Age classification of bowhead whales using recursive partitioning

JUNE G. MORITA[1] AND J.C. GEORGE[2]

Contact e-mail: june@stat.washington.edu

ABSTRACT

An algorithm was derived for using morphometric data to classify bowhead whales into three age brackets: over 90 years ('very old'); 60–90 years ('old'); and under 60 ('younger'). Recursive partitioning was applied to a subset of the data from post mortem examinations. This subset consisted of whales with higher quality data scores and with either estimated ages or characteristics of very old animals such as: near-maximum body length and baleen length; heavy scarring; and ancient weapons embedded in them. Statistical analysis suggested that for males, body length and peduncle girth provide the most useful information for this age classification. For females, anterior flipper length and body length were the key variables for classifying age. If anterior flipper length is not available for females, then body length, baleen length and peduncle girth may be used to classify age.

KEYWORDS: CLASSIFICATION TREES; MORPHOMETRIC GROWTH; BOWHEAD WHALE; POPULATION PARAMETERS; NORTHERN HEMISPHERE; ARCTIC; WHALING – ABORIGINAL; AGE DETERMINATION

INTRODUCTION

The subsistence harvest of bowhead whales (*Balaena mysticetus*) in the Bering-Chukchi-Beaufort (BCB) Seas stock provides important nutritional and cultural needs for several coastal Alaskan native communities and Russian native communities in the Chukotka region. The Alaska Eskimo Whaling Commission (AEWC) locally manages the harvest through an agreement with the US National Oceanic and Atmospheric Administration (NOAA). The hunt has been the subject of scientific scrutiny from both the US and international scientific community since the 1970s. In 1977, the International Whaling Commission (IWC) set a zero catch limit for the hunting, citing concerns about the population size and increased hunting mortality. Following this, in 1978 at an IWC special meeting, a quota system for the hunt was established. The quota was uninterrupted until 2002, gradually increasing as better information on population size and rates of increase became available (IWC, 1986, pp.17–18; 1989, p.20, p.50; 1992, pp.27–28, p.49, pp.61–62; 1995, pp.21–23, pp.73–75). However, at the 2002 IWC meeting (Shimonoseki, Japan), the quota renewal was blocked based on concerns about possible stock sub-structure within the BCB bowhead whale population (IWC, 2003, pp.18–22).

At the 2004 annual meeting of the IWC, the US committed to conducting bowhead whale stock structure research. Elements of the stock structure programme were discussed during the 2004 meeting of the IWC Scientific Committee (IWC, 2005a, pp.23–24; 2005b).

Givens *et al.* (2004) provided some of the first genetic evidence of population structuring in BCB bowhead whales. They also found evidence of age related genetic structuring termed 'generational gene shift' (GGS) and concluded that:

'As yet, it is impossible to determine if observed differences among groups are attributable to:

(1) a single stock exhibiting generational gene shift;

(2) a sub-stock harvested around St. Lawrence Island;

(3) two stocks having different temporal migration patterns past Barrow;

(4) inadequate data with small sample sizes consisting of unrepresentative whales and potentially unreliable genetic loci; or

(5) some combination of the above.'

Jorde *et al.* (2007) also found evidence of temporal genetic structure in whales migrating past Point Barrow in autumn. This structure could be related to age classes since there is stock size/age structure in both the spring and autumn migration, and the magnitude was unclear. Givens *et al.* (2010) used a larger data set, but were unable to detect multiple populations in the western Arctic bowhead whale population, although the population was distinct from those in the eastern Canada and in the Okhotsk Sea. They also did not incorporate the temporal structure suggested by Jorde *et al.* (2007).

Interpretation of genetic data from samples collected during the bowhead whale hunt is complicated by two factors: (1) the population is out of genetic equilibrium resulting from a recent history of a large reduction (from commercial whaling) followed by a rapid expansion; and (2) the hunt is known to be non-random with respect to age (smaller animals are often preferred) (Archer *et al.*, 2010). To aid in interpreting empirical data, simulations were conducted to emulate the population dynamics and the sampling. The latter required age estimates of the whales sampled (B. Taylor, pers. comm.; Martien *et al.*, 2007).

Expected patterns of genetic heterogeneity can be computed under the age model and compared to previously observed data (Archer *et al.*, 2010). Relevant cohorts for this comparison are 'very old', 'old' and 'younger' whales. The 'very old' whales were mostly born before 1909, which was near the end of commercial hunting and represents whales

[1] *Principal Lecturer, Department of Statistics, University of Washington, WA 98195-4322, USA.*
[2] *Wildlife Biologist, North Slope Borough, Department of Wildlife Management, Box 69, Barrow, Alaska 99723, USA.*

with a genetic structure which pre-dates the potential genetic bottleneck caused by commercial whaling. It is estimated that the whales in this group were believed to be at least 90 years old when harvested. 'Old' whales are defined to be between 60 and 90 years in age. All others are 'younger' whales.

More generally, age classification based on basic morphometric data can provide valuable input to models and analyses that rely on age information for bowhead whales lacking more direct estimates of age. The research summarised in this paper was motivated by such bowhead whales.

METHODS

A subset of the bowhead whale harvest database maintained by the North Slope Borough (1976–2005) was used. The variables included in this study were: whale identification code; an assessment of the data quality; sex; body length; length of longest baleen plate; testis length; anterior flipper length; peduncle girth; white peduncle patch; white eyebrow; corpora count; estimated age; aging technique; and verbal comments describing other characteristics of note. In addition, ratios of morphometric measurements were also included. These were peduncle girth/body length, anterior flipper length/body length, peduncle girth/anterior flipper length and baleen length/body length.

A subset, with 74 females and 49 males, was selected according to the following criteria. Whales were included that had the highest data quality scores (1 and 2; scale 1–5), estimated age or age category, and data on at least two morphometric measurements. Due to the small number of 'very old' whales, and because the goal was to classify whales into the three age cohorts of Martien *et al.* (2007), whales were also included in the dataset that did not have estimated ages, but that were believed to be particularly old based on verbal comments from scientists and hunters. Suitable comments included 'stone point in blubber' since it is acknowledged that hunting with stone harpoon points ceased in ~1880 with the advent of alternative weapons for hunting. Thus a whale with a stone point in its blubber must have been very old, and certainly alive before 1909. Whales with extreme corpora counts (e.g. whale 89B3, with corpora count 41) or testes sizes (e.g. whale 95B7, testis length 110 cm) also were classified as 'very old'.

Recursive partitioning (Clark and Pregibon, 1992) is a statistical method for classifying multivariate data points into categories; in the case of this study, age is divided into three bins referred to hereafter as age classes. The ability to predict membership in more than two categories gives recursive partitioning a critical advantage over categorical data methods (such as logistic regression) that only apply to two categories (Neter and Wasserman, 1974). The input covariate data may be qualitative or quantitative. The output dependent variable is categorical.

The recursive partitioning-algorithm creates a classification tree by a series of binary splits of the data based on covariate values. At each branching node of the tree, the data are partitioned into two subgroups based on a binary split at a selected value and covariate. The covariate and the splitting value for a node are selected to maximise the impurity reduction, which is measured as the sum over category '*i*' of the simple Gini index $f(p_i) = p_i(1 - p_i)$ (Breiman *et al.*, 1984). Here p_i is the proportion of individuals placed into category '*i*' that actually belong in category '*i*'. For example, if individuals A1, A2, A3, B1 and B2 are split into group A = {A1,A2} and group B = {A3,B1,B2} then the value of the Gini index would be $(1)(1 - 1) + (2/3)(1 - (2/3)) = 0.22$. If all individuals at a node are correctly categorised, then the impurity is zero. Ideally, the final subgroups at the end of the splitting process would each contain individuals from only one of the categories.

In recursive partitioning a tree can be 'grown' and/or 'pruned'. In addition, to limit overspecification, *minsplit* is a parameter that can be set as the minimum number of observations that must exist in a node, in order for a split to be attempted (Therneau and Atkinson, 2006, function *rpart.control*). For this study, *minsplit* = 5 was used. Pruning is the removal of nodes to simplify a tree (Breiman *et al.*, 1984). For the present analysis the trees branched on only a small number of variables, resulting in simple trees (see Figs 1–3), therefore pruning was not needed.

Using recursive partitioning, individuals with only partial information can be included. Any individual with missing information for some covariate(s) is not used in setting the

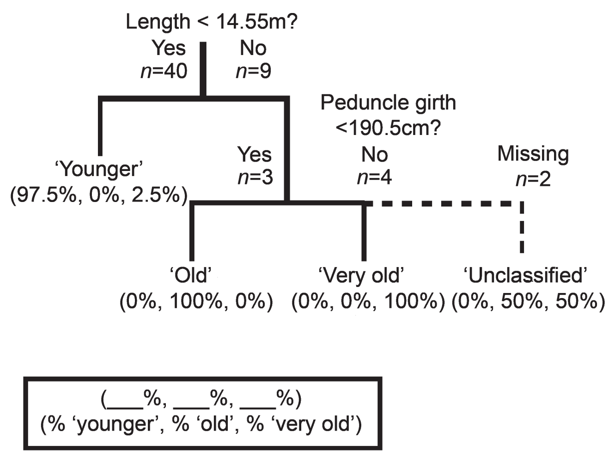

Fig. 1. Partition for age classification of male bowhead whales using body length and penduncle girth.

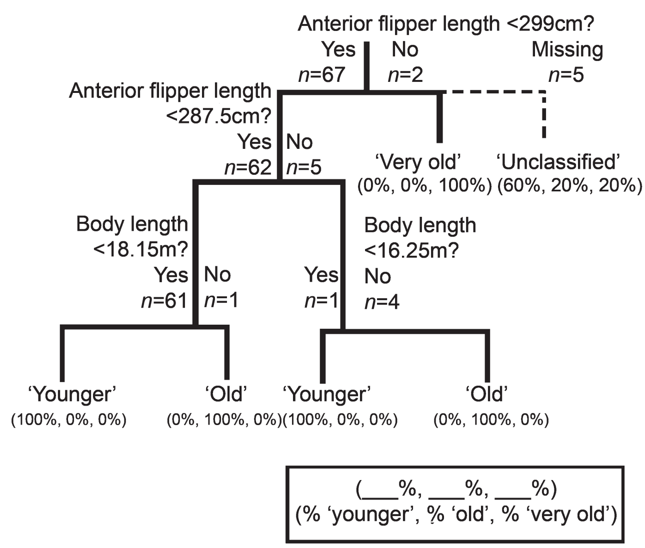

Fig. 2. Partition for age classification of female bowhead whales using anterior flipper length and body length.

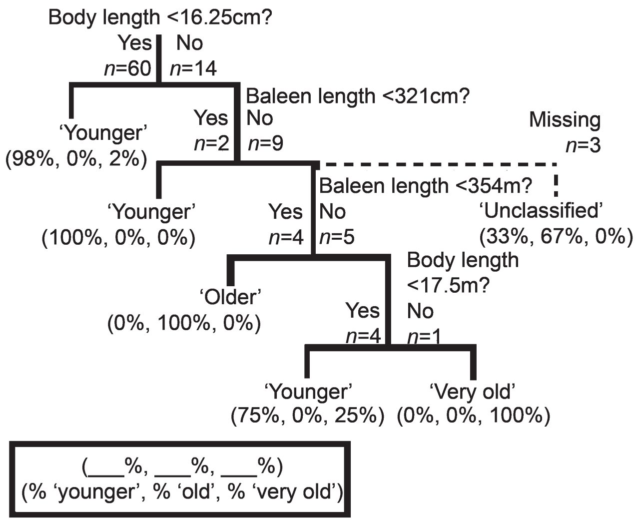

Fig. 3. Partition for age classification of female bowhead whales using body length, baleen length and penduncle girth.

split value for covariate(s) that it is missing, but that individual is included in setting the split values when the relevant covariate data are available. That is, if the peduncle girth measurement for a whale is available, but baleen length is missing, then that whale would be included in setting a split value based on peduncle girth, but could not be used in setting a split value based on baleen length. If a whale is missing a covariate value at any node of the classification tree, then it is classed as 'unclassified'.

Recursive partitioning was implemented using the *rpart* algorithm in the R statistical package (Therneau and Atkinson, 2006). Males and females were analysed separately because growth curves differ noticeably for the two sexes of bowhead whales (Lubetkin *et al.*, 2012); one goal of the study was to partition these whales into age categories based on morphometric measurements that vary with sex (Lubetkin *et al.*, 2012). Separate models are appropriate.

Cross validation provides an assessment of how well a procedure will perform on future data. Assessment of whether a whale is classified correctly via partitioning is based on the estimated age or age class in the data set. For brevity herein this is termed 'actual' age class. 'Leave-one-out cross validation' was used to assess the recursive partitioning modelling algorithm for these data. A partition is computed on the full data set, excluding one observation. It is then determined whether the resulting partition correctly classifies the excluded observation. This process is iterated for each observation in the data set. In addition, the resulting partitions were compared to see how they varied with the slightly reduced data sets. Leave-one-out cross validation is computationally time consuming for large data sets, but feasible for the present data.

Ovarian corpora counts are likely good predictors of age for females (George *et al.*, 2011). Graphical data exploration suggests that females were categorised less successfully than are the males using the variables at hand, except for corpora counts. In the current data set, the age values of many of the females, and of all of the older females, were estimated based on corpora counts. Therefore, it would be circular and not valid to use corpora counts for determining the age class of females.

RESULTS

Males

Based on recursive partitioning of the 49 male bowhead whales in the data set, the initial division was based on body length. The 40 whales with body length less than 14.55m were classified as 'younger'. All 39 of the whales with estimated ages less than 60 years were successfully partitioned off in this step. The longer whales (length at least 14.55m) were classified at this point as 'very old'. This group subsequently underwent a second split based on peduncle girth. The three whales with peduncle girth <190.5cm were reclassified as 'old' (aged 60–90 years), and the four with peduncle girth >190.5cm remained classified as 'very old' (aged over 90 years). Thus all four whales classified as 'very old' and all three classified as 'old', were correctly identified at this final step. In this group of longer whales, one 'very old' and one 'old' were missing peduncle girth data and therefore were 'unclassified'. The classification algorithm consisting of these two splits, based on body length and peduncle girth, correctly classified all but one of the 47 male whales in the data set that had body length less than 14.55m, peduncle girth recorded or both.

The one 'very old' whale (95B16) that was not classified correctly measured 14.1m in length with a peduncle girth of 169cm. It was noticeably the smallest 'very old' whale. The others measured from 15.2 to 17.7m in length, with peduncle girths from 193 to 230cm. Whale 95B16 was aged via aspartic acid racemisation (George *et al.*, 1999) to be 91 years (standard error = 16 years) and was at the low end of the 'very old' age category. The field notes for whale 95B16 were done later and said 'morphometric data suspect' because the examiners were inexperienced – thus in further analyses, this whale should probably be excluded from the dataset.

The classification tree is displayed in Fig. 1 and summarised in Table 1. In interpreting Fig. 1, it can be seen that in the leftmost end node, the partition has classified 40 whales as 'younger'. The vector (97.5%, 0%, 2.5%) under the corresponding end node indicates that 97.5% (39 out of 40) of these whales were estimated to be 'younger'. Similarly 0% (0 out of 40) were estimated to be 'old' and 2.5% (1 out of 40) were estimated to be 'very old'. The vectors under the other end nodes similarly give the age classification percentages.

Empirical probabilities (proportions) are also given in the Table 1. They are *P*('actual' class *i*|partitioning based class *j*). For example, the 40 whales classified via partitioning as 'younger' (up to 60 years) are represented in the 'younger' row for age class via partitioning; 39 of them were actually 'younger' and one was actually 'very old' (over 90 years). Thus, in the 'younger' partitioned row of Table 1, 39 of 40, or 97.5% of the whales were actually 'younger'. This was similar for the other age classes too.

Graphical displays of the data are useful for evaluating the validity of the partitioning results. Fig. 4 shows body length versus peduncle girth for the 47 male bowhead whales with sufficient data to be classified. The points are coded by age class. It is readily apparent from this plot that body length and peduncle girth would be good predictors for age class. The dotted lines added to the plot indicate the subgroupings from the recursive partitioning algorithm. Whales with points

Table 1

Empirical classification counts for male bowhead whales, based on body length and peduncle girth.

Age class via partitioning	'Actual' (estimated) age class			
Count (% within estimated age class)	Under 60 years 'younger'	60–90 years 'old'	Over 90 years 'very old'	Total
Under 60 years 'younger'	39 (97%)	0 (0%)	1 (2.5%)	40
60–69 years 'old'	0 (0%)	3 (100%)	0 (0%)	3
Over 90 years 'very old'	0 (0%)	0 (0%)	4 (100%)	4
Unclassified due to missing data	0 (0%)	1 (50%)	1 (50%)	2
Total	39	4	5	49

to the left of the vertical dotted line were classified as 'younger'. The crosses indicate the whales that actually were 'younger'. From Fig. 4 it can be seen that all of the 'younger' whales were correctly classified by the recursive partitioning algorithm. Whales with points to the right of the vertical dotted line and below the horizontal dotted line were classified as 'old'. The circles indicate the whales that actually were 'old'. Whales 95B7 ('very old') and 83G1 ('old') are missing from the plot since their peduncle girth measurements are missing. The algorithm classified all whales in the upper section of the plot as 'very old'. The whales classified in the data set as 'very old' correspond to the triangular plot points. The triangular point outside this region corresponds to a 'very old' whale classified as 'younger' by recursive partitioning.

Cross validation analysis for males yielded that six of the 49 leave-one-out iterations resulted in misclassifications and two resulted in 'unclassified' status due to missing data. In the full dataset procedure, one of the 49 whales was misclassified and two were unclassified (see Table 3). The resulting classification tree was the same as that from the full data results in 44 of the 49 leave-one-out runs. In four of the remaining five runs, the cut-off values differed slightly (differences of up to 0.25m for length and up to 5.5cm for peduncle girth). All the misclassified individuals were 'near the border'. These data partition so finely that leaving one out along the boundary between adjacent categories could result in a slight shift in the algorithm's cut-off values, causing the left-out observation to be misclassified into the adjacent category. This would not be surprising in any data set, especially in this analysis where some age classes have few members.

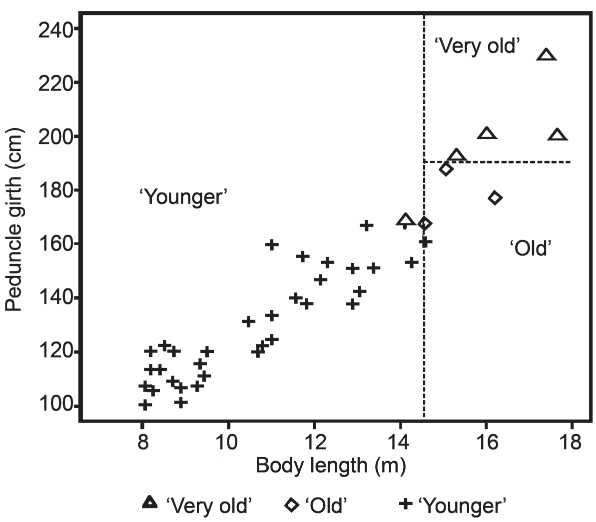

Fig. 4. Body length versus penduncle girth for 49 male bowhead whales.

Females

For the 74 female whales in the data subset, the first two binary splits were based on anterior flipper length. The first is at 299cm, and the second at 287.5cm. Five of the 74 females were missing anterior flipper values and therefore could not be classified. Further divisions within the resulting groups of the remaining 69 whales classify individuals based on body length. Within the 287.5–299cm flipper length group, individuals at least 16.25m in length were classified as 'old' (60–90 years). The shorter individuals were classified as 'younger' (under 60 years). Within the <287.5cm flipper length group, individuals that were at least 18.15m in length were classified as 'old' (60 to 90 years). Again, the shorter individuals were classified as 'younger' (under 60 years). The resulting classification tree is shown in Fig. 2. It yielded perfect classification for the 69 female whales having anterior flipper data.

In recognition that not all whales have anterior flipper length measurements, which was the first variable used in this classification tree, a second binary tree was made for when this information was unavailable. The resulting tree (Fig. 3) used body length at the first split and then baleen length. Classification results are summarised in Table 2. This tree yields correct classifications for 69 of the 71 whales in

Table 2

Empirical classification counts for female bowhead whales, based on body length and peduncle girth.

Age class via partitioning	'Actual' (estimated) age class			
Count (% within estimated age class)	Under 60 years 'younger'	60–90 years 'old'	Over 90 years 'very old'	Total
Under 60 years 'younger'	64 (97%)	0 (0%)	2 (3%)	66
60–69 years 'old'	0 (0%)	4 (100%)	0 (0%)	4
Over 90 years 'very old'	0 (0%)	0 (0%)	1 (100%)	1
Unclassified due to missing data	1 (33%)	2 (67%)	0 (0%)	3
Total	65	6	3	74

Table 3

Cross-validation results for male bowhead whales. Available numerical age estimates given for misclassified whales.

Age class via partitioning	‘Actual’ (estimated) age class			
Count (% within estimated age class)	Under 60 years ‘younger’	60–90 years ‘old’	Over 90 years ‘very old’	Total
Under 60 years ‘younger’	38	1	1	40
60–69 years ‘old’	1 (58 years)	1	2 (160 years)	4
Over 90 years ‘very old’	0	1	2	3
Unclassified due to missing data	0	1	1	2
Total	39	4	6	49

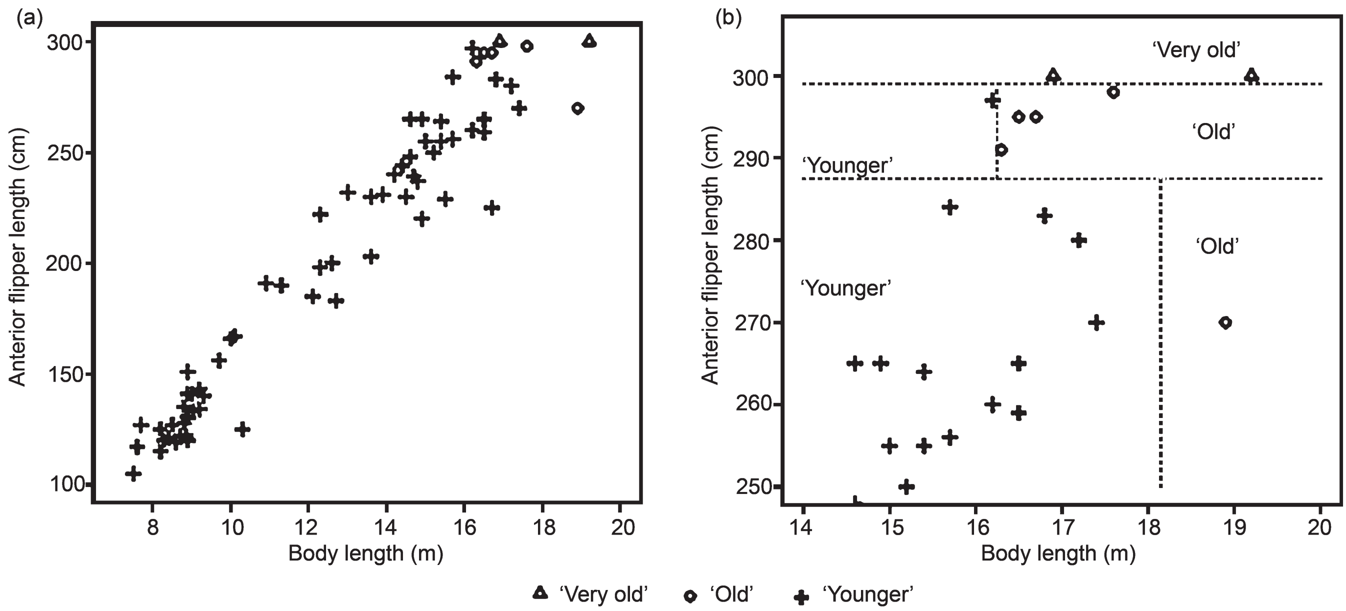

Fig. 5a. Anterior flipper length versus body length for 74 female bowhead whales.
Fig. 5b. Anterior flipper length >250cm versus body length >14m for female bowhead whales.

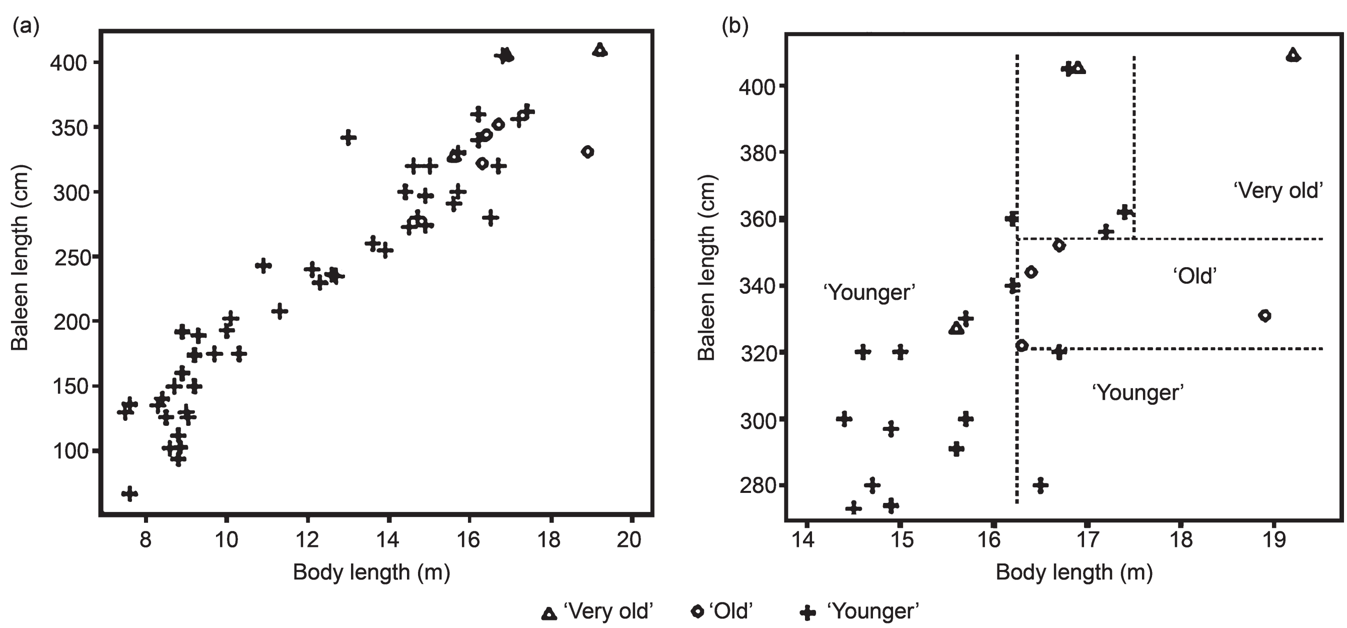

Fig. 6a. Body length versus baleen length for 74 female bowhead whales.
Fig. 6b. Body length >14m versus baleen length >275cm for female bowhead whales.

the data set having body length <16.25m, baleen lengths recorded or both.

Graphical evaluation of the results for the 69 female whales with anterior flipper length in the data set in Fig. 5a shows anterior flipper length versus body length, corresponding to the main recursive partitioning algorithm. Fig. 6a shows body length versus baleen length for these whales. These are the primary variables used in the back-up partitioning algorithm for the case when anterior flipper length was unavailable. Fig. 5b and 6b focus on the upper ranges of the displayed variables to show the partitions more clearly.

Cross validation analysis for the females using anterior flipper length and body length yielded three misclassifications in the 74 leave-one-out iterations. These corresponded to whales 82WW1, 92B2 and 92B4. The two misclassifications in the original runs were whales 92B2 and 03B9. Whales 82WW1 and 92B4 both had two of the four longest anterior flipper measurements, 298cm and 297cm, respectively. In the runs when these whales were left out, the initial split was not made that separated off the whales with longest anterior flipper length. Whale 92B2's short body length resulted in its consistent misclassification. It was shorter than all of the whales assigned to the 'old' age class, and shorter than 15% of the whales assigned to the 'younger' age class.

DISCUSSION

With so few whales in the 'very old' and 'old' age classes, it is not surprising to have slight shifts in the classification trees when one of them is removed from the data set. Changes in the classification trees and in the misclassification rates from the leave-one-out iterations were minor. The recursive partitioning algorithm appears to function well and to give reasonably stable results for age classification of the data set of bowhead whales considered.

In assessing the accuracy of the recursive partitioning algorithm for age classification, it was assumed that the age class assigned to each whale in the data set was accurate. In fact, the age classes are based on age estimates from a variety of estimation procedures including corpora counts for females, aspartic acid racemisation and field notes. Incorrect age classifications in the data set would impact the numerical assessments of the effectiveness of recursive partitioning for these data. In Tables 1 and 2 'Actual' (estimated) age class are referred to.

The recursive partitioning algorithm performs well in identifying age classes for these bowhead whales, achieving a 97–100% correct classification result for whales with key data recorded. Leave-one-out cross validation results indicate that the algorithm is reasonably stable.

These analyses were based on small sample sizes and the data in the upper age range were sparse. Several of the oldest whales did not have numerical estimates for age, but based on qualitative findings (e.g. heavily scarred) were deemed to be 'very old'. The results therefore have limited reliability, especially in the upper age range. The small numbers of 'very old' and 'old' whales likely increase sensitivity of the estimated threshold values at tree nodes, especially for those age classes of particular interest.

There are substantially more data for the younger age classes; hence, richer models could be developed for those animals (Lubetkin *et al.*, 2008; Lubetkin *et al.*, 2012). Such models could potentially yield numerical estimates of ages rather than relying on age classes and will be a subject of further research. The use of age classes in this analysis was appropriate in the present study since a primary concern was with the detection of 'very old' whales.

The morphological growth patterns are of some interest. For females, an allometric relationship was found and that suggests the pectoral limbs (flippers) for very old females are disproportionately larger than younger whales of similar body length. For males, body length and peduncle girth provide the most useful information for age classification. The latter suggests that the caudal region of old males is more robust than younger males of similar length. The evolutionary significance of these growth patterns (for both males and females) are unknown.

ACKNOWLEDGEMENTS

We acknowledge the efforts of the Alaska Eskimo Whaling Commission to secure funding for the bowhead stock structure studies. We are grateful to the former Alaska Senator Ted Stevens for his support of these studies, and Stanley Speaks with the Bureau of Indian Affairs for helping secure additional funding (through BIA) for this project. We appreciate the contributions of the research staff who have helped with this and other bowhead whale research at (alphabetically) the Alaska Fisheries Science Center, Colorado State University Statistics Department, North Slope Borough Department of Wildlife Management, Southwest Fisheries Science Center, Texas A&M University Genetics, University of Washington Statistics Department. We thank the whale hunters of Alaska and Russia for their collaboration and support. The suggestions of our colleagues in Norway, Russia, and Japan have contributed greatly to the bowhead whale stock structure research program. Review and comments by Marina Meila, Department of Statistics, at the University of Washington and anonymous reviewers led to improvements in this paper.

REFERENCES

Archer, F.I., Martien, K.K., Taylor, B.L., LeDuc, R.G., Ripley, B.J., Givens, G.H. and George, J.C. 2010. A simulation-based approach to evaluating population structure in non-equilibrial populations. *J. Cetacean Res. Manage.* 11(2): 101–14.

Breiman, L., Friedman, J.H., Olshen, R.A. and Stone, C.J. 1984. *Classification and Regression Trees*. Chapman and Hall, New York. 368pp.

Clark, L.A. and Pregibon, D. 1992. Tree-based models. pp.377–419. *In*: Chambers, J.M. and Hastie, T.J. (eds). *Statistical Models.* Chapman and Hall, New York. 608pp.

George, J., Follmann, E., Zeh, J., Sousa, M., Tarpley, R., Suydam, R. and Horstmann-Dehn, L. 2011. A new way to estimate the age of bowhead whales (*Balaena mysticetus*) using ovarian corpora counts. *Can. J. Zool.* 89(9): 840–52.

George, J.C., Bada, J., Zeh, J., Scott, L., Brown, S.E., O'Hara, T. and Suydam, R. 1999. Age and growth estimates of bowhead whales (*Balaena mysticetus*) via aspartic acid racemization. *Can. J. Zool.* 77: 571–80.

Givens, G.H., Bickham, J.W., Matson, C.W. and Ozaksoy, I. 2004. Examination of Bering-Chukchi-Beaufort Seas bowhead whale stock structure hypotheses using microsatellite data. Paper SC/56/BRG17 presented to the IWC Scientific Committee, July 2004, Sorrento, Italy (unpublished). 34pp. [Paper available from the Office of this Journal].

Givens, G.H., Huebinger, R.M., Patton, J.C., Postma, L.D., Lindsay, M., Suydam, R.S., George, J.C., Matson, C.W. and Bickham, J.W. 2010. Population genetics of bowhead whales *(Balaena mysticetus)*: Regional differentiation but no structure within the western Arctic. *Arctic* 63: 1–12.

International Whaling Commission. 1986. Chairman's Report of the Thirty-Seventh Annual Meeting. *Rep. int. Whal. Commn* 36:10–29.

International Whaling Commission. 1989. Chairman's Report of the Fortieth Meeting. *Rep. int. Whal. Commn* 39:10–32.

International Whaling Commission. 1992. Chairman's Report of the Forty-Third Meeting. *Rep. int. Whal. Commn* 42:11–50.

International Whaling Commission. 1995. Chairman's Report of the Forty-Sixth Annual Meeting. *Rep. int. Whal. Commn* 45:15–52.

International Whaling Commission. 2003. Chair's Report of the Fifty-Fourth Annual Meeting. *Ann. Rep. Int. Whaling Comm.* 2002:1–53.

International Whaling Commission. 2005a. Report of the Scientific Committee. *J. Cetacean Res. Manage. (Suppl.)* 7:1–62.

International Whaling Commission. 2005b. Report of the Scientific Committee. Annex F. Report of the Sub-Committee on Bowhead, Right and Gray Whales. *J. Cetacean Res. Manage. (Suppl.)* 7:189–208.

Jorde, P.E., Schweder, T., Bickham, J.W., Givens, G.H., Suydam, R. and Stenseth, N.C. 2007. Detecting genetic structure in migrating bowhead whales off the coast of Barrow, Alaska. *Mol. Ecol.* 16(10): 1993–2004.

Lubetkin, S.C., Zeh, J., Rosa, C. and George, J.C. 2008. Age estimation for young bowhead whales (*Balaena mysticetus*) using baleen growth increments. *Can. J. Zool.* 86: 525–38.

Lubetkin, S.C., Zeh, J.E. and George, J.C. 2012. Statistical modeling of baleen and body length at age in bowhead whales (*Balaena mysticetus*). *Can. J. Zool.* 90: 915–31.

Martien, K.K., Archer, E. and Taylor, B. 2007. Genesis of simulated genetic data and sampling to emulate empirical bowhead whale samples. Paper SC/J07/AWMP5 presented to the Bowhead *Implementation Review* intersessional meeting, Seattle, 12–16 January 2007 (unpublished). 6pp. [Paper available from the Office of this Journal].

Neter, J. and Wasserman, W. 1974. *Applied Linear Statistical Models*. Richard D. Irwin, Inc., Homewood.

Therneau, T.M. and Atkinson, B. 2006. *rpart: Recursive Partitioning. R package version 3*. 34pp. [Available from: *http://CRAN.R-project.org/package=rpart*].