients for the constant and the descriptor, respectively (Agresti 2007). Geographic variation was considered by running separate models for each subspecies, to identify which variable could discriminate better the sexes of these taxa. Since the minimum number of events in the response variable (i.e., the number of individuals in the less sampled sex) affects the number of independent variables a model could have (Agresti 2007), we applied univariate models for each taxon, due to our relatively small sample. In addition, given these sample sizes we tested the effect of each variable through Likelihood Ratio Tests (LRT) instead of Wald tests (Agresti 2007). The global goodness of fit was tested using the Le Cessie-van Houwelingen-Copas-Hosmer unweighted sum of squares test in the rms package (Harrell 2016), and the Hosmer-Lemeshow test (Hosmer et al. 1997). Finally, significant models were compared considering the percentage of correctly classified individuals and the second-order Akaike Information Criterion (AICc) (Burnham & Anderson 2002).

RESULTS

Sexual size dimorphism. We found that males were larger than females in the *Henicorhina leucophrys* subspecies considered in this study, although overlap between sexes was evident (Figure 1). Measurement errors were lower than 10%: wing (6%), tail (4%), bill lengths (2%), and bill depth (9%), with the exception of tarsus length (11%), and bill width (16%). These two characters were not considered in posterior statistical analyses due to their high error values (following Bailey & Byrnes 1990). Significant differences between sexes (based on *t*-tests) were found within all subspecies in the variables with lower measurement errors (i.e., wing, tail, and bill lengths) (Figure 1). Bill depth showed significant sex differences ($P <$ 0.05) in all taxa but *venezuelensis* (t = 0.73, $P = 0.47$). We obtained the same pattern using the Mann-Whitney test for bill length in *manastarae* ($U = 175$, $P <$ 0.01). Finally, males of *sanluisensis* (N = 4) had generally larger mean values than the single adult female available (males mean ± SD [mm], female measure [mm]; wing: 56.8 ± 3.2, 51.0; tail: 26.5 ± 1.3, 25.0; tarsus: 23.16 ± 0.86, NA; bill length: 10.51 ± 0.34, 9.55; bill width: 3.05 ± 0.12, 3.10; bill depth: 3.43 ± 0.12, 3.35).

Sex determination models. The morphometric analyses correctly classified sex for most of the specimens within taxa (83-93%), resulting in better models with different variables associated to each subspecies (Table 1). Most variables had a significant effect

(LRT's $P < 0.05$), with the exception of bill depth in *venezuelensis*. The goodness of fit of the selected LRA was adequate following Hosmer-Lemeshow (not shown) and Le Cessie-van Houwelingen-Copas-Hosmer tests. The best models were those that had the highest proportion of correctly classified individuals, being wing, tail, or bill lengths the preferred descriptors. In *tamae*, however, we chose tail length as a better variable for sex determination, because the percentages of correctly classified males and females from this model were more similar (83.3% for both sexes) than those obtained using bill length (75% for females and 94.4% for males), the variable with the highest overall classification percentage (Table 1). Lastly, bill depth was a poor descriptor for all subspecies (i.e., misclassification around 50%).

Using the selected models, we were able to classify from 83% to 93% of the subspecies' males and between 70–93% of the females, obtaining predicted probability curves for values within our sample (Table 1, Figure 2). Wing length was the variable that better discriminated sexes in both *manastarae* and *meridana* data sets. The application of this method allowed us to estimate that in both subspecies an individual has higher probabilities of being male if it has a wing value of at least 54 mm. Using the tail length model, we assessed that *tamae* birds with a measure ≥ 28 mm would be also classified as males. Finally, the bill length model was the most useful to differentiate sex in *venezuelensis*, estimating that there is a higher expectation that a measurement lower than 10.55 mm will correspond to a female.

DISCUSSION

We found evidence that populations of *Henicorhina leucophrys* distributed in Venezuela exhibit sexual size dimorphism. Males have larger sizes in all morphometric descriptors, as it has been found in other species within this genus (Fitzpatrick et al. 1977, Winker et al. 1996). To our knowledge, only an additional study has statistically tested sexual dimorphism in a nominal *leucophrys* population from northeastern Ecuador (Dingle 2009), finding significant differences in all measures except bill width (see also Salaman et al. 2003). Studies that have used living birds and museum specimens suggest that sexual size dimorphism is common in wrens (Brumfield & Remsen 1996, Montalti et al. 2004, Mennill & Vehrencamp 2005, Lara et al. 2012). Moreover, it has been shown that in monogamous wren species pairs, the male tends to be larger than his partner (Gill & Vonhof 2006, Haggerty 2006), which may allow assigning sex tentatively to both partners in population or behavioral studies.

High measurement errors increase the likelihood of type II errors (Yezerinac et al. 1992) and could affect the discrimination ability of classification analyses (Dechaume-Moncharmont et al. 2011). In that sense, a morphometric descriptor's usefulness is related to its repeatability (*r*) (Harper 1994, Sweeney &
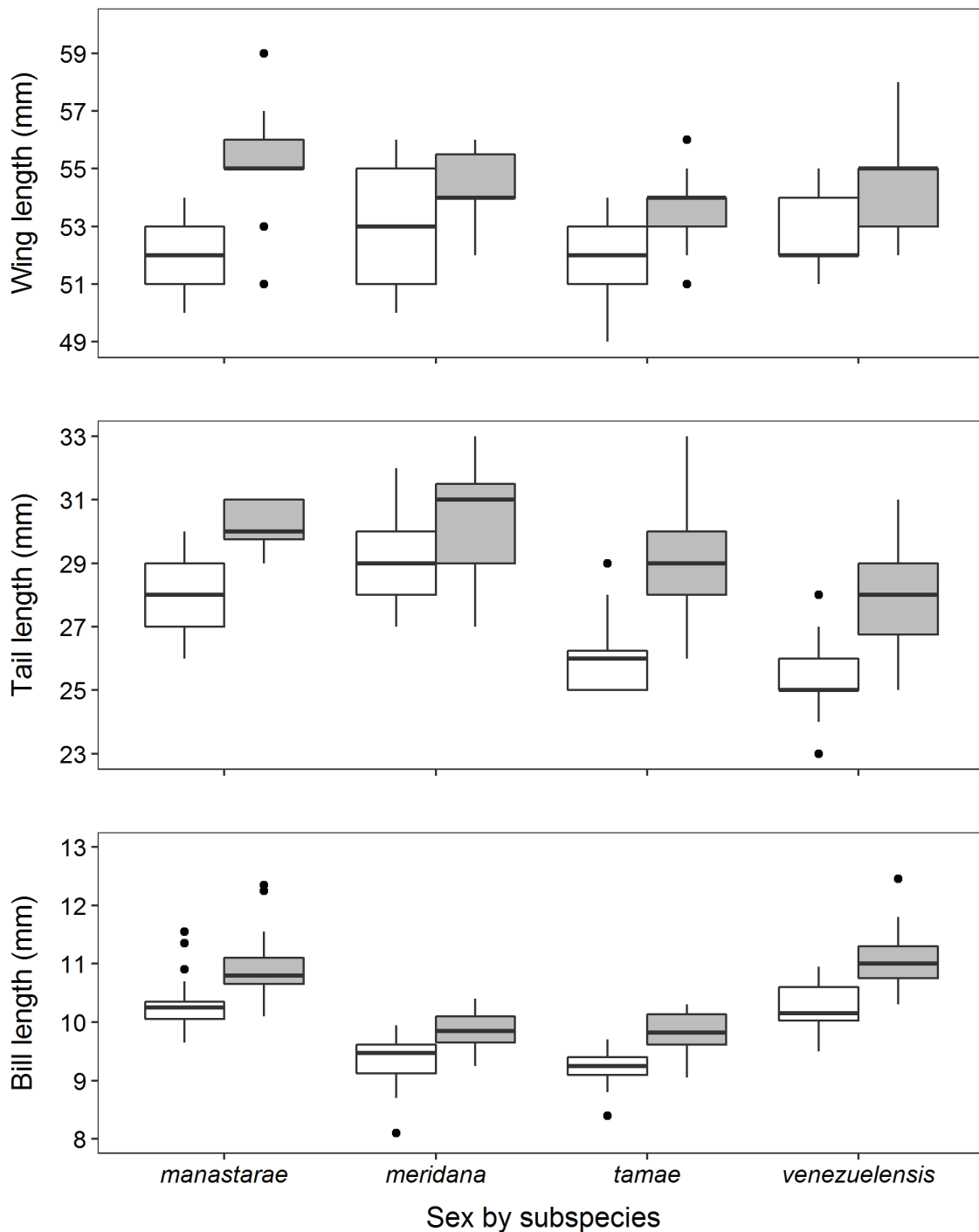
Figure 1. Distribution of morphometric characters of males (gray) and females (white) Gray-breasted Wood-Wren (*Henicorhina leucophrys*) specimens for the subspecies *manastarae* (N = 32), *meridana* (N = 27), *tamae* (N = 34), and *venezuelensis* (N = 39). Box plots include the quartile range (box or spread), the median (bar within box), whiskers that extend to values lesser than 1.5 times the spread beyond the quartiles, and outlier values beyond this distance (black points). All variables showed significant differences ($P < 0.05$) between sexes.

Tatner 1996), which can be thought as the measurement error's complement ($1-r$). In general, we obtained low measurement error percentages (< 10% ME; Lougheed et al. 1991), and our repeatability values were higher (wing and tail lengths) than those obtained in other wren studies (Sweeney & Tatner 1996, Gill & Vonhof 2006).

Logistic Regression (Gill & Vonhof 2006) and Discriminant Analyses studies (Haggerty 2006) on wren species have reported higher classification percentages for each sex (c. 95%). These field studies measured single populations extensively (e.g., measurements of paired wrens), and consequently had larger sample sizes than our collection-based and

Table 1. Results from logistic regression models to determine sex for Gray-breasted Wood-Wren (*Henicorhina leucophrys*) subspecies in Venezuela. The best two models are presented from top to bottom within each taxon, according to correct classification percentages and the second-order Akaike Information Criterion (AICc). Only specimens without missing data were used. [1]The models formula was P (male) = 1 / 1+e-(α + βX). [2]Le Cessie-van Houwelingen-Copas-Hosmer unweighted sum of squares test of Goodness of fit (GoF).

Subspecies	Model[1] (α + βx)	% Correct classification			AICc	GoF (P)[2]
		Females	Males	All		
manastarae	−142.0 + 2.64*Wing	93.3	91.7	92.6	12.7	0.37
(N_F = 15, N_M = 12)	−60.5 + 2.06*Tail	86.7	75.0	81.5	23.8	0.38
meridana	−44.6 + 0.84*Wing	70.0	92.9	83.3	29.7	0.86
(N_F = 10, N_M = 14)	−44.3 + 4.64*Bill	70.0	78.6	75.0	27.2	0.47
tamae	−31.2 +1.15*Tail	83.3	83.3	83.3	27.3	0.65
(N_F = 12, N_M = 18)	−53.5 + 5.65*Bill	75.0	94.4	86.7	27.4	0.98
venezuelensis	−51.1 + 4.86*Bill	70.0	89.5	82.8	23.6	0.37
(N_F = 10, N_M = 19)	−27.3 + 1.06*Tail	60.0	89.5	79.3	29.3	0.77

geographically broader approach. A larger sampling effort would allow the application of multivariate models (Winker et al. 1996), which may have the potential of producing better classifications. Additionally, post-taxidermy shrinkage could be a potential shortcoming of our models, considering shrinkage percentages for wing length in passerine species (0.5–1.4%, Winker 1993). Consequently, measuring live birds for confirmation and validation could be advisable, although shrinkage might not differ among sexes. Nevertheless, our simple approach led us to recognize different single variables with low measurement errors, and resulted in models with suitable classification rates for each taxon, which could be useful when study skins are damaged, a variable cannot be measured (e.g., molting) or field time is limited. With these limitations and advantages in mind, we present our models as a preliminary step to unravel and depict the morphological patterns of *H. leucophrys* populations.

Patterns of sexual dimorphism found in this study highlight the need of considering geographic variation. Our best sex determination models differed in the morphometric variable selected for each subspecies, based on their classification success. In that sense, variables such as wing length showed high sex discrimination in some subspecies (i.e., 92.6% of *manastarae* specimens), while being a poor choice for distinguish sex in others (i.e., 76.7% of *tamae* specimens), pointing out that sexual patterns are diverse among populations. Previous studies have shown that mixing populations in sex determination procedures, with distinct migration patterns (Ellrich et al. 2010), or from different subspecies (Gates et al. 2013), increased misclassification rates. *Henicorhina leucophrys* subspecies have been described based on plumage differences, and this research has shed light on an unrecognized geographic variation pattern. A null expectation would be that if no morphometric differences exist between subspecies, the same variables would discriminate sex similarly between them. Our results suggest that a revision of geographic variation in size, accompanied by color comparisons, is needed for the species (Machado-Stredel et al. in prep.).

To our knowledge, the present research constitutes the first sex determination study for a Neotropical passerine that considers intraspecific taxonomy, and a contribution to the understanding of patterns of sexual dimorphism in *Henicorhina leucophrys.* We stress the need for tackling morphometric models with large sample sizes, taking into account taxonomy and multiple variables with low measurement errors, to characterize cryptic sexual dimorphism in Neotropical species. Since *Henicorhina* wood-wrens show considerable genetic divergence among and within taxa (Dingle et al. 2006), elevational replacements with contact zones (Dingle et al. 2008, Caro et al. 2013) and isolated high-altitude populations along its distribution (Fitzpatrick et al. 1977, Cadena et al. 2016), morphometric studies provide an excellent tool for addressing taxonomic and evolutionary inquiries in this Neotropical wren, as well as in other monochromatic species in the region.
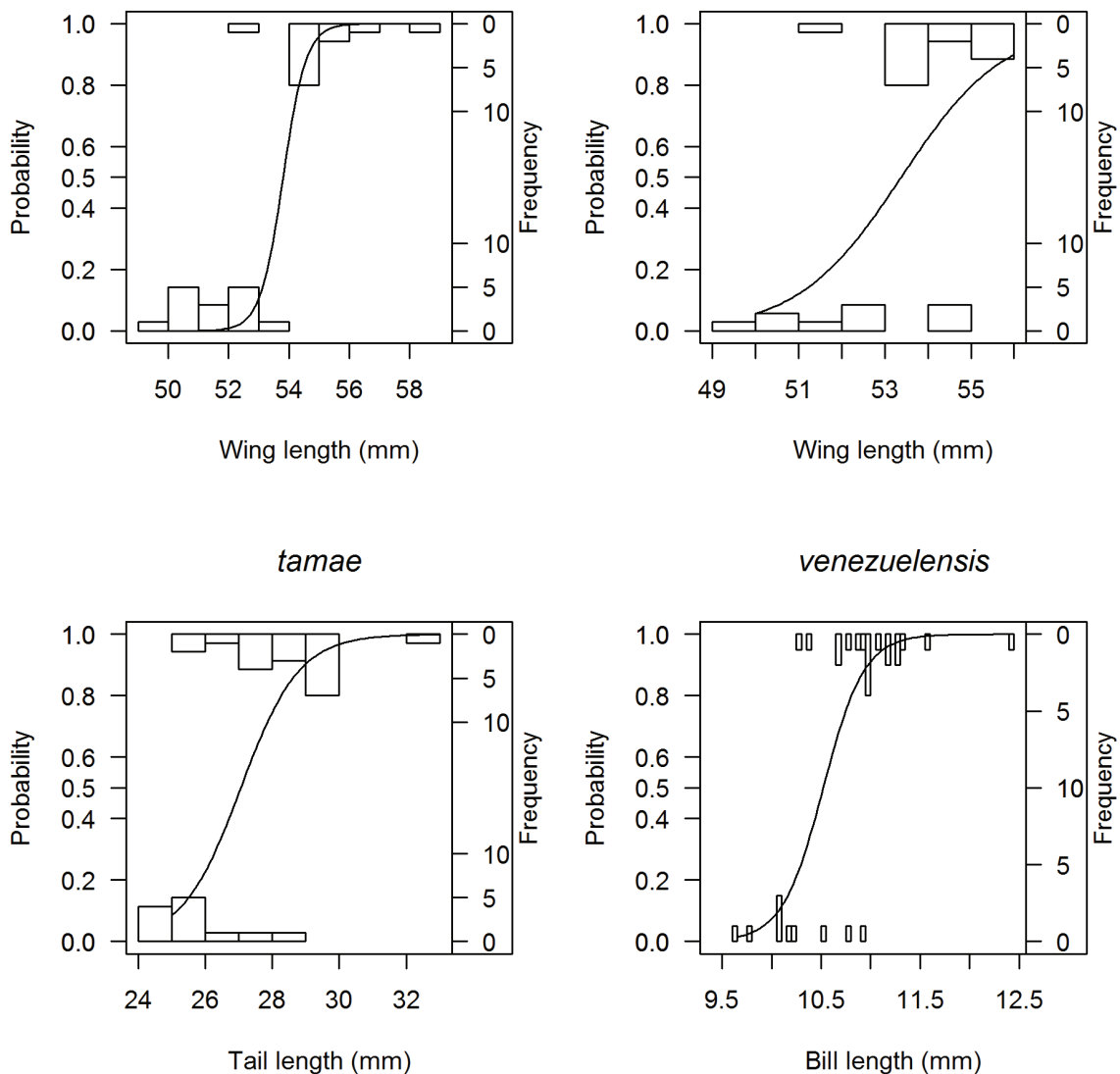
tamae

venezuelensis

Figure 2. Probability of predicting male specimens (first Y-axis) for four different Gray-breasted Wood-Wren (*Henicorhina leucophrys*) subspecies, obtained with the selected variable (first X-axis) in LRA (Table 1). Frequency values for females (bottom) and males (top) are shown in the second Y-axis.

insightful comments on morphometric and statistical analyses.

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