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Original Article

Validating the Deuterium Dilution Method to Measure Body Composition of Common Eider

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ABSTRACT We conducted the first validation of the deuterium dilution method as a nonlethal technique for estimating body composition of a sea duck. We captured male ($n = 11$) and female ($n = 8$) American common eiders (*Somateria mollissima dresseri*) during winters of 2011–2012 and 2012–2013 in southern New England, USA, and compared their directly measured body composition with that estimated using deuterium-dilution. The best-supported linear regression models predicted wet lean and fat mass with, on average, 2.0% and 20.2% relative errors, respectively. The deuterium dilution method provides field biologists and managers with a nonlethal method for accurately estimating body composition of common eider during winter. The method is broadly applicable to other migratory birds and can be used to evaluate the effects of ecological and anthropogenic drivers on body composition dynamics. © 2016 The Wildlife Society.

KEY WORDS body composition, body condition, common eider, deuterium dilution, *Somateria mollissima*.

Wildlife biologists often use fat content adjusted for morphometrically estimated size as an index of body condition in animals because it represents accumulated energy capital (Green 2001, Peig and Green 2009, Labocha and Hayes 2012). Investigations of body condition are relevant for the ecology and management of free-living wildlife because body condition changes with habitat quality, and in preparation for migration, breeding, and wintering (Alisauskas and Ankney 1992, Servello et al. 2005, Moon et al. 2007, Anteau and Afton 2009, Schummer et al. 2012). Body condition can be a useful integrative indicator of environmental quality and disturbance at a variety of scales including that associated with global climate change, disease, and anthropogenic development (Klaassen et al. 2012).

Direct or indirect methods can be used to assess body condition of animals (Campbell and Leatherland 1980, Speakman 2001, Jamieson et al. 2006). Direct methods are lethal because they involve a necropsy to directly measure the total amount of fat and lean mass (protein) in individuals (Hicks 1967, McLandress and Raveling 1981, Alisauskas et al. 1990, Ellis and Jehl 1991, Jamieson et al. 2006). Jamieson et al. (2006) recommended directly measuring body composition of common eider (*Somateria mollissima*) and this method has been commonly used for other waterfowl (Ankney and MacInnes 1978, Reinecke and Stone 1982, Baldassarre et al. 1986, Schummer et al. 2012). Indirect methods allow body composition to be estimated without the need to sacrifice the birds, avoid the laborious dissections and complex laboratory analyses required for directly measuring body composition, and make possible repeated measures of an individual's body composition (Johnson et al. 1985, Speakman 2001, McWilliams and Whitman 2013). Deuterium dilution is an indirect method that has been successfully applied to estimate body composition of a variety of wild vertebrates (Speakman 2001) including passerine birds (McWilliams and Whitman 2013) and barnacle geese (*Branta leucopsis*; Eichhorn and Visser 2008), although no previous studies have used this indirect method to assess body composition of sea ducks.

Our goal was to validate the deuterium dilution method for estimating body composition of one species of sea duck, the common eider. Common eider (hereafter, eider) is the largest species of North American sea duck and is widespread and abundant during winter in northeastern North America (Goudie et al. 2000, Silverman et al. 2013). Thousands of American common eiders (*S. m. dresseri*) winter nearshore in southern New England, USA (Klimstra and Padding 2012, Silverman et al. 2013).

STUDY AREA

We conducted fieldwork in nearshore waters of southern Rhode Island and Wellfleet Bay, Massachusetts, USA

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(Fig. 1). In Rhode Island, birds were primarily captured in southern Narragansett Bay, near Point Judith, off breachways entering coastal ponds (Ninigret and Quonochotaug Ponds), and near Watch Hill, where there were rocky reefs with mussel beds in shallow waters and common eider were relatively abundant.

METHODS

Field Methods

We used floating mist nets and decoys to capture 21 adult eiders throughout the winter (early winter, 13 Nov–14 Dec 2011, $n = 12$, 15–16 Nov 2012, $n = 4$; midwinter, 6–16 Feb 2011, $n = 4$; late winter, 15–19 Mar 2011, $n = 1$ [Brodeur et al. 2008]). We determined age and sex of captured eiders using wing plumage characteristics (Carney 1992). The 21 adult eiders were a representative sample across the range of body masses of all adult eiders ($n = 148$) that we captured (early winter $n = 81$, midwinter $n = 39$, late winter $n = 28$) as part of a larger companion study.

Within 30 min of capture in the field, we used a prefilled, disposable 1-mL insulin syringe (Fisher Scientific, 22004270 [Pittsburgh, PA, USA]) to inject $1{,}066 \pm 4.5$ mg ($\bar{x} \pm$ SE) of 99.9% deuterium oxide (Sigma–Aldrich, St. Louis, MO, USA) into the pectoral muscle of each of 17 eiders. We injected $3{,}148 \pm 34.3$ mg of the 99.9% deuterium oxide solution into 4 eiders captured in Wellfleet, Massachusetts. We used this larger volume as part of a separate study to compare the accuracy and precision of different instruments for measuring deuterium concentrations in our laboratory. We measured actual mass of deuterium oxide injected into each bird by reweighing syringes after injection and subtracting this from the preinjection mass of the same syringe plus deuterium oxide solution. After injection, we weighed birds with a Pesola scale (± 10 g) and then housed birds in individual pet crates (48 cm × 32 cm × 26 cm ht) for approximately 90 min to allow deuterium oxide to reach equilibrium in their pool of body water (Eichhorn and Visser 2008). On average, 97 min (± 9 min) after injection, we collected approximately 200 μL of blood into heparinized capillary tubes (Fisher Scientific) after pricking the medial metatarsal vein of each bird with a sterile 27G needle (Fischer Scientific). In the field, we used clay to seal capillary tubes containing blood; later the same day, we flame-sealed the glass capillary tubes and stored blood samples at 4.4° C.

After drawing blood, we euthanized eiders selected for the validation using cervical dislocation. We stored carcasses in the field for a maximum of 6 hr in zip-lock bags at ambient temperature until we returned to the laboratory. We measured structural size in the validation birds in the laboratory (i.e., head and bill characters, tarsus length, wing chord, $n = 21$) rather than in the field because of the limited time we held the eiders to minimize handling stress and accurately measuring these structural size characters was difficult in small skiffs on the ocean during winter. In the laboratory, we reweighed each specimen using an electronic balance (± 0.1 g), double-bagged each bird in a freezer zip-lock bag, and stored frozen specimens (−17° C) until we completed total carcass analysis. All methods were approved by the University of Rhode Island Institutional Animal Care and Use Committee (Protocol no. AN 11-09-004).

Laboratory Methods

Total carcass analysis.—We used eiders selected as validation birds to develop the predictive relationship between total body water (estimated using deuterium dilution) and body composition as directly measured from carcass analysis (Eichhorn and Visser 2008, McWilliams and

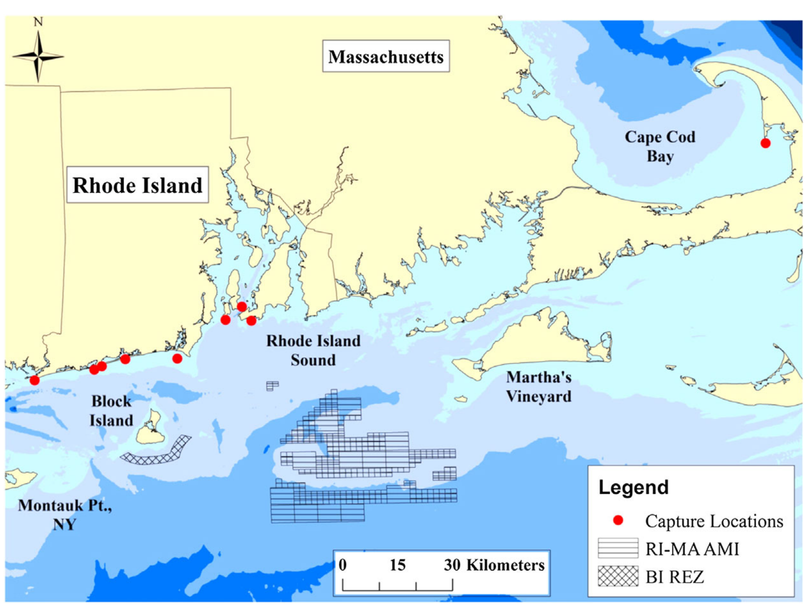

Figure 1. Sites in southern New England, USA, where common eiders were captured (red circles) during the winters of 2011–2012 and 2012–2013 in Rhode Island and Massachusetts, USA. The location of an active offshore wind-energy facility within the Block Island Renewable Energy Zone (BI REZ; black hatched lines) and federal lease blocks for an offshore facility (Area of Mutual Interest [AMI]; black lines) are also depicted.

Whitman 2013). We used standard techniques outlined by Dobush et al. (1985) and Speakman (2001) to directly measure body composition (total body fat mass, protein, water, and feathers; $n = 21$). We estimated wet lean mass of each eider as body mass minus feather and fat mass and dry lean mass as wet lean mass minus water mass. We measured the following structural characters with digital calipers (± 0.01 mm): culmen length, culmen width at nares, head length, and tarsus length (Dzubin and Cooch 1992). We also measured flattened wing chord to the nearest mm.

Measuring total body water.—We dried 6 50-g samples of each homogenized carcass in aluminum trays at 90° C until constant mass. We calculated water content (%) of the sample as the difference between the fresh wet mass and dry mass of the sample divided by the fresh wet mass of the sample multiplied by 100. We estimated total body water by multiplying the mean water content (%) of the 6 subsamples by the shaved wet carcass mass.

Measuring fat mass.—We dried 4 50-g samples of each homogenized carcass in aluminum trays at 60° C until mass was constant (Dobush et al. 1985). Once dry, we combined the samples and homogenized them using a blender. From this dry, homogenous mixture, we weighed 5 1.0-g subsamples into cellulose thimbles that we had previously dried at 60° C and weighed. We placed thimbles into a Soxhlet extractor and refluxed the samples with petroleum ether for a minimum of 8 hr (Dobush et al. 1985). After a visual inspection verified that the ether flushing through the thimbles was clear and free of fat, we removed the thimbles and dried them overnight at 60° C. We reweighed the dried thimbles and calculated fat (%) as the difference between dry sample mass and lean-dry sample mass, divided by the dry sample mass. We estimated total fat as the mean percent fat of the 5 samples multiplied by the dry shaved carcass mass.

Measuring protein.—We combined the lean, dry samples resulting from fat extraction from each carcass and ground the combined sample in a Wiley Mill (screen size 40). We measured 5 1-mg replicates of lean, dry homogenate into 4×6-mm aluminum capsules (Costech, Inc., Valencia, CA, USA) and then directly measured nitrogen content using a continuous-flow isotope ratio mass spectrometer (Elementar Americas, Mt. Laurel, NJ, USA). For 11 of 21 eiders, our measurement of nitrogen content had coefficients of variation (CV) that were >5%, so we remeasured nitrogen content for 5 additional replicates to reduce the CV to <5%. We estimated nitrogen content of the carcass as the mean percent nitrogen of the replicates multiplied by the lean dry shaved carcass mass. We determined the amount of protein in each bird by multiplying the nitrogen content by 6.25 (Parker and Holm 1990). As expected, total protein estimated from nitrogen content was closely related to total lean dry mass across individuals ($r^2 = 0.87$, $P < 0.001$), so we report below only the results for total lean dry mass. We used a *t*-test to compare body measurements and composition to between males and females (SAS Institute, Inc., Cary, NC, USA).

Measuring deuterium concentration.—We measured the deuterium concentration (atom %) in each eider blood sample ($n = 21$) to estimate the total body water and body composition of eider throughout winter. We first micro-distilled each blood sample following procedures described by Nagy (1983) to recover a blood water sample. The University of Arkansas Stable Isotope Laboratory (Fayetteville, AR, USA) measured deuterium concentration in blood water by using a high-temperature-conversion elemental analyzer (Thermo/Finnigan; Thermo Fisher Scientific, Waltham, MA, USA) interfaced with a Conflo III (Thermo/Finnigan) to a Delta plus XP with electrostatic filter mass spectrometer (Thermo/Finnigan). We analyzed 4 1-uL subsamples of each blood water sample, with the last 2 retained and averaged while the first 2 replicates were discarded to minimize carry over from the previous sample. We converted deuterium enrichment in parts per million (ppm) to atom percent concentration using the following equation:

$$\text{Atom }\% = (100 \times 0.0001557 \times (X/1,000 + 1)/(1 + 0.0001557 \times (X/1,000 + 1),$$

where 0.0001557 was the mole fraction of deuterium in Vienna Standard Mean Ocean Water (Coplen et al. 2002) and X was the measured deuterium enrichment (ppm) of the sample.

Measuring background deuterium.—We measured background deuterium concentration (atom %) in 4 eiders that were not used in the validation of the deuterium dilution method or for estimation of body composition. Mean background deuterium concentration was $0.01536 \pm 2.091\,\mathrm{e}^{-5}$ atom %. We corrected measured deuterium concentrations of all blood samples by subtracting the mean background deuterium concentration.

Estimating total body water.—We used the following equation from Karasov and Pinshow (1998) and McWilliams and Whitman (2013) to estimate deuterium space (total body water) for each of the 21 eiders:

$$E = 100 \times \{0.999 \times (B/20)/[0.999 \times (B/20) + 0.001 \times (B/18) + (S/18)]\}$$

where E was the measured enrichment (atom %) of deuterium in the sample after background correction, 0.999 was the proportion of injected solution that was deuterated water, 0.001 was the proportion of injected solution that was unlabeled water, B was the injection mass in grams, 20 was the molar mass of deuterated water, 18 was the molar mass of unlabeled water, and S was deuterium space (or body water) in grams. Knowing actual amount of deuterium injected (B) and measured enrichment (E), we rearranged the equation to estimate the deuterium space (total body water):

$$S(g) = 18 \times \{(\{100 \times [0.999 \times (B/20)]\}/E) - [0.999 \times (B/20)] - [0.001 \times (B/18)]\}$$

Estimating Body Composition

Model development.—We used multiple regression analysis to compare predictive models to estimate wet lean and fat mass of eider given deuterium-estimated total body water, structural size, body mass, and sex of each bird. We used principal component analysis to condense the 5 structural measurements and body mass into 2 orthogonal principal components that were then included in the multiple linear regression analyses. We used Levene's test and examination of Q–Q plots to ensure the dependent variables met the assumptions of normality and homoscedasticity. We used SAS 9.2 (SAS Institute, Inc., Cary, NC, USA) to perform all statistical analyses unless otherwise noted. We used an alpha level of 0.05 for all statistical tests.

Model selection and evaluation.—We used Akaike's Information Criterion corrected for small sample sizes (AIC_c) and estimates of the accuracy of model predictions to select the best model(s), with a jack-knife approach for model validation. We assessed the accuracy of these estimated values by comparing the root mean square error (RMSE), absolute error, and relative errors for each model. We calculated root mean square error using the following equation:

$$\sqrt{(\sum(y_p - y_m)^2/n)}$$

where y_p is the predicted value, y_m was the measured value, and *n* was the number of birds over which the squared difference between predicted and measured was summed (Olden and Jackson 2000). We also calculated for each individual bird the absolute error (g) as |predicted − measured| and the relative error (%) as (absolute error/measured) × 100.

RESULTS

Capture of Eider

We captured 144 adult and 71 juvenile (first and second year) eiders during winter 2011–2012 in Rhode Island and 4 adult and 4 juvenile eiders in November 2012 in Wellfleet, Massachusetts. Mean body mass of all adult eiders was 1,934.8 g (range = 1,420–2,320 g, $n = 143$), whereas that of adult eiders used for this validation was 1,957.3 g (range = 1,595–2,298 g, $n = 19$; Table 1).

Table 1. Body-mass frequency distribution for all adult common eiders captured during winters 2011–2012 and 2012–2013 in Rhode Island and Massachusetts, USA, including those that were injected with deuterium but not used in the validation study (injected-only) and those selected for the validation study and used to develop predictive models for estimating body composition.

	All adult eiders[a]		Injected-only		Validation-only[b]	
Mass (g)	*n*	%	*n*	%	*n*	%
1,350–1,500	1	0.7				
1,501–1,650	5	3.5	1	1.1	1	5.3
1,651–1,800	28	19.6	13	14.4	5	26.3
1,801–1,950	49	34.3	35	38.9	3	15.8
1,951–2,100	36	25.2	25	27.8	4	21.1
2,101–2,250	21	14.7	15	16.7	4	21.1
2,251–2,400	3	2.1	1	1.1	2	10.5

[a] Five of 148 adult eiders were not weighed at capture on account of unfavorable field conditions.

[b] Two of the 21 eiders originally selected for the validation study were later excluded because their estimated total body water was biologically unrealistic (>80% of body mass; McWilliams and Whitman 2013).

Body Composition and Size of Validation Eider

Male eiders averaged 280 g, heavier than females, had 133 g more water 210 g more wet lean mass, and 68 g more dry lean mass, than females (Table 2). Wing chord of male eiders averaged 14 mm longer than female, heads were 10 mm longer, and culmen length was 6 mm longer (Table 2). There were no differences in fat and feather mass, culmen width, or tarsus length between male and female eiders (Table 2). The 4 eiders captured in Wellfleet did not differ in body composition or structural size from eiders captured in Rhode Island ($P > 0.05$ for all variables).

Structural Size of Eider

The first principal component (PC1 = 0.894(head) + 0.831(wing chord) + 0.823(body mass) + 0.705(culmen length) + 0.616(culmen width) + 0.261(tarsus)) accounted for 52% of the total variance. The second principal component (PC2 = 0.868(tarsus) − 0.4768(culmen width) + 0.267(culmen length) + 0.132(head) − 0.163(wing) − 0.126 (body mass)) accounted for an additional 19% of the total variance. Eiders with greater loadings for the first principal component (PC1) had a larger head, wing, and culmen, and were heavier; whereas those with greater loadings for the second principal component (PC2) had a longer tarsus and shorter culmen width. We used these first 2 principal components in our predictive models to account for the contribution of body size to variation in body composition.

Predictive Models for Estimating Body Composition of Eider

Deuterium-estimated total body water (deutmw) for the adult eiders ($n = 19$) used in the validation was strongly and linearly related to directly measured total body water as well as predicted total body water (pwat), where pwat = −97.511 + 0.957(deutmw), $r^2 = 0.93$. Deuterium dilution consistently overestimated measured total body water by 13.30% ± 0.73% (8.63–20.86%) as found in all previous studies (Karasov and Pinshow 1998, Speakman 2001, Eichhorn and Visser 2008, McWilliams and Whitman 2013). The highest ranked model for predicting total body water included sex and deuterium-estimated total body water; however, the slope of the relationship between the measured and deuterium-estimated total body water for each sex was similar and intercepts did not differ from zero ($P > 0.20$ in all cases). We, therefore, excluded sex from the final model for predicting total body water (pwat) given estimated deuterium space. This model predicted total body water within 21.54 ± 4.67 g absolute error and 1.90% ± 0.45% relative error.

The best supported model for estimating lean mass (Model 1) of the 6 candidate models (Table 3) included predicted total body water as well as both of the principal components that described structural size and sex. The best supported models without structural measures (Models 3 and 4) included predicted total body water and sex with the most parsimonious of the models (Model 4) providing the lowest RMSE and lowest absolute and relative error of the 6 competing models.

Table 2. Body composition and morphometrics of 19 adult common eiders used to develop predictive models for estimating eider body composition. All birds were captured during the winters of 2011–2012 and 2012–2013 in Rhode Island and Massachusetts, USA. Values presented are the mean ± standard error (SE) and the range. Test statistic (*t*-test) compared males and females for each component.

	Sex					
	Male ($n = 8$)		Female ($n = 11$)		Test statistic	
Component	**Mean ± SE**	**Range**	**Mean ± SE**	**Range**	t_{17}	***P***
Body mass (g)	2,075 ± 54.6	1,742–2,298	1,795 ± 60.2	1,595–2,030	−3.41	0.003
Wet lean mass (g)	1,731 ± 36.2	1,515–1,949	1,521 ± 44.5	1,387–1,765	−3.31	0.004
Dry lean mass (g)	507 ± 10.6	450–562	439 ± 13.3	400–502	−4.03	<0.001
Fat mass (g)	226 ± 36.6	122–569	162 ± 16.3	108–256	−1.40	0.178
Water mass (g)	1,231 ± 28.5	1,065–1,388	1,098 ± 34.1	987–1,263	−2.99	0.008
Feather mass (g)	111 ± 6.3	80–141	96 ± 3.6	77–108	−1.91	0.073
Tarsus length (mm)	56 ± 1.1	50–61	54 ± 0.6	51–56	−0.93	0.366
Culmen length (mm)	60 ± 0.7	56–64	54 ± 0.7	51–57	−5.72	<0.001
Culmen width (mm)	22 ± 0.2	21–24	22 ± 0.4	20–23	−1.97	0.065
Head length (mm)	135 ± 1.6	127–145	125 ± 1.4	120–132	−4.55	<0.001
Wing chord (mm)	308 ± 3.1	293–320	294 ± 3.1	285–306	−3.08	0.007

The best supported models for estimating fat mass (Models 1 and 2) of the 6 candidate models (Table 4) included predicted total body water, sex, and either structural size or body mass, although Model 1 provided a much lower RMSE and among the lowest absolute and relative errors of the 6 competing models. Deuterium dilution accurately estimated wet lean mass within 32.4 ± 5.18 g (absolute error) or 2.0% ± 0.4% (relative error) of actual lean mass, and estimated fat mass within 35.9 ± 5.6 g or 20.2% ± 3.9% of actual fat mass (Table 5).

DISCUSSION

Validation of the Deuterium Dilution Method for Estimating Body Composition of Eider

We provide the first validation of the deuterium dilution method for indirectly measuring body composition of a sea duck, the American common eider. These predictive models required measurement of body mass, determining age and gender of each bird, and estimating total body water using the deuterium dilution method. Models from Jamieson et al. (2006) for indirectly estimating total carcass lipid (fat) of northern common eiders given body mass and structural size estimated fat mass within 32.7–38.9 g (RMSE), whereas direct measures of carcass fat mass were much more accurate (RMSE of 14.6 g). In a validation of the deuterium dilution method for estimating body composition of barnacle geese, fat mass was estimated with a relative error of 10.1% ± 10.1% while fat-free (lean) mass was estimated with a relative error of 1.2% ± 1.4% (Eichhorn and Visser 2008). Recently, McWilliams and Whitman (2013) used deuterium dilution to estimate fat and lean mass of 3 migratory passerines, with relative errors of 26.36 ± 18.6 to 34.13% ± 10.25% for fat mass and 1.96% ± 0.70% to 5.31% ± 1.55% for lean mass depending on species. Previously, Karasov and Pinshow (1998) used deuterium dilution to estimate lean mass of blackcaps (*Sylvia atricapilla*) with a relative error of 6.7% ± 1.2%. In summary, the accuracy of the deuterium-dilution models that we developed to estimate wet lean mass (~1–3%) and fat mass of eiders (~20%) are comparable to those from studies of other migratory birds including geese and songbirds (1–5% and 10–34%, respectively). Given the typical dynamics of body composition in these migratory birds, we conclude that deuterium dilution provides an adequately accurate nondestructive technique for investigating seasonal changes in lean and fat mass of eider as well as other migratory birds.

Methodological Considerations

Deuterium dilution and the associated predictive models that we presented should only be used to estimate body composition of eiders of the same subspecies (*S. m. dresseri*)

Table 3. *A priori* candidate models used to estimate wet lean mass of adult common eiders captured in Rhode Island and Massachusetts, USA, during the winters of 2011–2012 and 2012–2013. Root mean square error (RMSE g), absolute (Abs g), and relative (Rel %) errors ± standard errors (SE) are provided as indicators of model accuracy.

			Error				
Model[a]	AIC_c[b]	ΔAIC_c	**RMSE (g)**	**Abs (g)**	**SE**	**Rel (%)**	**SE**
pwat, PC1, PC2, sex	169.4		55.65	44.81	7.78	2.82	0.53
pwat, PC1, sex	176.0	6.6	51.31	41.83	7.01	2.63	0.49
pwat, mb, sex	184.1	14.7	63.13	43.53	10.78	2.73	0.70
pwat, sex	184.4	15.0	48.59	38.62	6.95	2.45	0.49
pwat, mb	194.2	24.8	64.76	43.75	11.25	2.75	0.73
mb	213.6	44.2	82.49	49.80	15.50	3.00	0.96

[a] pwat = predicted total body water given deuterium-estimated body water; [(pwat) = −97.5109 + 0.9571(deutmw)]; PC1 = first principal component; PC2 = second principal component; mb = body mass; and sex = 1 for female and 0 for male.

[b] AIC_c = Akaike Information Criterion corrected for small sample size, ΔAIC_c = differences in AIC_c from top model.

Table 4. *A priori* candidate models used to estimate wet fat mass of adult common eiders captured in Rhode Island and Massachusetts, USA, during the winters of 2011–2012 and 2012–2013. Root mean square error (RMSE g), absolute (Abs g), and relative (Rel %) errors ± standard errors (SE) are provided as indicators of model accuracy.

			Error				
Model[a]	AIC_c[b]	ΔAIC_c[c]	RMSE (g)	Abs (g)	SE	Rel (%)	SE
pwat, mb, sex	189.9	0.0	79.64	53.43	13.92	27.31	5.82
pwat, PC1, PC2, sex	191.2	1.3	122.34	72.80	23.17	34.48	8.56
pwat, mb	199.7	9.8	80.70	51.52	14.64	25.93	6.09
pwat, PC1, sex	200.5	10.6	118.41	72.48	22.07	35.07	7.63
pwat, sex	211.7	21.8	108.28	61.24	21.05	30.00	6.72
mb	215.8	25.9	88.43	52.01	16.86	23.26	4.29

[a] pwat = predicted total body water given deuterium-estimated body water; [(pwat) = −97.5109 + 0.9571(deutmw)]; PC1 = first principal component; PC2 = second principal component; mb = body mass; and sex = 1 for female and 0 for male.
[b] AIC_c = Akaike Information Criterion corrected for small sample size.
[c] ΔAIC_c = differences in AIC_c from top model.

during winter that are within the range of body masses used for the validation (1,595 g and 2,298 g) because differences could exist between different subspecies or different populations (Castro and Myers 1990). Other validation studies will be required to estimate body composition of female eiders during spring and summer because the physiological changes associated with preparations for reproduction, egg laying, and incubation (Milne 1976, Korschgen 1977, Parker and Holm 1990) may not be accurately predicted by the models that we present.

Our highest ranked models for estimating wet lean mass require measuring body mass and taking structural measures of all eiders injected with deuterium. Future investigations of eider body composition during winter are likely to be carried out over water and in challenging field conditions, thus making it difficult to accurately measure these structures in the field prior to release of captured eider. Our jackknife validation of models used to estimate wet lean mass showed no substantial differences in predicted body composition when models included or excluded the structural measures. We recommend that, whenever possible, biologists measure structural size of eiders; however, in the event that taking structural measures is not practical, our models without structural measures can be used to predict wet lean mass and fat mass with known accuracy given measures of body mass, sex, and deuterium-estimated total body water.

Size and Body Composition of American and Northern Common Eider

As expected, we found that males were on average larger, heavier, and had more total body water, and wet and dry lean mass than females. Mean wing chord, tarsus, and culmen lengths that we reported were slightly larger than those reported by Palmer (1976). The mean body mass of eider wintering in southern New England was 50 g heavier on average than the 70 northern common eiders used by Jamieson et al. (2006) to develop their predictive models of body composition. In comparison to Jamieson et al.'s (2006) source and test groups, eiders in our study had 17 g and 20.2 g more fat, 89 g and 41 g more water, and were structurally larger (i.e., wing chords were 22 mm longer, tarsus 5 mm longer, and head–bill lengths 12 mm longer) than those reported by Jamieson et al. (2006). These results confirm that American common eiders are on average heavier and larger than northern common eiders (Palmer 1976, Goudie et al. 2000).

MANAGEMENT IMPLICATIONS

Deuterium dilution provides field biologists and managers with a nonlethal method for accurately estimating the body composition of eider during winter, as well as for other migratory birds (Karasov and Pinshow 1998, Eichhorn and Visser 2008, McWilliams and Whitman 2013). Measuring the dynamics of body composition in migratory birds provides a useful way to assess habitat quality

Table 5. Final predictive models for estimating wet lean and wet fat mass of adult common eiders given predicted total body water, 2 principal components of body size, body mass, and sex based on measurements from all validation eiders ($n = 19$) collected during winters 2011–2012 and 2012–2013 in Rhode Island and Massachusetts, USA. Root mean square error (RMSE g), absolute (Abs g), and relative (Rel %) errors ± standard errors (SE) are provided as indicators of model accuracy.

		Error				
Component	Model[a]	RMSE (g)	Abs (g)	SE	Rel (%)	SE
Wet lean	$y = 209.99 + 1.2427(pwat) + 10.2941(PC1) + 2.6881(PC2) - 39.1209(sex)$	39.14	32.39	5.18	2.04	0.36
	$y = 169.45 + 1.2819(pwat) - 52.0223(sex)$	39.40	32.03	5.41	2.02	0.38
Wet fat mass	$y = -99.4324 - 1.0591(pwat) + 0.7813(mb) + 32.0247(sex)$	42.98	35.86	5.58	20.24	3.94

[a] pwat = predicted total body water given deuterium-estimated body water; [(pwat) = −97.5109 + 0.9571(deutmw)]; PC1 = first principal component; PC2 = second principal component; mb = body mass; and sex = 1 for female and 0 for male.

and effectiveness of habitat management programs that are designed to protect and conserve habitat for migrating birds (Moore and Yong 1991, Dunn 2000, Parrish 2000, Petit 2000, McWilliams and Karasov 2005). Our study demonstrates that estimating the body composition of eider during winter in southern New England provides a useful technique to evaluate effects of anthropogenic disturbance and disease.

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