

BROAD-WINGED HAWK SIZE VARIES BY SEX AND LATITUDE IN NORTH AMERICA

ZACHARY E. BORDNER AND REBECCA A. MCCABE¹

Acopian Center for Conservation Learning, Hawk Mountain Sanctuary Association, 410 Summer Valley Road, Orwigsburg, PA 17961 USA

DAVID BRINKER

Maryland Department of Natural Resources, 580 Taylor Avenue, Annapolis, MD 21401 USA

ROBERT N. ROSENFELD

Department of Biology, University of Wisconsin-Stevens Point, 2100 Main Street, Stevens Point, WI 54481 USA

EUGENE A. JACOBS

Linwood Springs Research Station, 1601 Brown Deer Lane, Stevens Point, WI 54481 USA

CHARLOTTE ENGLAND AND MALCOLM WILSON

Simcoe Raptor Research Group, Toronto, ON L9S 2C6 Canada

LAURIE J. GOODRICH

Acopian Center for Conservation Learning, Hawk Mountain Sanctuary Association, 410 Summer Valley Road, Orwigsburg, PA 17961 USA

ABSTRACT.—Divergent life histories by sex are common within species of birds; thus, the ability to accurately determine sex is essential in many studies of avian ecology and can possibly lead to more effective conservation strategies. However, sex determination can be difficult in species not displaying dimorphic plumage, including most raptors, and size dimorphism has limited use during observations but is promising for determining sex of raptors in hand. The Broad-winged Hawk (*Buteo platypterus*), known for its long-distance migrations between North and South America, has yet to be examined for morphometric variation across its wide range. We analyzed body mass, wing chord, and tail length data for 119 adult Broad-winged Hawks captured in eastern North America during the breeding seasons from 1974 to 2020. We found that adult female Broad-winged Hawks were larger than adult males overall. Hawks from Wisconsin were larger than hawks from Pennsylvania and Maryland, and hawks from Ontario were larger than those from other populations, suggesting geographic variation in size. Using linear discriminant analysis, we showed that it was possible to determine sex of adults with 99% accuracy in Wisconsin populations using only body mass as a predictor, and 100% accuracy in Pennsylvania and Maryland populations using body mass, wing chord, and tail length as predictors. Morphometric measurements combined with discriminant function analysis proved useful in discerning sex of breeding-season Broad-winged Hawks, and results of this study can guide researchers working in similar regions. We encourage researchers to collect body measurements for this species and other monomorphic raptors to further inform sex determination.

KEY WORDS: *Broad-winged Hawk*; *Buteo platypterus*; *discriminant function analysis*; *morphometrics*; *raptor*; *sexual dimorphism*.

EL TAMAÑO DE *BUTEO PLATYPTERUS* VARÍA SEGÚN EL SEXO Y LA LATITUD EN NORTEAMÉRICA

¹ Email address: mccabe@hawkmountain.org

RESUMEN.—Las historias de vida divergentes según el sexo son comunes en aves, por lo que la capacidad de determinar con precisión el sexo es esencial en muchos estudios de ecología aviar y posiblemente puede conducir a estrategias de conservación más efectivas. Sin embargo, la determinación del sexo puede ser difícil en especies que no muestran dimorfismo de plumaje, incluida la mayoría de las aves rapaces, y el dimorfismo de tamaño tiene un uso limitado durante las observaciones, pero es prometedor para determinar el sexo de las aves rapaces en la mano. *Buteo platypterus*, conocido por sus migraciones de larga distancia entre América del Norte y América del Sur, aún debe ser estudiado para determinar la variación morfométrica a lo largo de su amplia área de distribución. Analizamos los datos de masa corporal, cuerda alar y longitud de la cola de 119 individuos de *B. platypterus* capturados en el este de América del Norte durante las temporadas reproductivas de 1974 a 2020. Encontramos que, en general, las hembras adultas de *B. platypterus* eran más grandes que los machos adultos. Los individuos de Wisconsin eran más grandes que los de Pensilvania y Maryland, y los individuos de Ontario eran más grandes que los de otras poblaciones, lo que sugiere una variación geográfica en tamaño. Usando un análisis discriminante lineal, mostramos que era posible determinar el sexo de los adultos con un 99% de precisión en las poblaciones de Wisconsin usando solo la masa corporal como predictor, y con un 100% de precisión en las poblaciones de Pensilvania y Maryland usando la masa corporal, la cuerda alar y la longitud de la cola como predictores. Las mediciones morfométricas combinadas con análisis de función discriminante demostraron ser útiles para discernir el sexo de *B. platypterus* en la temporada reproductiva, y los resultados de este estudio pueden guiar a los investigadores que trabajan en regiones similares. Alentamos a los investigadores a recopilar medidas corporales de esta especie y de otras rapaces monomórficas para avanzar en la determinación del sexo.

[Traducción del equipo editorial]

INTRODUCTION

Divergent life histories by sex within species are common in animals; thus the ability to accurately determine sex is essential in many studies of avian ecology (Catry et al. 2005). Knowledge of niche variation and survival by sex can shed light on species' population dynamics and possibly lead to more effective management and conservation strategies. However, sex determination can be difficult in species not displaying dimorphic plumage, such as many *Buteo* and *Accipiter* species (Ferguson-Lees and Christie 2005). Although molecular techniques, behavioral observations, and anatomical inspection allow for sex identification, these methods can be overly invasive, time consuming, and costly for researchers (Dechaume-Moncharmont et al. 2011). Most raptor species are sexually monomorphic, but exhibit some degree of reverse sexual size dimorphism (Krüger 2005), which can facilitate sex identification through statistical analysis of body measurements. Because different sexes of raptors can display distinctive movement, migration range, habitat use, and foraging behavior (Kerlinger 1989, Newton 2008), knowledge of the sex of individuals can better inform our understanding of their life cycle, ecology, survivorship and current conservation challenges.

The Broad-winged Hawk (*Buteo platypterus*) is a small woodland raptor that breeds across central and eastern United States and southern Canada, and as

far west as British Columbia, Canada (Phinney 2015, Goodrich et al. 2020). As with other members of the genus *Buteo*, Broad-winged Hawk plumage does not differ by sex and thus they can be challenging to accurately sex in the field and in the hand, with the exception of breeding-season females exhibiting a brood patch. Though this species exhibits reverse sexual size dimorphism (Mosher and Matray 1974, Snyder and Wiley 1976), individual measurements are not always useful for sexing Broad-winged Hawks due to significant overlap between sexes (Pyle 2008). As a result, Broad-winged Hawks are almost always recorded as unknown sex when trapped by banders (Johnson et al. 2020). Because spatial sexual segregation and differential migration by sex have been documented in several raptors (Smallwood 1988, Goodrich et al. 2012, Tomalty et al. 2016), the ability to add sex identification to banding encounter data would provide valuable insights into the migration movements and dispersal of this rarely trapped migrant.

Discriminant function analysis of body measurements is a widely used tool for producing morphological sexing criteria for birds, which may then be used as a fast and effective means of sexing individuals in the field (Dechaume-Moncharmont et al. 2011). Several members of the genus *Buteo* have been sexed with 97% or greater accuracy using discriminant equations, including Red-tailed Hawks (*Buteo jamaicensis*; Donohue and Duffy 2006), Red-shouldered Hawks (*Buteo lineatus*; Dykstra et al.

2012), and Swainson's Hawks (*Buteo swainsoni*; Kochert and McKinley 2008). Species with large distributional ranges, such as the Broad-winged Hawk, are subject to diverse environmental, climatic, and ecological pressures that may result in unique intraspecific morphologies. Thus, care must be taken when applying discriminant equations to geographically distinct populations (Pitzer et al. 2008, Montalti et al. 2012). Up to 76% of bird species adhere to Bergmann's Rule—the ecogeographic trend that describes the tendency for similar organisms to be larger in size in cold climates (or higher latitudes) and smaller in warmer ones (Ashton 2002, Meiri and Dayan 2003, Millien et al. 2006). For example, Bald Eagles (*Haliaeetus leucocephalus*) have longer wing chord, tail length, culmen, tarsus, and toe measurements, and a greater body mass in more northern populations throughout their range (Friedmann 1950, Smith et al. 2016, Buehler 2020). In Britain, Eurasian Sparrowhawks (*Accipiter nisus*) have longer wing chords in higher latitudes compared to individuals in the southern part of their range (Wyllie and Newton 1994). Morphological differences have been documented over longitudinal gradients in northern populations of Cooper's Hawks (*Accipiter cooperii*; Rosenfield et al. 2010). Intraspecific geographic size variation has been linked to many factors, including thermoregulatory demands, evapotranspiration gradients, primary productivity, prey size, and migration distance (Rosenzweig 1992, Terribile et al. 2009, Sonsthagen et al. 2012).

In this study, we (1) investigate sexual size dimorphism in nesting Broad-winged Hawks, (2) characterize geographic variation in morphology of eastern breeding populations, and (3) explore the utility of discriminant function analysis using morphological characteristics for determining sex of Broad-winged Hawks. We predict that body size in the Broad-winged Hawk increases with latitude in accordance with Bergmann's Rule and that females are larger than males across latitudes, in all measureable characters. We also anticipate that the discriminant function analysis will prove to be a useful tool for sex determination of the Broad-winged Hawk. The ability to sex Broad-winged Hawks morphometrically will enhance our ability to study their behavior and ecology.

METHODS

Study Sites and Data Collection. We captured 119 Broad-winged Hawks during the breeding season

(May–July) in the United States and Canada. Broad-winged Hawks were captured and banded in Wisconsin (WI), USA (45°15'N, 88°33'W), Maryland (MD), USA (39°39'N, 78°51'W), Pennsylvania (PA), USA (40°37'N, 75°59'W), and Ontario (ON), Canada ([44°55'N, 79°22'W], [45°03'N, 77°51'W]; Fig. 1). Birds were captured within breeding territories from 1974–1994 (WI), 1999–2000 (MD), 2014–2020 (PA), and 2019–2020 (ON).

Broad-winged Hawks were trapped near nest sites in WI and MD using a bal-chatri trap baited with gerbils, or mist nets and a live Great Horned Owl (*Bubo virginianus*; Bloom et al. 1992, Bloom et al. 2007), and in PA near nest sites using mist nets, a mechanical Great Horned Owl and call as a lure (Jacobs 1996, McCloskey and Dewey 1999). Hawks in ON were trapped along forested roads using a bal-chatri trap baited with live mice. All birds received a US Geological Survey aluminum leg band and birds caught in PA and ON also received color bands for individual identification. Only birds in adult plumage $\geq \sim 2$ yr of age (i.e., after second year) were included in this study. We sexed individuals by (1) the presence/absence of brood patch ($n = 107$), (2) observation of bird position during copulation ($n = 2$), or (3) behavior of paired birds where we trapped and banded both adults ($n = 10$), and where subsequent nest observations confirmed the individual attending and defending the nest the majority of time and the individual delivering most of the prey, as female and male, respectively, based on literature (Burns 1911, Matray 1974, Mosher and Matray 1974, Lyons and Mosher 1987, Crocoll 1984, McCabe et al. 2019).

All birds captured were weighed (g) using either a triple beam balance or digital scale. We measured unflattened wing chord (mm) by laying a bent wing on a ruler and measuring from the joint above the primaries to the longest feather. We measured tail length (mm) by inserting a ruler between the two central tail feathers up to the base of the pygostyle, and then measuring the length of the two central tail feathers (Baldwin et al. 1931, Pyle 1997). Tarsus, culmen, and tail band width data were gathered from some individuals but are not included here due to limited sample size. Because PA and MD sample sizes were relatively small compared to WI and encompassed roughly the same latitudinal distance (approximately 2°), we combined the populations into a single group (PA/MD) to increase statistical power. We presumed similarities between the two populations, as they both fell within the same Bird

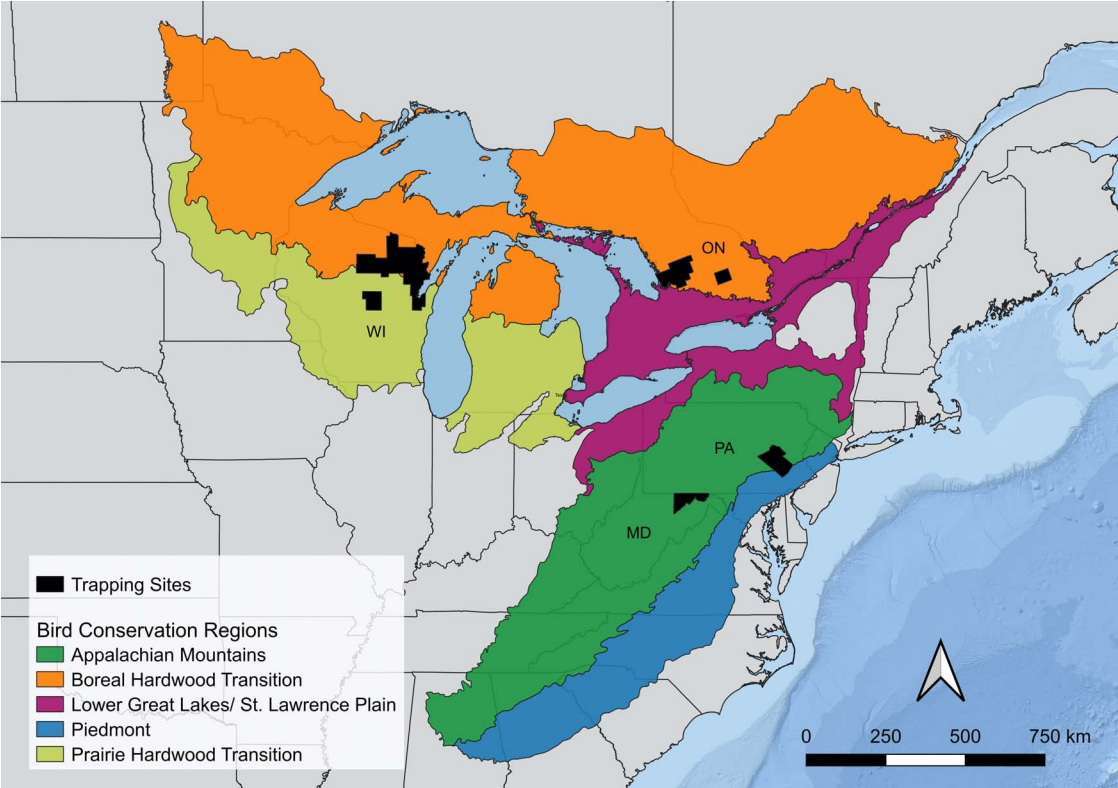


Figure 1. Trapping sites in Bird Conservation Regions in USA and Canada where morphological data were collected from adult Broad-winged Hawks ($n = 119$) captured during the breeding season (May–July) from 1974 to 2020.

Conservation Regions (Fig. 1), which are ecological units comprised of similar bird communities, habitats, and resource concerns (Bird Studies Canada and North American Bird Conservation Initiative 2014).

Statistical Analyses. For our first analysis investigating sexual size dimorphism of Broad-winged Hawks, we used a subset of data containing 105 adults of known sex (38 male, 67 female) from WI and PA/MD populations. To test for overall size differences between sexes, we used a multivariate analysis of variance (MANOVA) with three morphometric characters (i.e., body mass, wing chord, tail length) as dependent variables and Pillai’s trace test (Pillai 1955). Contingent on a significant MANOVA, we followed up with a univariate analysis of variance (ANOVA) for each measurement. To assess geographic variation in morphometrics for males and females, we used ANOVA and included the sample of known-sex adults from ON (14 females, 0 males). Because females were compared across three loca-

tions, we used Tukey’s HSD test to determine which specific sites differed from others in pairwise comparisons. Storer’s (1966) dimorphism index (DI) was used to calculate relative sexual size dimorphism for both WI and PA/MD populations:

$$DI = \frac{(\text{parameter of female} - \text{parameter of male})}{0.5 \times (\text{parameter of female} + \text{parameter of male})} \times 100$$

Similar to Earhart and Johnson (1970), we substituted the cube roots of body mass means in the equation. Statistical significance of differences in DI were evaluated using a Kruskal-Wallis test. Because the ON population included members of only one sex, the ON sample was not included in our assessment of dimorphism, nor is it included in the analysis of sex determination below.

To determine whether this species could be sexed using body measurements, we performed separate linear discriminant analyses (LDA) for the WI population and the PA/MD population. Instead of relying on an automated stepwise procedure to

Table 1. Morphometrics (average $\pm$ standard deviation) of male ($n=38$) and female ($n=67$) adult Broad-winged Hawks captured in Wisconsin, Pennsylvania, and Maryland, USA, from 1974–2020. Comparisons between sexes are based on post hoc ANOVA. Ranges for each variable measured are in parentheses.

CHARACTER	MORPHOMETRICS			
	MALE	FEMALE	$F_{1, 103}$	P
	MEAN $\pm$ SD (RANGE)	MEAN $\pm$ SD (RANGE)		
Body mass (g)	343.1 $\pm$ 19.0 (303–382)	444.3 $\pm$ 42.7 (341–559)	191.7	<0.001
Wing chord (mm)	269.9 $\pm$ 4.9 (260–278)	282.8 $\pm$ 6.5 (265–294)	112.6	<0.001
Tail length (mm)	153.7 $\pm$ 6.7 (135–169)	161.3 $\pm$ 4.8 (150–170)	45.8	<0.001

select appropriate variables for LDAs, we performed one for all individual variables and every possible combination of variables for both samples (Dechaume-Moncharmont et al. 2011). Accuracy of functions was assessed through a jackknife (leave-one-out) cross-validation procedure and the calculation of Cohen’s Kappa statistic, which represents the chance-corrected percentage of agreement between actual and predicted group memberships (Titus and Mosher 1984). Prior to conducting LDAs, we ran Box’s M test for homogeneity of variance-covariance matrices (Box 1949) to test M’s significance for the two regions and the regions combined (i.e., WI + PA/MD). Box’s M test is sensitive to non-normality: a significant value (<0.001) indicates either unequal covariance matrices, non-normality, or both (Tabachnick and Fidell 2007). WI data did not meet the requirements of Box’s M test ($\chi^2 = 30.35$, $df = 6$, $P < 0.001$); therefore, data were log-transformed and a second Box’s M test was conducted to reach an insignificant Box’s M test ($\chi^2 = 21.02$, $df = 6$, $P = 0.002$). PA/MD data met the criterion of Box’s M test ($\chi^2 = 12.84$, $df = 6$, $P = 0.05$) so we did not log-transform these data before proceeding with the LDA. For the combined region, the Box’s M test was significant ($\chi^2 = 26.30$, $df = 6$, $P < 0.001$); however, after we log-transformed these data, the Box’s M test was still significant ($P <$

0.001). Therefore the requirements of homogeneity of variance-covariance matrices were not met and LDA could not be performed for the combined region of WI + PA/MD. All statistical analyses were performed in R software (3.5.2).

RESULTS

We found a significant difference in morphometrics between male ($n = 38$) and female ($n = 67$) Broad-winged Hawks captured in WI and PA/MD ($F_{1, 103} = 126.10$, Pillai = 1.58, $P < 0.001$), with females having significantly greater body mass, and longer wing chord, and tail length compared to males (Table 1). Size dimorphism indices for the two geographic populations were similar for body mass and wing chord (Table 2). However, tail length indices were lower for PA/MD than for WI Broad-winged Hawks (Table 2). Despite the variation in tail length indices, mean dimorphism indices did not vary significantly between WI and PA/MD populations ($\chi^2 = 1.19$, $df = 1$, $P = 0.28$).

For our geographic variation analysis, we found WI hawks of both sexes were significantly larger than those in PA/MD in body mass and wing chord but not tail length (Table 3). In addition, ON females were larger than PA/MD females across all three characters, and compared to WI females, had larger

Table 2. Sexual size dimorphism indices of breeding Broad-winged Hawks captured in Wisconsin, Pennsylvania/Maryland, USA, and all three states combined from 1974–2020.

CHARACTER	SEXUAL SIZE DIMORPHISM INDEX		
	WISCONSIN	PENNSYLVANIA/MARYLAND	WISCONSIN + PENNSYLVANIA/MARYLAND
Body mass (g)	9.1	7.2	8.6
Wing chord (mm)	4.9	4.6	4.7
Tail length (mm)	5.8	−0.2	4.9
Mean index	6.6	3.9	6.1

Table 3. Morphometrics (average $\pm$ standard deviation) of male and female adult Broad-winged Hawks captured from three geographical regions (Wisconsin, Pennsylvania/Maryland, and Ontario) in USA and Canada from 1974–2020, and comparison among geographic regions based on ANOVA. Morphometric ranges are in parentheses. Superscripts (a, b, c) indicate variation among females of different populations; populations sharing the same letter do not differ.

SEX	CHARACTERS	MORPHOMETRIC MEASURES				F	P
		MEAN $\pm$ SD (RANGE)					
		WISCONSIN <i>n</i> = 33♂, 54♀	PENNSYLVANIA/MARYLAND <i>n</i> = 5♂, 13♀	ONTARIO <i>n</i> = 14♀			
Males	Body mass (g)	346.0 $\pm$ 18.3 (303–382)	324.4 $\pm$ 11.7 (310–336)	-	6.4	0.02	
	Wing chord (mm)	270.7 $\pm$ 4.6 (260–278)	264.6 $\pm$ 2.9 (260–267)	-	8.1	0.007	
	Tail length (mm)	152.9 $\pm$ 6.3 (135–162)	159.0 $\pm$ 7.3 (150–169)	-	4.0	0.05	
Females	Body mass (g)	454.3 $\pm$ 36.6 (375–559) ^a	403.0 $\pm$ 42.5 (341–475) ^b	502.1 $\pm$ 53.0 (382–587) ^c	20.0	<0.001	
	Wing chord (mm)	284.2 $\pm$ 5.9 (269–294) ^a	276.9 $\pm$ 5.9 (265–286) ^b	287.9 $\pm$ 6.8 (275–302) ^a	11.8	<0.001	
	Tail length (mm)	162.0 $\pm$ 4.4 (150–170) ^a	158.6 $\pm$ 5.9 (150–169) ^a	168.2 $\pm$ 5.5 (161–180) ^b	14.3	<0.001	

body mass and tail length but did not differ significantly in wing chord (Table 3).

LDAs for each individual trait showed that body mass (D1) was the best predictor of sex in WI hawks, and wing chord (D9) was most effective for the PA/MD population (Table 4). Tail length was the least effective predictor for both populations when considered alone. For WI birds, LDAs combining body mass with the other two traits were effective but none outperformed the discriminant equation using body mass alone: $D1 = 14.23 * \log(\text{mass}) - 85.54$. This equation correctly classified 99% of individuals after jackknife cross-validation (Table 4). Positive discriminant scores (D) indicated females and negative discriminant scores indicated males, with overlap occurring between -0.5 and -1.5 (Supplemental Material Fig. S1). The best equation for predicting sex in PA/MD hawks combined all three traits. The equation: $D8 = -0.02 * \text{mass} - 0.16 * \text{wing chord} + 0.12 * \text{tail length} + 33.27$, correctly classified 100% of individuals (Table 4). Negative values of D indicated females and positive values of D indicated males, with no overlap (Fig. S1).

DISCUSSION

Broad-winged Hawks breeding in WI, PA/MD, and ON exhibited variations in morphometric characteristics between sexes and among regions. Despite a 24% overlap in body mass, 47% overlap in wing chord, and 91% overlap in tail length between male and female Broad-winged Hawks, discriminant function analyses allowed us to successfully determine sex of 99% of adults in two parts of their breeding range (WI and PA/MD). Like most raptors, Broad-winged Hawks exhibit reverse sexual size dimorphism (i.e., females larger than males). The degree of dimorphism is moderate and similar to other North American congeners (e.g., Red-tailed Hawks, Red-shouldered Hawks, Swainson’s Hawks, Ferruginous Hawks (*Buteo regalis*), and Rough-legged Hawks (*Buteo lagopus*; Snyder and Wiley 1976), but far less pronounced than that of some other forest raptors such as members of the genus *Accipiter* (Snyder and Wiley 1976, Rosenfield et al. 2010). Of the three body characters measured, body mass was the most dimorphic in Broad-winged Hawks. Although our mean dimorphism index was comparable to that calculated by Snyder and Wiley (1976), we found body mass to be the most dimorphic trait in Broad-winged Hawks, as opposed to wing chord. This could be the result of regional, seasonal, or age-based variation (e.g., adult versus

Table 4. Accuracy of sexing Wisconsin and Pennsylvania/Maryland populations of adult Broad-winged Hawks using linear discriminant analysis of various combinations of morphologic measurements. Correct classification shows the percent of each sex properly classified in a jackknife cross validation. Sample size for Wisconsin was 54 females and 33 males; sample size for Pennsylvania/Maryland was 13 females and 5 males. Note: Table 4 is extended to the next page.

POPULATION	VARIABLES	EQUATION
Wisconsin	Mass	D1 = 14.23*log(mass) - 85.54
	Mass + Tail	D2 = -12.97*log(mass) - 0.08*tail length + 91.19
	Mass + Wing	D3 = -11.76*log(mass) - 0.08*wing chord + 94.11
	Mass + Wing + Tail	D4 = -11.70*log(mass) - 0.06*wing chord - 0.05*tail length + 95.53
	Wing + Tail	D5 = -0.148*wing chord - 0.07*tail length + 51.88
	Wing	D6 = 0.18*wing chord - 51.11
	Tail	D7 = 0.19*tail length - 30.63
Pennsylvania/ Maryland	Mass + Wing + Tail	D8 = -0.02*mass - 0.16*wing chord + 0.12*tail length + 33.27
	Wing	D9 = 0.19*wing chord - 51.68
	Mass + Wing	D10 = -0.02*mass - 0.14*wing chord + 44.38
	Mass + Tail	D11 = -0.03*mass + 0.10*tail length - 3.32
	Wing + Tail	D12 = -0.20*wing chord + 0.07*tail length + 44.98
	Mass	D13 = 0.03*mass - 10.24
	Tail	D14 = 0.16*tail length - 25.27

immature) in dimorphism, as location, age class, and breeding status of the individuals were not specified by Snyder and Wiley (1976). Other studies reported range-wide data on wing chord and tail length of Broad-winged Hawks (Burns 1911, Friedmann 1950). For example, Friedmann (1950) reported smaller wing chord measurements ($\bar{x}$ =263 mm, n =17) for males and longer tail lengths ($\bar{x}$ =171 mm, n =17) for female Broad-winged Hawks; however, these individuals were museum specimens collected throughout their range. Given the earlier date at which these studies were conducted, it is possible that temporal variation may play a role in producing these differences, as raptor size can differ in response to variance in environmental pressures, habitat, etc. across years (Tornberg et al. 1999), or this difference could be caused by differing methods for measuring tail length.

We found significant morphometric differences across both latitude and longitude. Our southernmost study site, PA/MD, had smaller birds than the populations in WI and ON, four degrees of latitude to the north. These results support Bergmann's Rule, which predicts larger body size at higher latitudes, or in areas with lower annual temperatures. Birds in WI and ON, sites that share a similar latitude but are approximately 700 km apart, also differed in body mass and size, though sample size for ON was small. Morphometric data

for Broad-winged Hawks captured in the central Adirondacks region, New York (Mosher and Matray 1974), indicated that these birds were heavier than the birds we measured in Wisconsin, but wing chords were similar. Geographically, the central Adirondacks region represents an intermediate point between WI and ON and PA/MD, but Mosher and Matray's (1974) data does not support the pattern of a northward size cline. For the five Broad-winged Hawk subspecies endemic to the Caribbean (i.e., *B. p. cubanensis*, *B. p. brunnescent*, *B. p. insicola*, *B. p. rivierei*, *B. p. antillarum*; Friedmann 1950, Blake 1977), average wing chord measurements were smaller than those of birds in our study. Geographic size variation has been documented in other *Buteo* species including Red-shouldered and Red-tailed Hawks. Although Red-shouldered Hawks exhibit a positive correlation between size and latitude (James 1970), Red-tailed Hawks appear to contradict this pattern, with the largest individuals occurring in desert regions of the Southwest and the smallest in the Pacific Northwest (Fitzpatrick and Dunk 1999). Additionally, Red-tailed Hawks vary in body size between eastern and western regions of their North American range, with individuals captured during migration at Cape May Point, New Jersey, USA, being heavier and having shorter wings and tails compared to individuals captured along the

Table 4. Extended. Note: Table 4 has been extended from the previous page.

WILK'S LAMBDA	CORRECT CLASSIFICATION			COHEN'S KAPPA	95% CI	P
	FEMALES (%)	MALES (%)	OVERALL(%)			
0.22	98.2	100	98.9	0.98	0.96–0.99	<0.001
0.19	98.2	100	98.9	0.98	0.96–0.99	<0.001
0.18	96.3	100	97.7	0.95	0.94–0.97	<0.001
0.17	96.3	100	97.7	0.95	0.94–0.97	<0.001
0.38	92.6	93.9	93.1	0.86	0.83–0.88	<0.001
0.40	88.9	97	92	0.84	0.81–0.87	<0.001
0.57	90.7	57.6	78.2	0.45	0.42–0.49	<0.001
0.23	100	100	100	1.00	1.00–1.00	<0.001
0.45	92.3	100	94.4	0.88	0.83–0.92	<0.001
0.32	92.3	100	94.4	0.88	0.83–0.92	<0.001
0.42	100	80	94.4	0.84	0.80–0.88	0.0015
0.41	92.3	100	94.4	0.88	0.83–0.92	0.0012
0.50	84.6	100	88.9	0.77	0.70–0.84	0.001
-	100	0	72.2			

Goshute Mountains of Nevada and the Manzano Mountains of New Mexico, USA (Pearlstine and Thompson 2004, Bonerbo and Goodrich 2020). It has been suggested that these size patterns may be linked more closely with prey size and the need to conserve water in dry environments rather than the more traditional association with thermoregulatory potential (James 1970, Fitzpatrick and Dunk 1999).

The best models for sex determination in adult Broad-winged Hawk varied by region. We suggest D₁ (mass) is the most useful function for predicting sex of WI breeding Broad-winged Hawks, based on its accuracy (99%) and simplicity. In the PA/MD region, D₈ (mass + wing + tail) was the most successful function for predicting sex. Because our sample of PA/MD birds was limited (only 13 females and 5 males), we consider these data preliminary and suggest that care should be taken when D₈ yields discriminant scores close to 0 until more data are available to revise the analysis. Small sample sizes ($n < 60$) and skewed sex ratios increase the likelihood that individuals will be sexed correctly by chance alone (Dechaume-Moncharmont et al. 2011). This function would likely see improved functionality with a larger sample size and near-equal numbers of each sex. Sexing methods reported here should only be applied to adults on their breeding grounds during the

nesting season, as body mass can vary seasonally and immature *Buteos* including Broad-winged Hawks (Johnson et al. 2020) have different body measurements than adults.

Because sex-based and geography-based differences in morphology and ecology occur in many birds including raptors (e.g., Ashton 2002, Rosenfield et al. 2010, Buehler 2020), it is important to develop sound methods of sex determination for monomorphic species. Although molecular techniques have great accuracy, they are more invasive if blood samples are required and cost (including equipment and lab analyses) may preclude their use. Importantly, the results of the assay are not immediately available to the field researcher, whereas the results of a discriminant function using morphometrics would be. The ability to efficiently determine sex in the field will help facilitate a deeper understanding of population dynamics, help identify population structure, evaluate differences in habitat use or behavior, and give insights into local selective pressures on morphology (Ardia and Bildstein 2001, Catry et al. 2005, Newton 2008, Rosenfield et al. 2010). Such information could enhance conservation and management strategies locally or regionally.

In this study, we have shown that linear discriminant analysis using body mass, wing chord, and tail length is an effective tool for sexing Broad-winged

Hawks in two regions of their breeding range. However, morphological data from additional locations of the breeding range, particularly PA/MD and southern latitudes as well as the western states and provinces, is still needed. We encourage banders and researchers to take a wide range of body measurements in addition to body mass, wing chord, and tail length, including bill length, tarsus length and width, and tail band width, all of which may be useful for assigning sex to raptors (Dykstra et al. 2012, Horita et al. 2020, Rosenfield et al. 2021). Although body mass alone is a good indicator of sex for many raptors, the mass of adult raptors can vary through the nesting season (Newton et al. 1983, Korpimäki 1990, Valentine-Darby et al. 1997) and throughout the year. Thus, linear measurements based on skeletal features may offer more temporal/seasonal stability (see Rosenfield and Bielefeldt 1999).

Morphometric measurements combined with discriminant function analysis can be useful for determining sex of breeding adult Broad-winged Hawks. Because raptors can show different habitat use, range, migration patterns between sexes (Smallwood 1988, Newton 2008, Goodrich et al. 2012), and as such can be subject to different conservation pressures, we encourage researchers to collect and report body measurements whenever possible.

SUPPLEMENTAL MATERIAL (available online). Figure S1: Discriminant scores calculated for adult Broad-winged Hawks in Wisconsin using body mass as the predictor variable and Pennsylvania and Maryland using body mass, wing chord, and tail length as predictor variables.

ACKNOWLEDGMENTS

We thank the landowners and agencies who granted access to nest sites for trapping, including the Pennsylvania Department of Conservation and Natural Resources (PA DCNR) and the Pennsylvania Game Commission. We thank all the field assistants, Hawk Mountain trainees, and volunteers, particularly David Barber and Bracken Brown. All participating banders possessed current valid permits for trapping and processing authorizations from the United States Bird Banding Laboratory and the Canadian Bird Banding Office. Funding was provided by D. F. Brinker for research in Wisconsin and from the Pennsylvania Game Commission's State Wildlife Grants Program, The Kittatinny Coalition, the Wild Resource Conservation Fund of PA DCNR, East Stroudsburg University, ATAS Inc., D. and D. Allison, D. and P. McNicholas, H. Stebbins, D. and N. Edge, and Hawk Mountain members and donors for research in Pennsylvania. This is Hawk Mountain conservation science contribution number 370.

LITERATURE CITED

- Ardia, D. R., and K. L. Bildstein (2001). Sex-related differences in habitat use of wintering American Kestrels. *The Auk* 118:746–750.
- Ashton, K. G. (2002). Patterns of within-species body size variation of birds: Strong evidence for Bergmann's Rule. *Global Ecology and Biogeography* 11:505–523.
- Baldwin, S. P., H. C. Oberholser, and L. G. Worley (1931). Measurements of birds. Scientific Publications of the Cleveland Museum of Natural History, Vol II. Cleveland, OH, USA.
- Bird Studies Canada and North American Bird Conservation Initiative (2014). Bird Conservation Regions. Published by Bird Studies Canada on behalf of the North American Bird Conservation Initiative. <https://www.birdscanada.org/bird-science/nabci-bird-conservation-regions>.
- Blake, E. R. (1977). *Manual of Neotropical Birds*, Vol. 1. University of Chicago Press, Chicago, IL, USA.
- Bloom, P. H., W. S. Clark, and J. W. Kidd (2007). Capture techniques. In *Raptor Research and Management Techniques* (D. M. Bird and K. L. Bildstein, Editors), Hancock House, Blaine, WA, USA and Surrey, BC, Canada. pp. 193–219.
- Bloom, P. H., J. L. Henckel, E. H. Henckel, J. K. Schmutz, B. Woodbridge, J. R. Bryan, R. L. Anderson, P. J. Detrich, T. L. Maechtle, J. O. McKinley, M. D. McCrary, et al. (1992). The dho-gaza with Great Horned Owl lure: An analysis of its effectiveness in capturing raptors. *Journal of Raptor Research* 26:167–178.
- Bonerbo, Z., and L. J. Goodrich (2020). Linking hawk watch sites to breeding and wintering catchment areas of Red-tailed Hawks. *Hawk Migration Studies: Journal of the Hawk Migration Association of North America* 46(2):9–16.
- Box, G. E. P. (1949). A general distribution theory for a class of likelihood criteria. *Biometrika* 36:317–346.
- Buehler, D. A. (2020). Bald Eagle (*Haliaeetus leucocephalus*), version 1.0. In *Birds of the World* (A. F. Poole and F. B. Gill, Editors), Cornell Lab of Ornithology, Ithaca, NY, USA. <https://doi.org/10.2173/bow.baleag.01>.
- Burns, F. L. (1911). A monograph of the Broad-winged Hawk (*Buteo platypterus*). *Wilson Bulletin* 23:143–320.
- Catry, P., R. A. Phillips, and J. P. Croxall (2005). Sexual segregation in birds: Patterns, processes and implications for conservation. In *Sexual Segregation in Vertebrates: Ecology of the Two Sexes* (K. E. Ruckstuhl and P. Neuhaus, Editors), Cambridge University Press, Cambridge, UK. pp. 351–380.
- Dechaume-Moncharmont, F. X., K. Monceau, and F. Cezilly (2011). Sexing birds using discriminant function analysis: A critical appraisal. *The Auk* 128:78–86.
- Donohue, K. C., and A. M. Dufty, Jr. (2006). Sex determination of Red-tailed Hawks (*Buteo jamaicensis calurus*) using DNA analysis and morphometrics. *Journal of Field Ornithology* 77:74–79.

- Dykstra, C. R., H. L. Mays, J. L. Hays, M. M. Simon, and A. R. Wegman (2012). Sexing adult and nestling Red-shouldered Hawks using morphometrics and molecular techniques. *Journal of Raptor Research* 46:357–364.
- Earhart, C. M., and N. K. Johnson (1970). Size dimorphism and food habits of North American owls. *The Condor* 72:251–264.
- Ferguson-Lees, J., and D. A. Christie (2005). *Raptors of the World*. Princeton University Press, Princeton, NJ, USA.
- Fitzpatrick, B. M., and J. R. Dunk (1999). Ecogeographic variation in morphology of Red-tailed Hawks in western North America. *Journal of Raptor Research* 33:305–312.
- Friedmann, H. (1950). *Birds of North and Middle America, Part 1*. US National Museum Bulletin No. 50. Washington, DC, USA.
- Goodrich, L. J., S. T. Crocoll, and S. E. Senner (2020). Broad-winged Hawk (*Buteo platypterus*), version 1.0. In *Birds of the World* (A. F. Poole, Editor), Cornell Lab of Ornithology, Ithaca, NY, USA. <https://doi.org/10.2173/bow.brwhaw.01>.
- Goodrich, L. J., C. J. Farmer, D. R. Barber, and K. L. Bildstein (2012). What banding tells us about the movement ecology of raptors. *Journal of Raptor Research* 46:27–35.
- Horita, M., T. Imamori, H. Natsukawa, and J. Nonaka (2020). Use of tail feather traits to determine sex of adult Grey-Faced Buzzards (*Butastur indicus*). *Journal of Raptor Research* 54:311–315.
- Jacobs, E. A. (1996). A mechanical owl as a trapping lure for raptors. *Journal of Raptor Research* 30:31–32.
- James, F. C. (1970). Geographic size variation in birds and its relationship to climate. *Ecology* 51:365–390.
- Johnson, C. B., G. K. Lahr, T. J. Underwood, and L. J. Goodrich (2020). Forty-five years of fall banding at Little Gap Raptor Banding Station, Danielsville, PA: Summary of captures and morphological measurements of raptors. *North American Bird Bander* 45:1–16.
- Kerlinger, P. (1989). *Flight Strategies of Migrating Hawks*. University of Chicago Press, Chicago, IL, USA.
- Kochert, M. N., and J. O. McKinley (2008). Use of body mass, footpad length, and wing chord to determine sex in Swainson's Hawks. *Journal of Raptor Research* 42:138–141.
- Korpimäki, E. (1990). Body mass of breeding Tengmalm's Owls *Aegolius funereus*: Seasonal, between-year, site and age-related variation. *Ornis Scandinavica* 21:169–178.
- Krüger, O. (2005). The evolution of reversed sexual size dimorphism in hawks, falcons and owls: A comparative study. *Evolutionary Ecology* 19:467–486.
- McCabe, R. A., L. J. Goodrich, T. L. Master, and Z. Bordner (2019). Broad-winged Hawk nesting behavior in forested landscapes of Pennsylvania. *Journal of Raptor Research* 53:293–308.
- McCloskey, J. T., and S. R. Dewey (1999). Improving the success of a mounted Great Horned Owl lure for trapping Northern Goshawks. *Journal of Raptor Research* 33:168–169.
- Meiri, S., and T. Dayan (2003). On the validity of Bergmann's Rule. *Journal of Biogeography* 30:331–351.
- Millien, V., S. K. Lyons, L. Olson, F. A. Smith, A. B. Wilson, and Y. Yom-Tov (2006). Ecotypic variation in the context of global climate change: Revisiting the rules. *Ecology Letters* 9:853–869.
- Montalti, D., M. Graña Grilli, R. E. Maragliano, and G. Cassini (2012). The reliability of morphometric discriminant functions in determining the sex of Chilean Flamingos *Phoenicopterus chilensis*. *Current Zoology* 58:851–855.
- Mosher, J. A., and P. F. Matray (1974). Size dimorphism: A factor in energy savings for Broad-winged Hawks. *The Auk* 91:325–341.
- Newton, I. (2008). *The Migration Ecology of Birds*. Academic Press, London, UK.
- Newton, I., Marquiss, M., and A. Village (1983). Weights, breeding, and survival in European Sparrowhawks. *The Auk* 100:344–354.
- Pearlstone, E. V., and D. B. Thompson (2004). Geographic variation in morphology of four species of migratory raptors. *Journal of Raptor Research* 38:334–342.
- Phinney, M. (2015). Broad-winged Hawk. In *The Atlas of the Breeding Birds of British Columbia, 2008–2012* (P. J. A. Davidson, R. J. Cannings, A. R. Couturier, D. Lepage, and C. M. Di Corrado, Editors). Bird Studies Canada, Delta, BC, Canada. <http://www.birdatlas.bc.ca/accounts/speciesaccount.jsp?sp=BWHA&lang=en>.
- Pillai, K. C. S. (1955). Some new test criteria in multivariate analysis. *Annals of Mathematical Statistics* 26:117–121.
- Pitzer, S., J. Hull, H. B. Ernest, and A. C. Hull (2008). Sex determination of three raptor species using morphology and molecular techniques. *Journal of Field Ornithology* 79:71–79.
- Pyle, P. (1997). Identification guide to North American birds: A compendium of information on identifying, ageing, and sexing “near-passerines” and passerines in the hand. Slate Creek Press, Point Reyes Station, CA, USA.
- Pyle, P. (2008). Identification guide to North American birds, Part II. Slate Creek Press, Point Reyes Station, CA, USA.
- Rosenfield, R. N., and J. Bielefeldt (1999). Mass, reproductive biology, and non-random pairing in Cooper's Hawks. *The Auk* 116:830–835.
- Rosenfield, R. N., L. J. Rosenfield, J. Bielefeldt, R. K. Murphy, A. C. Stewart, W. E. Stout, T. G. Driscoll, and M. A. Bozek (2010). Comparative morphology of northern populations of breeding Cooper's Hawks. *The Condor* 112:347–355.
- Rosenfield, R. N., W. E. Stout, A. C. Stewart, T. G. Driscoll, S. A. Sonsthagen, and J. P. Seibel (2021). Are there Gloger tail bands in British Columbia Cooper's Hawks? *British Columbia Birds* 31:51–57.
- Rosenzweig, M. L. (1992). Species diversity gradients: We know more and less than we thought. *Journal of Mammalogy* 73:715–730.

- Smallwood, J. A. (1988). A mechanism of sexual segregation by habitat in American Kestrels (*Falco sparverius*) wintering in south-central Florida. *The Auk* 105:36–46.
- Smith, N. R., A. D. Afton, and T. J. Hess, Jr. (2016). Morphometric sex determination of after-hatch-year Bald Eagles in Louisiana. *Journal of Raptor Research* 50:301–304.
- Snyder, N. F. R., and J. W. Wiley (1976). Sexual size dimorphism in hawks and owls of North America. *Ornithological Monographs* 20:1–95.
- Sonsthagen, S. A., R. N. Rosenfield, J. Bielefeldt, R. K. Murphy, A. C. Stewart, W. E. Stout, T. G. Driscoll, M. A. Bozek, B. L. Sloss, and S. L. Talbot (2012). Genetic and morphological divergence among Cooper's Hawk (*Accipiter cooperii*) populations breeding in north-central and western North America. *The Auk* 129:427–437.
- Tabachnick, B. G., and L. S. Fidell (2007). *Using Multivariate Statistics*, Fifth Ed. Allyn and Bacon, New York, NY, USA.
- Terribile, L. C., M. Á. Olalla-Tárraga, J. A. F. Diniz-Filho, and M. Á. Rodríguez (2009). Ecological and evolutionary components of body size: Geographic variation of venomous snakes at the global scale. *Biological Journal of the Linnean Society* 98:94–109.
- Titus, K., J. A. Mosher, and B. K. Williams (1984). Chance-corrected classification for use in discriminant analysis: Ecological applications. *American Midland Naturalist* 111:1–7.
- Tomalty, K. M., A. C. Hull, A. M. Fish, C. W. Briggs, and J. M. Hull (2016). Differential migration and phenology of adult Red-tailed Hawks in California. *Journal of Raptor Research* 50:45–53.
- Tornberg, R., M. Mönkkönen, and M. Pahlkala (1999). Changes in diet and morphology of Finnish Goshawks from 1960s to 1990s. *Oecologia* 121:369–376.
- Valentine-Darby, P. L., R. E. Bennetts, and W. M. Kitchens (1997). Breeding season masses of Snail Kites in Florida. *Florida Field Naturalist* 25:60–63.
- Wyllie, I., and I. Newton (1994). Latitudinal variation in the body-size of Sparrowhawks *Accipiter nisus* within Britain. *Ibis* 136:434–440.

Received 5 July 2021; accepted 22 June 2022
Associate Editor: Petra Sumasgutner