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SEXUAL SIZE DIMORPHISM AND AGE-RELATED SIZE VARIATION IN BALD EAGLES

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Abstract: Patterns of size variation between sex and among plumage classes of bald eagles (*Haliaeetus leucocephalus*) were examined by measuring 10 variables on museum study skins. Using multivariate statistical techniques, a field method was devised to correctly identify the sex of 98.1% of bald eagles examined. Plumage maturation in this species and the problems associated with previous descriptions of plumage succession are discussed.

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Sexual size dimorphism has been a frequent topic of discussion in the literature on raptorial birds (Newton 1979). Although of practical value, criteria for sex discrimination have not been quantified for many species of birds of prey. Similarly, although raptors usually have distinct immature and adult plumages, morphological correlates of plumage type and their possible adaptive value have only recently been quantitatively examined (e.g., Mueller et al. 1981). The objectives of this paper are to present criteria for sex discrimination on the basis of size, to quantify age-related size variation, and to discuss plumage maturation of the bald eagle.

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METHODS

Museum study skins of 135 bald eagles were measured. Only *H. l. alascanus* from Canada, Alaska, and the northern United States were included in the analyses, to reduce the effect of latitudinal variation in size. Only winter specimens from eastern Canada and the northeastern United States were considered because there are historic (Broley 1947) and recent records of immature southern bald eagles (*H. l. leucocephalus*) occurring as far north as Ontario, Quebec, and the Maritime Provinces in summer. Skins lacking information on either place or date of collection were not measured.

Some specimens had damaged or missing parts. To ensure a large sample for the multivariate analyses, estimates of missing data were calculated for each variable by regressing the variable of interest on all other variables. Only specimens with 1 or rarely 2 of the 10 variables missing were included. Estimates comprised 3% of the total number of measurements. Only the

original data (no estimates) were used in univariate tests and calculation of means and standard deviations (SD).

Data were obtained on four captive eagles of known age and sex (by laparoscopy), measured over 2 years. These birds hatched in northwestern Ontario, but were raised together in southern Ontario (near Milton) from approximately fledging age. Tail lengths were the only available feather measurements for these birds.

Length of exposed culmen without cere (ClLn), bill depth at the leading edge of the cere (BDp), and length of hallux claw (HalCl) were measured with dial calipers (Fig. 1). These measurements should be equally applicable to both museum specimens and living birds. Other characters measured with calipers, such as width of the bill at the point where feathers and cere meet at the top of the head (BWd), length of the bill from gape (Gape) (Fig. 1), and tarsus width, may be less widely applicable. Tarsus width was approximated by taking the mean (MTrW) of two orthogonal measures of the diameter of the tarsus taken at the narrowest point just above the phalanges. In 25–30% of the specimens, tendons had been cut and/or removed from the tarsi. However, this appeared to have a minor (if any) influence on MTrW and was independent of the age and sex of the bird.

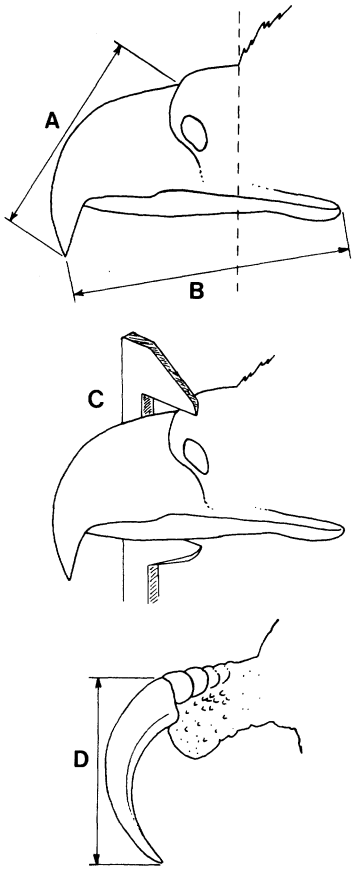

Fig. 1. Diagrams of (A) length of exposed culmen without cere, (B) length of culmen from gape, (C) bill depth (calipers must be held flush against the entire underside of bill), and (D) length of hallux claw. Dashed line represents plane where bill width was measured.

Unflattened wing chord (WnCh) (chord of arc) was measured with a tape measure. Tail length (Tail) was measured by inserting a thin metal ruler between the central rectrices to the point of their insertion. Similarly, the ruler was inserted between the eighth and ninth primaries, and between the first primary and first secondary, for eighth primary (EPr) and first secondary (FSec) lengths, respectively. WnCh and perhaps Tail are likely applicable to a field study, but EPr and FSec appear to be too strongly influenced by the drying of study skins to be comparable to these measures on live birds.

Bill depth was frequently unmeasurable because of poor specimen preparation (mouth open). Because the multivariate tests used estimates in place of missing data, BDp was excluded from all multivariate analyses to minimize the use of estimated values.

Based on examination of variability shown by birds in museum collections as

well as on extensive observations of wild birds of known age (including the same color-marked individuals studied by Gerrard et al. 1978), four plumage classes were delineated. They are not intended to represent unequivocal age-classes, although they are closely associated with age. These plumage classes are:

Young Immature (*YI*).—Eagles in their first-year juvenal plumage, as well as second-year birds, predominantly dark brown with varying amounts of lighter brown over most of the body. The underwing coverts are heavily mottled with white. The tail is generally dark brown mottled with white.

Old Immature (*OI*).—Individuals with a predominantly whitish head (mixed with specks of brown) usually with a dark brown streak through the eye. The body is mottled brown and white, and the tail, although variable, is generally whiter than that of younger immatures.

Subadult (*SA*).—Birds with the head usually dull white with a small amount of beige or light brown, particularly around the eye and on the crown. This brown is often largely confined to the rachi of the feathers. The tail is white except for a few small dark spots. The body feathers are brown like those of adults, except some are white at the base.

Adult (*AD*).—Birds with bright white heads and tails and dark brown bodies. Some birds retain one or two small dark brown spots in the tail and a few beige rachi in their head feathers for several years.

Because bald eagles are sexually monomorphic in plumage and apparently not exclusively sexually dimorphic in size, the only reliable information regarding sex is reference to gonads. Because too few (only 5.8%) of the skins had such data, the sex of specimens was determined by statistical analysis of morphology.

RESULTS

Sex Classification

A principal component analysis (PCA) was conducted for each plumage class ($N = 35$ AD, $N = 27$ SA, $N = 25$ OI, $N = 48$ YI). In all four analyses, the first three principal components explained between 81.2 and 90.8% of the variance, with the first component (PC 1) accounting for 56.9–77.3%. In each of the analyses, all variables were highly positively correlated with PC 1, suggesting that PC 1 was size-related; i.e., the major source of common variation in the data set is size and associated allometric shape change (Pimentel 1979).

Component scores for individuals in each plumage class were plotted along their respective PC 1 axes. Adult males and females (sex as on labels) were completely segregated along PC 1 (i.e., no overlap between the sexes). Subadults also separated into two groups presumably based on sex, although each group contained one individual whose sex identification on the label did not agree with its position in the distribution (Fig. 2). These two possibly misclassified birds, as well as those specimens completely lacking data on sex, were entered into a discriminant function analysis (DFA) as "unknowns," to be classified by comparison with the remaining birds, all of "known" sex. Unclassified adults were treated in the same manner in a separate analysis. For both age-groups, a significant discriminant function was obtained (AD: $P < 0.001$; SA: $P < 0.001$) that described the differences between sexes. The adequacy of the functions was checked using the classification phase of the DFA program (Nie et al.

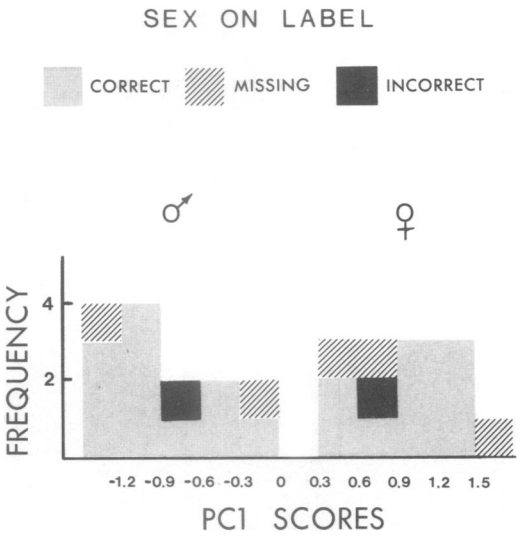

Fig. 2. Distribution of principal component scores for SA male and female bald eagles. Assessment of sex was made by discriminant analysis and compared to sex on labels.

1970); in both cases, 100% of the individuals of "known" sex was correctly identified. Therefore, sex of a specimen was considered to be incorrectly classified if the sex on the label did not agree with that assigned to it by DFA (Fig. 2, two errors for SA).

The data for both the YI and OI plumage classes were ordinated into two groups by PCA (similar to the result for the AD and SA classes). However, the sex information on the labels failed to clearly identify these groups as male and female, i.e., "males" and "females" were widely dispersed over the entire range of scores. This may indicate that OI and YI classes exhibit much less sexual dimorphism or, more plausibly, that sex of younger birds is commonly misclassified. In addition, the frequency of unclassified specimens varied inversely with age, perhaps because of the difficulty of identifying undeveloped gonads. Therefore, the data from YI and OI specimens could not be used to calculate functions for discriminating between

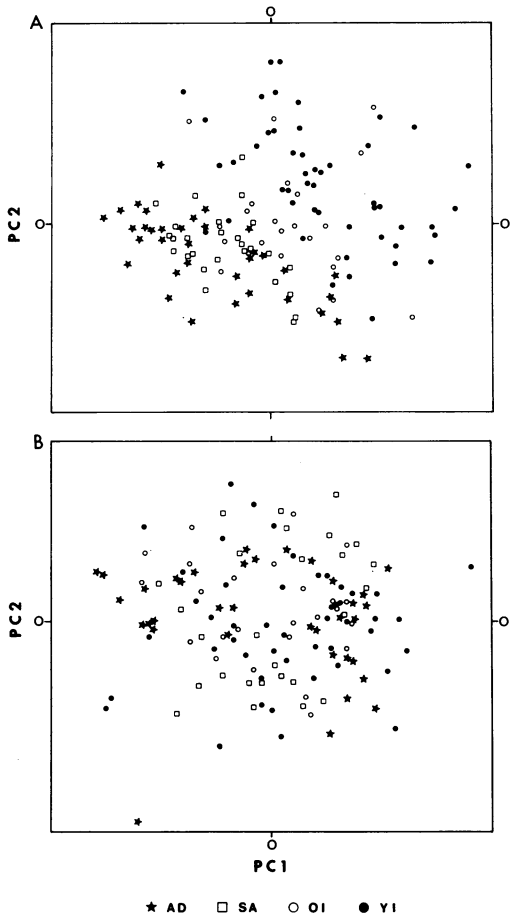

Fig. 3. Distribution of the PC 1 and PC 2 scores for bald eagles of all plumage classes in a PCA using (A) feather variables and (B) non-feather variables.

the sexes of immature birds as was done for the AD and SA classes. An alternative method of ascertaining the sex of OI and YI birds using data from eagles of the older age-classes was therefore used.

Although some flight feathers are known to vary in size with age (Imler and Kalmbach 1955), some body parts may not, and thus can be used for sex discrimination of eagles irrespective of age. Immature bald eagles are reported to be as large as adults with respect to skeletal dimensions (Amadon 1980, no data presented) and have the

Table 1. Sex and plumage class variation in size of bald eagles. All measurements are in mm.

Variable	Plumage class	Males				Females			
		N	$\bar{x}$	SD	Range	*N*	$\bar{x}$	SD	Range
WnCh	AD	21	569.9	12.89	541–589	14	629.3	6.87	592–664
	SA	14	581.3	12.60	565–600	12	610.2	16.34	585–639
	OI	13	602.3	13.70	579–623	11	631.5	23.88	600–680
	YI	29	608.5	19.97	555–651	19	651.4	17.90	620–683
EPr	AD	21	407.3	15.18	374–437	13	452.1	16.18	430–472
	SA	14	414.9	9.14	397–433	11	434.4	11.24	414–449
	OI	13	426.4	13.36	405–454	10	454.9	16.25	436–486
	YI	29	441.2	19.54	406–478	19	472.3	12.94	450–493
Tail	AD	20	254.7	10.67	236–274	14	288.6	16.07	247–308
	SA	14	262.6	7.99	254–278	12	284.2	4.97	279–295
	OI	10	284.4	11.30	267–308	10	312.6	19.00	291–350
	YI	28	313.2	18.47	266–351	17	328.9	22.19	300–372
FSec	AD	18	325.9	13.48	307–356	14	369.3	15.00	342–394
	SA	13	337.3	8.80	321–351	13	362.5	12.96	338–386
	OI	13	359.8	20.58	313–390	11	384.2	13.46	353–399
	YI	29	368.2	18.60	316–398	15	402.1	18.97	361–430
ClLn	AD	21	50.8	1.42	47.8–53.3	14	57.2	1.41	53.8–59.9
	SA	14	50.9	1.53	48.3–52.9	12	54.4	2.98	51.2–60.6
	OI	14	51.7	1.63	48.4–54.3	11	55.2	1.89	53.0–58.8
	YI	27	50.3	2.75	41.7–53.6	18	54.3	2.32	50.4–58.7
BDp	AD	18	32.2	1.07	29.6–34.6	12	36.9	1.63	34.5–39.2
	SA	10	32.1	0.50	31.3–32.7	10	35.9	1.27	33.8–37.8
	OI	12	32.4	1.11	30.9–34.3	8	34.9	1.46	32.6–37.5
	YI	23	32.2	1.27	29.6–34.2	15	35.8	2.08	33.0–41.2
BWd	AD	20	29.5	2.68	24.7–34.9	14	33.3	1.67	30.5–35.9
	SA	14	30.7	1.75	28.4–33.9	11	31.8	1.85	28.2–34.8
	OI	14	29.8	2.03	25.5–32.7	11	33.6	2.09	29.7–36.9
	YI	29	29.9	1.89	26.6–34.4	18	32.2	2.38	28.2–38.1
Gape	AD	21	72.6	3.28	67.2–79.3	13	79.7	2.90	74.1–83.8
	SA	13	72.1	2.49	68.5–76.8	13	76.8	2.88	72.6–81.9
	OI	14	73.1	1.28	71.5–75.1	11	76.4	3.19	70.8–80.8
	YI	27	72.5	2.43	67.4–77.3	17	77.0	3.77	69.9–81.7
MTrW	AD	21	14.4	0.77	12.8–15.9	14	16.6	1.21	15.4–20.3
	SA	13	14.3	1.24	12.9–16.4	13	16.1	0.84	14.9–18.1
	OI	14	14.3	0.70	13.4–15.5	11	15.9	0.78	14.1–17.1
	YI	29	14.5	0.92	13.1–16.2	19	16.6	1.08	14.8–18.9
HalCl	AD	20	39.8	1.42	37.7–41.8	13	45.7	1.93	41.2–48.6
	SA	14	39.8	1.44	38.0–43.0	12	43.9	1.78	41.3–47.8
	OI	14	40.4	1.33	38.0–42.7	11	45.0	1.42	42.6–47.7
	YI	29	39.1	2.07	32.7–42.6	19	44.2	1.93	41.4–48.9

same average bill length (Imler and Kalmbach 1955). To investigate this further, we conducted two separate PCA's using only feather variables (WnCh, EPr, Tail, FSec) and non-feather variables (ClLn, BWd, Gape, HalCl, MTrW). The results (Fig. 3) showed a strong age-dependent ordination of individuals with respect to feather lengths, but a random arrangement with non-feather variables. Furthermore, no growth occurred in non-feather variables for the four captive eagles. These results confirm that data for the non-feather variables of AD and SA could be used to discriminate between the sexes of the OI and YI birds.

A DFA using non-feather variables was first conducted for each sex separately to confirm size uniformity between AD and SA. Because no significant function resulted, individuals in these two classes were combined and entered into a DFA as "known"-sex birds. Eagles of OI and YI age were included in the analysis as "unknowns," to be classified with respect to sex. The sex assigned to each immature by the resulting significant discriminant function ($P < 0.001$) was considered to be correct. Reducing the number of variables from nine to five decreased the accuracy of classification from 100% to 96.8% (two errors). It is therefore possible that the sex of a few of the YI and OI birds is incorrect. However, when the OI and YI classes were subsequently analyzed in separate DFA's using a posteriori knowledge of the "correct" sex (but using all nine variables), significant functions were produced (OI: $P < 0.001$, 100% correctly classified; YI: $P < 0.001$, 97.9% correctly classified, one error). These results verified the power of the original model and suggested that the sexes were quite distinct.

The morphological data varied for each sex and plumage class (Table 1). In each plumage class, males and females were significantly different from each other in all dimensions (37 t tests, $P < 0.001$; 2 t tests, $P < 0.01$), with the exception of BWd in the SA group ($P > 0.05$). After correction for misclassified and unclassified specimens, the sex ratios for all plumage classes did not deviate significantly from 1:1 ($P > 0.05$), although the original uncorrected sex ratio for the YI did (1:2.44, $\chi^2 = 4.64$, $P < 0.05$). Sex of OI and YI eagles was often incorrectly classified (28.0 and 29.2%, respectively), whereas AD and SA birds were rarely misclassified (0 and 7.4%, respectively). Also, the younger birds most frequently lacked sex data on the label: AD 8.6%, SA 18.5%, OI 12.0%, and YI 35.4%.

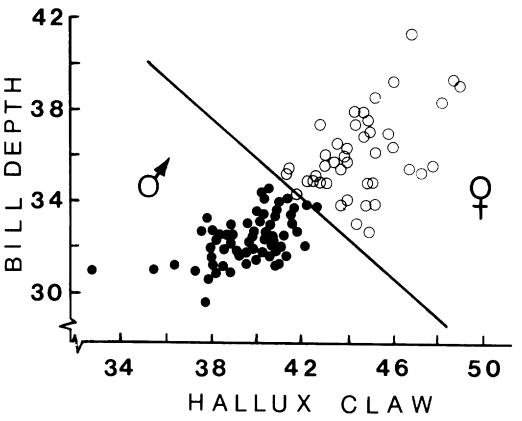

Fig. 4. Relationship between bill depth and length of hallux claw (mm) for all ages of bald eagles. The line illustrates the plane which separates males from females.

Field Criteria for Sex Discrimination

A predictive model for discriminating between sexes using BDp and HalCl was developed for use in the field. These two variables were highly dimorphic, had good agreement between museum specimens and live birds, and could be easily measured by other researchers. They were therefore used in a DFA of all specimens with complete data (no estimates or missing values). The resulting significant function ($P < 0.001$) correctly classified 98.1% of the birds (two errors) using the formula (BDp × 0.392) + (HalCl × 0.340) − 27.694, where positive values indicate females and negative values males (Fig. 4). Adding ClLn to the DFA reduced the number of classification errors by one, but a third dimension introduced unnecessary complexity into the analysis.

Data from the four captive birds, one wild AD of each sex from Saskatchewan, and an AD female from Ontario (sex of adults was ascertained at necropsy or laparoscopy) were used as a test of the ac-

Table 2. Tail lengths (mm) of known-age captive bald eagles and those of study skins of presumed similar age.

	Age			
	Second winter	Third winter	Fourth winter	Fifth winter
Captives				
Female	320	304		
Female		307	282	
Study skins[a]				
Females				
Mean	328.9	312.6	284.2	288.6
Range	300–372	291–350	279–295	247–308
Males				
Mean	313.2	284.4	262.6	254.7
Range	266–351	267–308	254–278	236–274
Captives				
Male		274	273	
Male			281	260

[a] Sample sizes as shown in Table 1.

curacy of the formula. Sexes of all were classified correctly.

Plumage Class Variation in Feather Lengths

There was a progressive decrease in feather length with increasing age (i.e., among plumage classes) (Table 1). Most *t*-test comparisons among plumage classes for each sex showed significant differences (P usually <0.001). The few exceptions that exist for males were consistent with the general pattern; the WnCh and FSec of YI vs. OI and the EPr of AD vs. SA were not different ($P > 0.05$). The situation was less clear for females, however, as 7 of 24 tests yielded nonsignificant differences (AD vs. SA for all variables, AD vs. OI for WnCh and EPr, OI vs. YI for Tail). This imperfect pattern of a decrease in length with age for females may be the result of small sample sizes coupled with random sampling error biased toward large adult females.

The supposed bias in the adult female group was substantiated by an examination of the size of non-feather variables. For males, only 1 of 36 *t* tests of interclass comparisons for each of ClLn, BWd, BDp, Gape, HalCl, and MTrW revealed a significant difference between plumage classes (YI vs. OI for HalCl, $P = 0.03$). Adult females, however, had longer ClLn than all other females, larger BDp than OI, and longer HalCl than both SA and YI (all $P < 0.05$). Among nonadult females alone, there was an interclass size difference (between SA and OI, $P < 0.05$) only in Gape. Adult females were 3.8% larger in the size of their non-feather parts than were SA (mean of the percent difference for each variable), but were only 2.6% larger in feather lengths. This suggests that AD females have proportionately shorter wings and tails than subadults, reflecting the same general pattern observed for males. The data on Tail for the four captive eagles were similar to those for study skins (Table 2).

DISCUSSION

Bald eagles are known to travel long distances from their natal areas (Postupalsky 1976, Gerrard et al. 1978), and birds on any one wintering ground may have come from several distant breeding areas

(Griffin et al. 1980). Therefore, the likelihood of a bias in my sample toward any one population is small. Analysis of a single breeding population, with restrictions on date of collection (to reduce variance due to molt and feather wear), would likely maximize the probability of identifying patterns of morphology attributable to age and sex. My less restricted sample may be of more practical use, especially in field studies in which the origin of the eagles is not known.

Sex Classification

Several factors may be responsible for the lack, or inaccuracy, of sex information on museum labels. Disregard for age-related size variation would bias sex estimation of bald eagles in favor of females. Friedmann (1950) presented only measurements of adults, and Brown and Amadon (1968) used these data without mention of age. Bent (1937) combined birds of all ages when calculating average sizes for the sexes. Comparison of specimens to standard references such as these may account for the prevalence of misclassified OI and YI males in this sample, because their wing and tail measurements overlap in size with older females. Museum skins of males were unclassified more often than females, perhaps because ovaries of eagles are more conspicuous than testes. In addition to accounting for age-related size variation, the statistical methods of sex classification presented here potentially reduce two sources of bias common to similar studies: the use of birds for which sex is subjectively classified (Mueller et al. 1976, Helander 1981) and the elimination of individuals of questionable or unknown sex (Storer 1966, Helander 1981). These two practices may bias results by the a priori creation of (perhaps artificially) distinct groups.

Both BDp and HalCl are not fully grown at fledging (Bortolotti, unpubl. data). Because it is not known when they reach mature size, sex criteria presented here should be applied with caution to birds that may only be a few months old.

Plumage Maturation

Most references to bald eagle plumage maturation describe a similar pattern of change with what is believed to be age: a gradual whitening of the head and tail and a change in body color from dark brown to mottled brown and white, to dark brown again in the adult (Bent 1937, Southern 1964, Sherrod et al. 1976, Gerrard et al. 1978). However, the number of age- and plumage classes, and their distinguishing criteria, have varied among studies. Only Gerrard et al. (1978) based their description on wild, known-age (color-marked) eagles. It would seem that most bald eagles attain adult plumage (i.e., Definitive, Palmer 1972) in their fifth year (4 years old). Use of the terms *x*-year-old and *x*th year interchangeably inevitably causes confusion, because they are not synonymous. Sherrod et al. (1976:146) referred to adult plumage as being attained in the bird's "5th" year, although it appears from their description of plumage succession that "5 years old" was intended. A bird in its fifth year is only 4 years old, but has its fifth dress of plumage. Wilson (1922) made a similar mistake, and Brown and Amadon (1968:22) erroneously reported Crandall's (1941) bird as having reached adulthood when in its fifth year (rather than 5 years old, sixth year).

Additional confusion over bald eagle plumages has resulted from Crandall's (1941) often-cited description of the plumage succession of a single captive eagle. This bird was likely not in adult plumage even when 5 years old. There are several possible explanations for this apparent delay in maturation. The most

plausible perhaps is that some conditions associated with captivity retard development. From his observations of golden eagles (*Aquila chrysaetos*), Jollie (1947) suggested that captive birds may take longer to attain adult plumage than wild birds. Other evidence supporting this possibility was summarized by Payne (1972).

The eagle described by Crandall (1941), although caged in New York, was originally from Georgia. Similarly, I have seen a slow-maturing individual that was raised in Maryland but had hatched in Florida. Such displacement from the natal site might result in an alteration of physiological processes associated with molt. Alternatively, southern bald eagles may take longer to mature than northern birds. Another eagle, taken and subsequently held in Michigan (Wilson 1922), appeared to follow the pattern of development proposed by Gerrard et al. (1978) for wild northern bald eagles.

Although Gerrard et al. (1978) documented variable plumage coloration for wild eagles of the same age, W. S. Clark (pers. commun.) recently recorded a striking example of plumage variation. He photographed two banded wild 4-year-old eagles along the mid-Atlantic coast, one of which had a white head and tail whereas the other had retained much brown speckling in these areas. Perhaps acquisition of adult plumage is partly dependent on individual condition; healthy birds may mature faster than those of poorer quality. The latter would be poor competitors for adult social position and might gain some advantage by retaining the appearance of younger birds. Retention of subadult characteristics could be achieved either by the acquisition of an extra year of immature-like feathers or by the interruption of normal molt (perhaps as a result of a nutritional deficiency, Payne 1972). Given what little is currently known about mechanisms of maturation, the use of plumage classes in describing the demography of populations (Southern 1964, Sherrod et al. 1976) is likely of limited value.

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