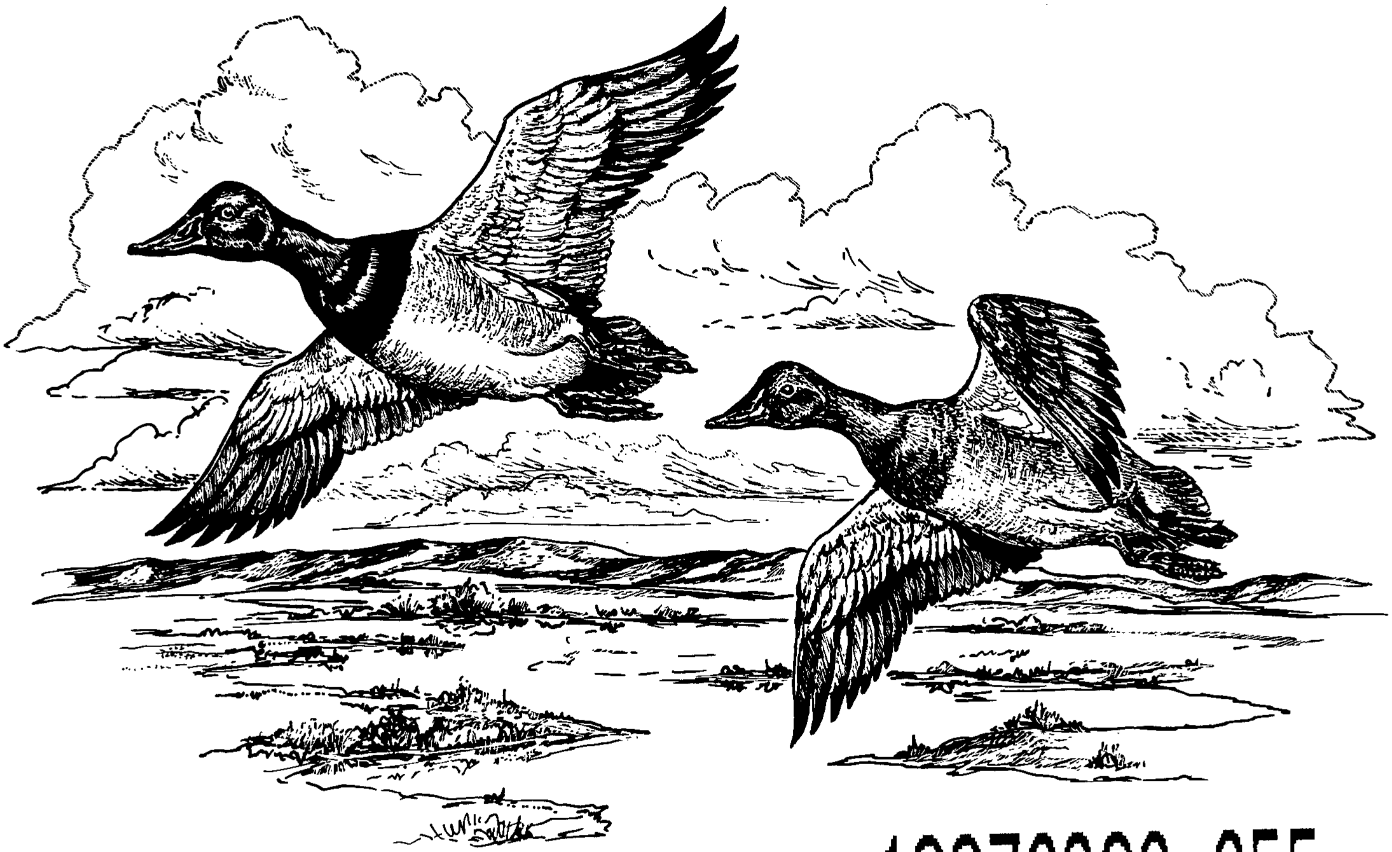
Biological Report 3
May 1992

An Evaluation of Regression Methods to Estimate Nutritional Condition of Canvasbacks and Other Water Birds



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An Evaluation of Regression Methods to Estimate Nutritional Condition of Canvasbacks and Other Water Birds

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Abstract. Regression equations that use mensural data to estimate body condition (i.e., the general health of a bird based on body reserves of fat or protein) have been developed for several water birds. These equations often have been based on data that represent different sexes, age classes, or seasons, without being adequately tested for intergroup differences. When compared to methods using total fat or moisture content, mensural equations frequently provide poor fits to measures of condition, or use body measurements that do not appreciably increase a model's precision. We used proximate carcass analysis of 538 adult and juvenile canvasbacks (*Aythya valisineria*) collected during fall migration, winter, and spring migrations in 1975–76 and 1982–85 to test regression methods for estimating body condition. We weighed, measured, and analyzed each canvasback for body fat, protein, and ash. Analyses of covariance provided estimates of total extractable fat ($R^2 = 0.71$), a condition index (total fat divided by fat-free dry mass; $R^2 = 0.64$), and protein ($R^2 = 0.74$) that could be accounted for by several explanatory variables. We adjusted each regression equation for significant effects of age–sex classes and seasons. Body mass, season, and age–sex class were useful in explaining condition, but mensural characters added only 1–3% to accountable variance.

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A previously published regression equation based on body mass of redheads (*Aythya americana*) provided a good fit to canvasback data but published equations for greater scaup (*A. marila*), lesser scaup (*A. affinis*), and ring-necked ducks (*A. collaris*) performed poorly. We conclude that, for canvasbacks, regression equations of condition can lead to biased estimates when applied to birds from different seasons, age–sex classes, or species. For other species of waterfowl, equations based on body mass alone or in combination with mensural characteristics tend to be less precise than direct measures of fat or body moisture, but may be preferred when birds cannot be sacrificed.

Key words: Condition indices, COANOVA, fat, protein, body mass, canvasbacks, *Aythya valisineria.*

Knowledge of nutritional condition in birds (i.e., their general health as reflected by fat reserves or protein) can provide insight into potential survivorship and reproduction. For example, nutrient reserves of female waterfowl before and during breeding are related to reproductive potential (Ankney and MacInnes 1978; Raveling 1979; Krapu 1981; Drobney 1982; Hohman 1986; Barzen and Serie 1990), fall survival during the hunting season (Hepp et al. 1986), and to probabilities of recapture later in winter and the following year (Haramis et al. 1986; Krementz et al. 1989).

Condition can be directly measured by grinding a carcass, drying it, extracting fat (including fatty oils and solids) with a solvent, ashing the remains, and estimating protein content by subtracting fat and ash from body mass (Randall 1974). Several less time-consuming or costly methods have been proposed to estimate condition. Estimates based on body water have been used by Child and Marshall (1970), Wishart (1979), and Campbell and Leatherland (1980) in passerines, American widgeon (*A. americana*), and snow geese (*Chen caerulescens*), respectively. Fat deposits, including omental fat in red-billed teal (*Anas erythrorhynchus*; Woodall 1978); abdominal fat in Canada geese (*Branta canadensis*; Thomas et. al. 1983); and skin fat in snow geese (Gauthier and Bedard 1985) have been used with some success. Whyte and Bolen (1984) combined masses of fat deposits with morphological measurements in mallards (*A. platyrhynchos*). These methods require sacrificing and processing birds.

Equations using body mass and external morphology have been widely used because they do not involve sacrificing animals and include data that can be readily collected in the field. Equations using these mensural characteristics to estimate total fat or related measures of condition have been derived for geese (Gauthier and Bedard 1985; Johnson et al. 1985; Moser and Rusch 1988), swans (Sears 1988), *Anas* spp. (Wishart 1979; Ringelman and Szymczak 1985; Miller 1989), *Aythya* spp. (Bailey 1979; Chappell and Titman 1983; Hohman and Taylor 1986; Serie and Sharp 1989), sandhill cranes (*Grus canadensis*; Iverson and Vohs 1982; Johnson et al. 1985), and great crested grebes (*Podiceps cristatus*; Piersma 1984). Walsberg (1988) and Castro et al. (1990) have recently developed an electrical conductivity method that seems promising for estimating fat in live birds.

Ringelman and Szymczak (1985); Ringelman (1985); and Castro and Myers (1990) cautioned against applying regression equations developed for a species in one location to other populations of the same species if there is considerable geographic or seasonal variation in body size or fat content. Inaccuracies in estimability are likely to be compounded when applying equations across species (Chappell and Titman 1983).

Our objectives were to

1. develop regression equations that yield precise and accurate estimates of condition in canvasbacks (*Aythya valisineria*) based on coefficients of determination (designated r^2 for single regression or R^2 for multiple linear regression) and examination of residuals;
2. compare regression equations from congeneric species for precision and accuracy in estimating condition in canvasbacks; and
3. contrast the efficiency (precision compared to ease of data collection) of other published regression methods of estimating condition.

Methods

Canvasbacks were collected by bait-trapping (1975–76) or shooting (all others) at the following times and places (Table 1):

1. fall migration, October–December 1975–76 on the Mississippi River near La Crosse, Wisconsin, and Keokuk, Iowa;

2. on wintering areas in North Carolina, November–early December 1982–83 on Lake Mattamuskeet, and December–February 1983–84 on Pamlico Sound;
3. spring migration, February–April 1984–85 on Lake Erie (Long Point Bay), the Mississippi River near Keokuk and La Crosse, and in North Dakota; and
4. soon after arrival at breeding areas near Erickson, Manitoba, April–May 1984.

Canvasbacks from the arrival period at Lake Mattamuskeet were included with the fall migration sample because these birds were at the end of migration. Descriptions of study areas and collection methods are in Lovvorn (1987), Barzen (1989), and Serie and Sharp (1989).

We weighed canvasbacks to the nearest 5 g; measured culmen, keel, wing, tarsus, and total lengths to the nearest 1 mm; and determined age by plumage characteristics to hatching-year for juveniles and for adults (Serie et al. 1982). Birds at the beginning of their first breeding season were considered juveniles. Culmen was measured from the notch at the dorsal base of the bill to the bill tip, keel along the external keel, tarsus length from the outside of the tarsal–metatarsal joint to the tarsal–phalangeal joint when flexed at right angles, wing length from tip of longest primary to the wrist joint, and total length from the tip of the longest rectrix to the tip of the bill along the dorsum.

In the laboratory we removed gonads and homogenized thawed carcasses. Duplicate 30–50 g subsamples of homogenates were dried to constant mass. We extracted fats by either Soxhlet or Randall (Randall 1974) procedures with petroleum ether or ethyl ether. These techniques differ primarily in the time required for extraction but not in percent fat extracted (Dobush et al. 1985). We estimated carcass protein by combusting samples and subtracting ash mass from fat-free dry mass (FFDM).

Table 1. *Sample sizes for canvasbacks used in this study.*

Season	Location[a]	Adults Males	Adults Females	Juveniles Males	Juveniles Females	Total
Fall	UMR	31	22	21	14	88
	LM	19	15	35	34	103
Winter	PS	38	34	25	28	125
Spring	UMR	44	47	2	9	102
	LE	24	11	8	2	45
	ND	16	28	1	2	47
	MB	13	12	0	3	28
Total		185	169	92	92	538

[a] UMR = Upper Mississippi River; LM = Lake Mattamuskeet (N.C.); PS = Pamlico Sound (N.C.); MB = Manitoba; ND = North Dakota; LE = Lake Erie.

We considered three measures of condition,

1. total fat, the amount of carcass fat that could be extracted with ether;
2. a condition index (CI) calculated by dividing total fat by FFDM; and
3. a protein fraction that contained most of the carcass protein and a small amount (<1%) of complex, insoluble carbohydrates (Robbins 1983).

Protein was not determined in the 1975–76 samples. We included CI because several studies (Johnson et al. 1985; Moser and Rusch 1988) have employed similar ratios. However, Packard and Boardman (1988) suggested that such ratios are only appropriate when their numerators and denominators are linearly related, a condition seldom tested in the literature and not met by FFDM and total fat in our study.

Initially we examined differences in condition measures (total fat, protein, and CI) across seasons and age–sex classes with analysis of variance. We then used analyses of covariance on a randomly selected half of the data set to derive preliminary equations to explain variance in condition measures. Initial group variables included age–sex class, season, and location of collection site within season, investigator, and relevant interactions among these variables. Variables that were considered independent estimators included body mass, culmen, wing, tarsus, keel, and total lengths. Complete equations, which included all relevant independent variables, were reduced by removing nonsignificant ($P > 0.10$) variables. Final equations were verified by applying them to the remaining half of the data and inspecting estimates and residuals (actual values minus estimates).

To compare equations derived for other *Aythya* species we used published regression equations on our data and compared resulting estimates and residuals among groups with analyses of variance. All analyses were performed with SAS (1987).

Results

Seasonal and Age–Sex Class Variation in Condition Parameters

Body mass differed significantly among seasons ($F = 31.16$, df = 2,538, $P < 0.0001$) and age–sex classes (F = 54.43, df = 3,538, $P < 0.0001$; Figure). Protein also differed among seasons (F = 103.66, df = 2,434, $P < 0.0001$) and age–sex classes (F = 91.28, df = 3,434, $P < 0.0001$). Both total fat (F = 56.80, df = 2,536, $P < 0.0001$) and CI (F = 79.55, df = 2,536, $P < 0.0001$) changed markedly among seasons. Total fat also varied among age–sex classes (F = 7.22, df = 3,536, $P < 0.0001$). Specific differences for portions of the total data set are reported in Barzen (1989), Barzen and Serie (1990), Lovvorn (1987) and Lovvorn and Barzen (unpublished).

Development of Regression Equations

For CI the complete equation yielded $R^2 = 0.64$ with tarsus, wing, keel, and total lengths dropping out as nonsignificant. Body mass was the most important explanatory variable in the reduced equation, followed by season, age–sex class and culmen (Table 2). The final equation for CI, based on a randomly selected half of the data was of the form:

$$\mathrm{CI} = -0.536 + \mathrm{CLASS} + \mathrm{SEASON} + 0.001\mathrm{BM} - 0.010\mathrm{CUL}$$

where values for CLASS and SEASON are expressed in Table 3 and BM = body mass and CUL = culmen length. Correction factors in Table 3 equalize the precision of equations across groups. Negative values are produced when uncorrected equations overestimate values for a subset whereas positive values reflect the converse. Omitted subsets in each category require no corrections.

For total fat, the complete equation yielded $R^2 = 0.71$ with only body mass, culmen, age–sex class, and season accounting for a significant amount of

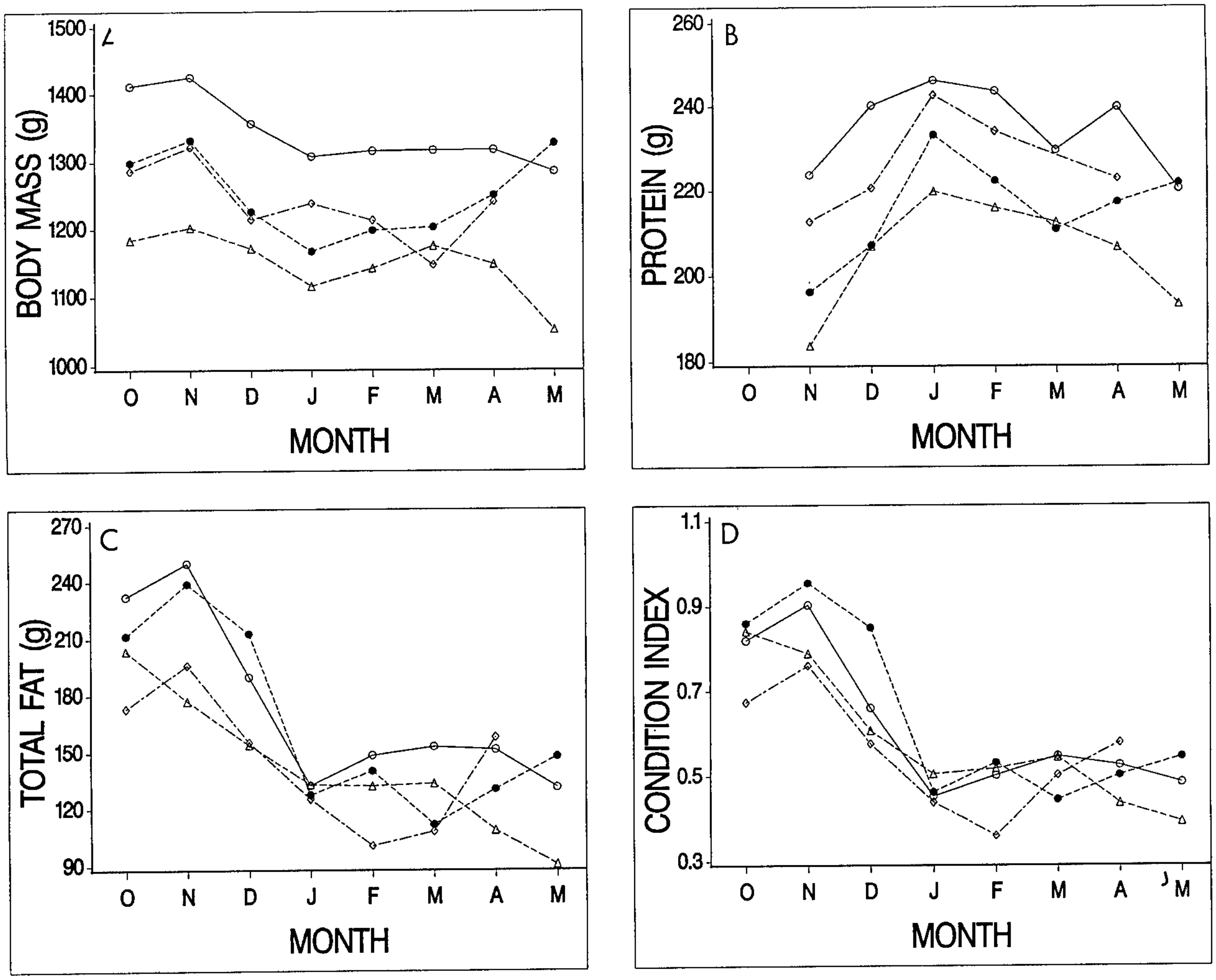

Figure. Mean body mass (A), protein (B), total fat (C), and condition index (D) by month for adult male (*open circles*), adult female (*dots*), juvenile male (*diamonds*), and juvenile female (*triangles*) canvasbacks (*Aythya valisineria*) during migration and winter.

variance. In the reduced equation, body mass and season included about 98% of the accountable variance (Table 2). The equation took the form:

$$\text{FAT} = -246.36 + \text{CLASS} + \text{SEASON} + 0.459\text{BM} - 2.511\text{CUL}$$

Values for CLASS and SEASON are in Table 3.

The complete equation for protein yielded $R^2 = 0.74$ with culmen, keel, and total lengths dropping out. The most important variables for protein were body mass and season (Table 2). The reduced equation had the form:

$$\text{PROTEIN} = -38.98 + \text{CLASS} + \text{SEASON} + 0.100\text{BM} + 1.536\text{TAR} - 0.098\text{WING}.$$

Table 2. *Relative importance and significance of explanatory variables used in estimating condition measures in canvasbacks.*

Condition measure	$\bar{X}$ ± S.D.	Regression variables	r^2/R^2	F	df	P
CI[a]	0.61 ± 0.18	Entire equation	64.4	67.6	7,268	0.0001
		Body mass	48.7	230.7	1	0.0001
		Season	17.5	41.4	2	0.0001
		Class	4.0	6.3	3	0.0004
		Culmen	1.2	5.8	1	0.0170
Total Fat	160.4 ± 44.7	Entire equation	70.9	90.9	7,268	0.0001
		Body mass	59.2	376.6	1	0.0001
		Season	9.4	29.8	2	0.0001
		Class	1.8	3.8	3	0.0110
		Culmen	0.9	5.8	1	0.0170
Protein	218.6 ± 11.5	Entire equation	73.9	74.3	8,217	0.0001
		Body mass	25.9	154.3	1	0.0001
		Season	37.4	111.0	2	0.0001
		Class	4.1	8.2	3	0.0001
		Tarsus	1.1	6.4	1	0.0120
		Wing	3.0	18.0	1	0.0001

[a] CI = total fat/fat-free dry weight.

Table 3. *Correction factors for significantly different group variables used in estimating condition in canvasbacks.*

Condition measure	Regression variable	Level	Correction[a]	
			Factor	(S.E.)
CI[b]	Y-Intercept		−0.536	(0.269)*
	Age–sex Class	Adult males	−0.166	(0.042)*
		Adult females	−0.087	(0.042)*
		Juvenile males	−0.159	(0.041)*
	Season	Fall	0.191	(0.031)*
		Spring	−0.069	(0.030)*
Total fat				
	Y-Intercept		−246.30	(66.50)*
	Age–sex Class	Adult males	−30.71	(10.38)*
		Adult females	−17.76	(8.97)*
		Juvenile males	−31.68	(10.18)*
	Season	Fall	30.03	(7.74)*
		Spring	−25.47	(7.42)*
Protein	Y-Intercept		38.98	(31.99)
	Age–sex Class	Adult males	11.00	(2.96)*
		Adult females	3.85	(2.59)
		Juvenile males	12.77	(2.96)*
	Season	Fall	−34.03	(2.36)*
		Spring	−1.16	(2.81)*

[a] Correction factors adjust for differences in predictability among groups, levels not represented need no correction factor;

[b] CI = total fat/fat-free dry weight.

* Denotes estimates significantly ($P < 0.05$) different from 0.0.

TAR = tarsus length, WING = wing length, and values for CLASS and SEASON in Table 3.

Verification of Equations

Application of the CI equation to the remaining half of the data set resulted in a mean (±S.D.) residual of 0.001 (±0.205) units which was <0.2% of the CI mean. Actual and estimated values correlated significantly ($r = 0.71$, $P < 0.0001$). Similarly, the mean residual from applying the equation for total fat to the other half of the data was 0.107 (±45.96) g (<0.1% of mean fat) and $r = 0.794$ ($P < 0.0001$). For the protein equation the mean residual was 0.312 (±12.30) g (<0.2% of mean protein) and $r = 0.805$ ($P < 0.0001$).

Equations Based on Ratios of Mensural Characteristics

For comparison with other studies (Bailey 1979; Wishart 1979; Whyte and Bolen 1984), we also regressed CI, total fat, and protein against ratios of body mass and mensural characteristics. These equations included age–sex class and season as group variables. Most of the regressions accounted for less variance than comparable regressions using only body mass, season, and age–sex class (Table 4).

Table 4. *Coefficients of determination* (r^2) *and significant* ($P<0.05$) *regression term for modeling fat, protein, and condition index as a function of body mass divided by a mensural characteristic.*

Regression term[a]	Total fat	Protein	Condition index
BM/(CULMEN + KEEL)	0.271	0.617	0.298
	S,C	S,C	S
BM/CULMEN	0.635	0.640	0.567
	S,S×C	S,C	S,C,S×C
BM/KEEL	0.664	0.671	0.589
	S,C,S×C	S,C	S,C,S×C
BM/WING	0.342	0.642	0.367
	S,C,S×C	S,C,	S,C
BM/TARSUS	0.494	0.674	0.478
	S,C,S×C	S,C,S×C	S,C
BM	0.682	0.694	0.588
	S,C,S×C	S,C	S,C,S×C

[a] BM = body mass, S = season, C = age-sex class, S×C = season by class interaction.

Comparisons With Regression Equations from Other Aythya *Species*

Of regression equations published using body mass or body mass divided by total length for ring-necked ducks, redheads, and greater and lesser scaup, those developed for redheads (Bailey 1979) provided the best fits to our data (Table 5), resulting in correlations above 0.73 between estimated and observed fat and underestimating fat by less than 14 g. Bailey's (1979) redhead sample was predominately males and, when applied to males in our data, his equation with body mass gave correlations exceeding 0.77 with canvasback total fat. Equations derived from greater and lesser scaup (Chappell and Titman 1983) and ring-necked ducks (Hohman and Taylor 1986) produced estimates that correlated with canvasback fat ($r = 0.67 - 0.79$) but underestimated it by 34–269 g, even when applied to comparable subsets of data (i.e., adults in spring and fall).

Contrast of Different Methods of Estimating Fat

We found 17 studies involving 15 species that used fat, either alone, or as part of a factor of condition, for our contrast of methods that estimated body condition in aquatic birds. We did not contrast methods of estimating protein because very few studies employed this measure of condition. We included 13 species of Anseriformes, one Podicipediformes, and one Charadriiformes (Table 6). Methods included body mass alone, body mass with one or more mensural characteristic, percent body water, or a fat deposit (abdominal, skin, or omental fat). The studies incorporated a variety of measuring techniques and a mixture of age and sex classes collected from different areas and seasons; thus we decided that nonparametric statistics were more appropriate for comparing these data than more conventional parametric techniques. Methods had to be compared in a pairwise fashion so we set the acceptable level of significance at 0.01. Although mean square error is important in evaluating regression, we chose the coefficient of determination to evaluate methods because this value was obtainable from all studies examined.

Body mass alone accounted for 18–81 % of the variation in fat, with a median value of 57%. The highest r^2 values came from greater and lesser scaup (Bailey 1979). Body mass coupled with mensural characteristics accounted for 49–90% of the

Table 5. *Correlations between observed values of canvasback body fat and estimates derived from regression equations developed for other* Aythya *species and applied to canvasback data.*

Species[a]	Equation[b]	Portion of canvasback data set[c]	r^{2d}	Mean residual (g)	SD[e] (g)
RH	-369.42 + 0.41BM	Entire	0.546	12.1	53.0*
		Males	0.687	-4.6	50.5
	-443.46 + 243.48BD	Entire	0.450	13.7	49.3*
		Males	0.605	3.4	42.4
GS	-462.50 + 0.59BM	Entire	0.546	-124.0	57.2*
		S,F adults	0.622	-139.8	54.7*
	-536.63 + 302.26BD	Entire	0.450	- 34.0	51.5*
		S,F adults	0.524	- 55.8	46.3*
LS	-346.57 + 0.60BM	Entire	0.546	-252.7	57.7*
		S,F adults	0.622	-268.8	55.1*
	-398.91 + 275.83BD	Entire	0.450	-108.4	50.2*
		S,F adults	0.524	-128.8	45.4*
RN	-159.4 + 0.34BM	Entire	0.546	-108.7	54.4*

[a] RH = redhead (Bailey 1978); GS = greater scaup, LS = lesser scaup (Chappell and Titman 1983); RN = ring-necked duck (Hohman and Taylor 1986).

[b] BM = body mass, BD = body mass/total length.

[c] S,F adults = adults collected in spring and fall.

[d] Squared correlation coefficient, all $P < 0.0001$.

[e] Standard deviation of residuals, * = 95% confidence intervals that do not include 0.

variance with a median value of 68%. The best fit for this method was for Canada geese (Moser and Rusch 1988). Comparison of r^2 values is confounded because studies used different mensural characteristics. When more than one equation with mensural characteristics was reported for a study, we only included the equation with the highest r^2 value. When compared to body mass alone for the same set of data (16 possible comparisons), body mass with mensural characteristics consistently provided higher r^2 values ($P = 0.001$, Sign Test, Siegel 1956); mensural characteristics added approximately 10 percentage points.

The other methods of estimating fat require dead birds. Body water accounted for 16–98% of the variation in fat with a median of 84%. The best estimates for this method came from snow geese (Campbell and Leatherland 1980). Eight comparisons between body water and body mass with mensural characteristics demonstrated no clear difference between methods ($P = 0.145$). Similarly, there was no detectable difference between body water methods and body mass alone ($P = 0.172$).

Abdominal fat was the most widely used fat deposit. It accounted for 61–91% of the variance (median = 84%) with the highest percent in grebes (Piersma 1984). Six comparisons were possible between this method and body water; three of these had abdominal fat with higher r^2 values and three had body water with higher values. Seven comparisons were possible between abdominal fat and body mass with mensural characteristics; one had equal r^2 values, and six showed abdominal fat with greater values. Abdominal fat increased the proportion of accountable variance by approximately 17% ($P = 0.016$). Methods employing abdominal fat improved precision by 22% compared with those using body mass alone ($P = 0.001$, $n = 10$). Coefficients of determination for skin fat varied from 0.72 to 0.94 (median = 0.90). Although blue geese had the highest coefficient with this method, mallards, widgeon, redheads, and greater scaup also had high correlations between skin fat or weight and total fat. Two studies employed omental fat and had r^2 of 0.81 and 0.91.

If we compare the fat deposit yielding the highest r^2 value to body mass alone, we find that fat deposits add about 27% to precision ($P = 0.001$, $n = 12$). Fat deposits added approximately 18% to accountable variance compared to body mass with mensural characteristics ($P = 0.008$, $n = 9$). However, half of the eight contrasts between fat deposits and body water gave body water the higher value and no difference between methods could be discerned.

Table 6. *Comparison of regression equations using body mass with and without mensural characteristics for estimating fat-related condition measures in 13 species of aquatic birds.*

Species	Age–sex class	Season	Condition measure[a]	Estimator[b]	r^2/R^2	References[c]
Podiceps cristatus	M	Winter	TF	BM	0.66	1
	F				0.57	
	M		BW	0.84		
	F				0.55	
	M			AF	0.91	
	F				0.72	
Branta canadensis	M,F	Spring–Summer	1	BM[d]	0.79	2
				BM,TL,TAR[d]	0.90	
	F	Prelaying	TF	AF	0.90	3
		Postlaying			0.80–0.91	
Anser albifrons	M,F	Spring	2	BM,TAR,WL[d]	0.80	4
				BM	0.71[e]	
				BW	0.81[e]	
Chen caerulescens	M	Spring	TF	BM	0.50	5
				BM/CUL	0.56	
	F			BM	0.45	
				BM/TAR	0.52	
	M,F			SF	0.94	
				AF	0.86	
	F	Prelaying	TF	AF	0.41–0.94	3
	M				0.61	
	F	Postlaying			0.78–0.86	
	M				0.80–0.88	
	M,F	Circumannual	%TF	BW	0.92[e]	6
	M,F–J				0.98[e]	
Anas platyrhynchos	M,F	Circumannual	TF	BM	0.49	7
				WS	0.90	
				OF	0.81	
				BM/WL	0.53	
	M,F	Winter	TF	BM	0.46	8
	M			BM+WL	0.64	
	F			BM+WL	0.68	
Anas acuta	M,F	Fall–Winter	TF	BM	0.63	9
				BM,CUL,WL,TAR	0.66	
	M			BW	0.95	
	F				0.92	
	M			AF	0.86	
	M,F			WS	0.90	
	M,F			FATDEP	0.94	
Anas americana	M,F	Circumannual	TF+PR	BM	0.51	10
				BM/(WL+TL)	0.55	
			TF	BW	0.82	
				SF	0.81	
				AF	0.83	
				AF + SF	0.92	
Anas erythrorhynchus	M,F	Spring	TF	BM	0.56[e]	11
				BM/WL	0.73[e]	
				BW	0.43[e]	
				OF	0.91[e]	
Aythya americana	M	Summer–Fall	TF	BM	0.65	12
				AF	0.83	
				SF	0.90	
				BM/TL	0.72	
Aythya valisineria	M,F	Fall	TF	BM	0.69	13
				BW	0.16	
				BM,CUL	0.71	
Aythya collaris	M,F	Circumannual	TF	BM	0.42	14
				AF	0.89	
				SF	0.72	
				AF,SF	0.96	

Table 6. (*Continued*).

Species	Age–sex class	Season	Condition measure[a]	Estimator[b]	r^2/R^2	References[c]
Aythya marila	M,F	Spring, Fall	TF	BM	0.81	15
				BW	0.95	
				BM/TL	0.82	
				AF	0.87	
				SW	0.91	
Aythya affinis	M,F	Spring, Fall	TF	BM	0.81	15
				BW	0.96	
				BM/TL	0.83	
				AF	0.84	
Grus canadensis	M,F	Winter–Spring	TF	BM	0.59	16
				BM/(TL+TAR)	0.68	
	M,F	Spring	1	BM	0.42	4
				BM,TAR,WL,CUL[d]	0.70	
				BW	0.87	
Calidris alba	M,F	Winter	TF	BM	0.07–0.29	17
				BM,TW	0.49	
				BM,HBL	0.75	

[a] Condition parameter: TF = total fat, %TF = percent total fat, PR = protein, 1 = Log(TF + PR)/skeletal volume, 2 = Log(Dry Mass/Fat-free dry weight).

[b] Estimator: BM = body mass, BW = percent body water, AF = abdominal fat, TL = total length, TAR = tarsus length, WL = wing length, FATDEP = AF + WS + intestinal fat, CUL = culmen length, SF = skin fat, WS = wet skin weight, OF = omental fat, TW = total wing spread, HBL = head – body length.

[c] References: 1 = Piersma (1984), 2 = Moser and Rusch (1988), 3 = Thomas et al. (1983), 4 = Johnson et al. (1985), 5 = Gauthier and Bedard (1985), 6 = Campbell and Leatherland (1980), 7 = Whyte and Bolen (1984), 8 = Ringelman and Szymczak (1985), 9 = Miller (1989), 10 = Wishart (1979), 11 = Woodall (1978), 12 = Bailey (1979), 13 = a portion of the present study in which body moisture was measured, 14 = Hohman and Taylor (1986), 15 = Chappell and Titman (1983), 16 = Iverson and Vohs (1982), 17 = Castro and Myers (1990).

[d] Values were log transformed before analysis.

[e] r^2 calculated as squared correlation coefficient.

Discussion

The most important variables in estimating condition in canvasbacks were body mass, season, and age–sex class. Culmen, tarsus, and wing length were occasionally significant but added only 1–3% to accountable variance. This increase in precision would probably be obscured by variability in measuring live birds. Thus, only body mass, sex, age, and season of capture are sufficient to predict condition in canvasbacks.

The importance of season as an explanatory variable in our equations resulted from seasonal changes in body composition of canvasbacks. For example, total fat in canvasbacks increased during fall migration (Serie and Sharp 1989), but body mass also increased, so correlation between the two variables was relatively high ($r = 0.803$, df = 189, $P < 0.0001$). Fat declined in midwinter and spring as body reserves were depleted (Lovvorn 1987) and did not follow body mass as reliably ($r = 0.643$, df = 345, $P < 0.0001$). Condition index also declined through this period but FFDM remained relatively constant. Because of these seasonal changes, total fat would be difficult to estimate precisely in late winter and early spring from equations developed from birds collected in autumn.

Our regression equations yielded coefficients of determination comparable to those from other studies that have employed morphological measurements. For example, body mass accounted for 65% and body mass per total length accounted for 72% of the variation in fat among redheads (Bailey 1979). Hohman and Taylor (1986) accounted for only 42% of the variation in total fat of ring-necked ducks using a regression equation employing body mass as the sole estimator, but obtained $R^2 = 0.67$ when regressing protein on body mass and bill width. Ringelman and Szymczak (1985) accounted for 64% of the variation in total fat for male mallards and 68% of the variation for females with equations using body mass and wing length. Body mass accounted for 81% of the variation in FFDM of migrant adult scaup (Chappell and Titman 1983). With the exception of Chappell and Titman (1983), however, equations that rely on mensural characteristics usually leave more than 25% of the variation in condition measures unaccounted.

Chappell and Titman (1983) suggested that regression equations might be used across very closely related species. The equations from male redheads (Bailey 1979) resulted in low residuals and high correlations between estimated and actual values when applied to our canvasbacks, but those from scaup (Chappell and Titman 1983) and ring-necked ducks (Hohman and Taylor 1986) resulted in estimates that were substantially different from observed values.

Of the methods routinely used to estimate body fat in aquatic birds, those that require dead birds (body water and fat deposits) yield higher coefficients of determination than those that can be used on living animals. No generalizations can be made about the relative precision of body water methods versus fat deposits. However, abdominal fat deposits can be excised from waterfowl harvested by hunters without impairing the quality of the game and are relatively easy to measure. Measurements of skin fat and body water require the total animal, and body water measurements necessitate further processing and desiccation. The greater variation in coefficients of determination for body water methods suggests that they would be less reliable for new species than fat deposits. This assumes that an investigator wanted to use a single measure for comparing the relative condition of a species in different sites or times without going through the process of fat extraction.

If waterfowl cannot be sacrificed because of study or population constraints (e.g., mark–recapture or a threatened species), a method employing body mass with mensural characteristics seems more appealing than one using body mass alone. The problem, however, is that there is no set of mensural characteristics which can be predicted, a priori, to yield the highest R^2 value. In many cases, arbitrary selection of a mensural characteristic contributes little to the precision of a regression and may actually detract from regressions based on body mass alone. Useful mensural characteristics can only be identified through repeatedly applying regression equations to known values of fat, protein, or condition indices.

The various methods of estimating condition in birds differ in their utility and efficiency. Greatest accuracy in estimating condition is obtained by processing entire carcasses with solvent extractions and Soxhlet analysis. Although variability may be introduced by homogenization, sampling of aliquots, or extraction procedures, the procedure provides the most direct way of sampling total fat and protein. If birds are dead or can be sacrificed, measurements of abdominal fat deposits may be more rapid than fat extraction procedures and still yield precise estimates of condition.

Although precision with body water methods can sometimes exceed 90%, these methods are the most variable of those employing dead birds. Body moisture techniques also require elaborate processing of birds, including dissection, grinding, and drying.

When birds cannot be killed, their condition can be estimated from body mass and mensural characteristics, but there is no way of predicting which mensural characteristic(s) provide the highest precision and accuracy without first comparing equations to fat-extracted samples. Body mass alone is the simplest estimation technique, but it tends to yield lower precision. As with any estimation technique, the quality of estimates may be substantially improved when age, sex, season, and location are taken into account.

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