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Sex identification and age estimation of bobcats and implications for management

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Abstract

Predictions obtained from wildlife population models may be prone to influences associated with the quality of the data available for parameterization. We assessed accuracy of furtaker-assigned sex of bobcats (*Lynx rufus*; $n = 123$) harvested during 2017–2018 across the western USA by comparing those data to genetically assigned sex, the latter of which we assumed was 100% accurate. We also compared the precision of individual age estimates obtained through cementum annuli analysis (CAA) of the canines and incisors of harvested bobcats ($n = 151$), where true age was unknown. Because cementum-line deposition may vary across populations and by sex, we hypothesized that environmental factors may affect precision of age estimates obtained via CAA. Sex of bobcats as reported by furtakers was accurate 82% of the time, and the direction of sex-assignment error was approximately equivalent. Canine teeth were more precise than incisors for estimating age, age estimates for male bobcats may be more precise than for females, and precision of age estimates may decrease with age. However, use of incisors corrected with known rates of error may be preferred in some instances, such as studies that require live capture and tooth extraction or where assignment to age class is sufficient. In addition, we found that sex, median age, and mean elevation may influence precision of age estimates, whereas mean precipitation and geographic location (latitude, longitude) were uninformative. Knowledge of different types of errors associated with sex

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identification and age estimation may be integrated into population modeling efforts based on management objectives.

KEYWORDS

Age determination, bobcat, cementum annuli, harvest management, *Lynx rufus*, population modeling, sex determination

Wildlife management has evolved over recent decades to rely on complex statistical approaches for modeling population trends (Bauer et al. 2015). However, as with any modeling effort, it is important to identify which datasets are most influential to the outcome, and to determine the associated level of parameter uncertainty, so that data quality can be considered in conjunction with specific management objectives (Riggio et al. 2016). For wildlife agencies tasked with managing harvests, ensuring that harvest levels are sustainable (or are otherwise meeting management objectives) is a high priority, including for furbearer management (Hiller et al. 2021*a*). Linking harvest data with population trends, and sustainable levels of harvest, via statistical population reconstruction (SPR) has become an increasingly popular tool for managing consumptive utilization (Gove et al. 2002, Broms et al. 2010, Sturludottir et al. 2018).

Quality and quantity of both harvest and auxiliary data are key to producing precise and unbiased model outputs. Harvest data collected from large mammals in the western USA are arguably among the most comprehensive datasets available (Carpenter 2000, Bleich and Thompson 2018) and therefore, presumably provide robust modeling predictions (French et al. 2020). Although types of data collected vary by jurisdiction and by species, the age and sex of harvested individuals are among the most common variables, and both are fundamental components for several approaches to modeling populations, such as reconstructing populations using SPR (Skalski et al. 2005, Conn et al. 2008). However, little work has been done to assess the quality of harvest data commonly used in SPR modeling, in particular, the levels of uncertainty associated with particular types of data. Within the western USA, some furbearer management programs include collection of species-specific data that may vary in quality and quantity, thereby lending themselves to finer-scale exploration of the influence of dataset components on modeling outcomes (Hiller et al. 2018, Hiller et al. 2021*a*).

Bobcats (*Lynx rufus*) are among the furbearing species for which comprehensive harvest data have been collected for decades by many state fish and wildlife agencies. Efforts for data collection increased starting ca. 1977, which coincided with the species' listing under Appendix II of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES; Federal Register 1977). Although the listing has been challenged on the basis that bobcats do not meet the CITES listing criteria that its wild populations are adversely impacted by international trade (Association of Fish and Wildlife Agencies 2014), the resultant datasets have proven beneficial from a management standpoint by providing a biological basis for monitoring long-term population trends for this species.

As a charismatic carnivore, bobcats also serve to illustrate the increasing sociopolitical pressures associated with harvest of furbearers, and how these pressures increasingly are influencing management decisions (Creel et al. 2015, Hiller et al. 2021*b*). To help ensure that management decisions are informed and defensible, a better understanding of errors in biological parameters such as sex identification and age estimation is necessary. The magnitude and direction of such errors could influence model outputs, and therefore have direct bearing on harvest-management decisions, including levels of harvest (Hiller et al. 2014). Further, from a research standpoint, when data collection includes age estimation of live bobcats, knowledge of precision between age estimates derived from standard (canine) and nonstandard (incisor) tooth types is beneficial. This may be particularly useful when use of a nonstandard tooth type may reduce the potentially negative impacts of tooth extraction (e.g., potentially reduced ability of the released carnivore to deliver a killing bite; Van Valkenburgh 1996).

Our objective was to provide managers and researchers with quantifiable levels of uncertainty for integration into contemporary large-scale population modeling efforts for bobcats. Specifically, we quantified uncertainty associated with sex assignment (reported by furtakers [i.e., trappers and hunters] versus genetically determined) and age estimation (based on cementum annuli analysis of repeated samples), and an evaluation of factors that affect precision of age estimates for bobcats harvested in the western USA.

STUDY AREA

Our study was conducted with samples obtained from Arizona, Kansas, North Dakota, Oregon, South Dakota, Utah, and Wyoming, USA (hereafter, western USA). Our study area spanned a range of >2,300 km linearly west to east (longitude = −124.158 to −94.8425) and >1,600 km linearly north to south (latitude = 32.73013 to 47.36161). Physical topography and climate among states varied considerably, from Sonoran Desert in the south (AZ) to Pacific Northwest temperate rain forest in the west (OR) to the Great Plains (KS, ND, SD). Elevations ranged from 206 m (OR) to 2,450 m (UT). Temperatures and precipitation varied within and among states. Mean minimum temperatures ranged from lows of −1.5°C primarily east of the Rocky Mountains (parts of ND, SD, WY, but also highest elevations of UT) to 9.9°C in desert areas (AZ). Mean maximum temperatures ranged from 11.9°C (highest elevations of UT) to 24.6°C (Mojave Desert of AZ). Lowest mean annual temperatures (≤10°C) were predominately in high-elevation canyon lands (ND, SD, UT, WY) and high deserts (OR). Highest mean annual temperatures (>15°C) occurred in AZ. Mean annual precipitation varied widely, from a low of <30 cm (AZ, UT, high deserts of southeastern OR), to intermediate amounts of >100 cm (parts of KS), to the highest amounts of 146–315 cm (temperate rain forests of the Coast Range in western OR).

METHODS

Sample collection

We contacted several state fish and wildlife agencies in the western USA with programs of either voluntary or mandatory collection of mandibles from harvested bobcats and requested samples collected during the 2017–2018 season. For state agencies that did not collect harvest data, we directly contacted state trapping associations and individual furtakers and requested mandibles in accordance with respective state regulations through coordination with the appropriate state fish and wildlife agencies. We requested that agencies and furtakers, if possible, submit samples that were distributed among multiple counties within a state. With each mandible, we requested information about location of harvest (state, county or management area), sex of bobcat, and date of harvest (mo, yr). Our study was designed to replicate the data collection process used by many state agencies to support decisions related to management of bobcats (and certain other harvested furbearing species). We received and processed uncleaned mandibles of 156 bobcats harvested from the western USA (AZ [$n = 15$], KS [$n = 27$], ND [$n = 12$], OR [$n = 21$], SD [$n = 25$], UT [$n = 24$], WY [$n = 32$]) during the 2017–2018 season (Figure 1). After excluding individuals with missing data (i.e., sex not reported by furtakers, missing canine or incisor), our dataset included 123 and 151 individuals for assessment of sex and age, respectively.

Sex assignment and accuracy

To verify the sex of each bobcat, we extracted DNA from tissue samples of each mandible using the DNeasy Blood and Tissue Kit (Qiagen, Valencia, CA, USA) and performed a PCR test developed specifically for felids that targets

FIGURE 1 Geographic distribution of mandible samples collected from harvested bobcats (*Lynx rufus*) in 7 states in the western USA, during 2017–2018. Dots indicate approximate locations of ≥1 sample/county.

the amelogenin gene region (Pilgrim et al. 2005). The 10 µL PCR reactions contained 1× PCR buffer with 2 mM $MgSO_4$, 0.2 mM each dNTP, 1 µM each forward and reverse primer, 1.5 mg/mL BSA, 0.5 U IDProof polymerase (ID Labs, London, ON, Canada), and 20 ng of template DNA. The PCR profile was 94°C/5 min, (94°C/1 min, 51°C/1 min, 72°C/30 s) × 35 cycles, 72°C/7 min. We visualized the PCR products on 2% agarose gels with SYBR Safe stain (Invitrogen, Carlsbad, CA, USA). Because the Y-chromosome copy of the amelogenin gene has a 20-base-pair (bp) deletion when compared with the X-chromosome copy, females produced a single band (194 bp), whereas males produced 2 bands (194 bp and 214 bp).

To check data quality, we randomly repeated the testing procedure for 28 samples and found a 100% match to the original assignments. In addition, Hiller et al. (2014) found that the amelogenin PCR test we used provided results in bobcats completely concordant with an independent PCR test that targets the zinc-finger region. Thus, we assumed the genetic sexing test provided the correct assignment and calculated error rates of field sex identification. We performed likelihood-ratio chi-square tests in SAS 9.4 (SAS Institute, Cary, NC, USA).

Age estimation

We processed collected bobcat mandibles for age determination using cementum annuli analysis (CAA) at a laboratory (Matson's Laboratory, Manhattan, MT, USA). We soaked mandibles overnight in a Tergazyme® (Alconox, White Plains, NY, USA) solution and cleaned them in a warm-water bath. From each sampled bobcat, both lower canines (C1) and both lateral incisors (I3) were extracted and decalcified in HCl, fixed in formalin, embedded using the paraffin method (Presnell and Schreibman 1997), and sectioned at 14 µm using a microtome (Model RM 2155; Leica Biosystems, Buffalo Grove, IL, USA). Sectioned samples were mounted to slides, stained (Giemsa stain, RICCA Chemical Co., Arlington, TX, USA), and cover-slipped for microscopic examination. Age determinations were assigned in accordance with the Matson's Laboratory North American bobcat canine model (Matson 1981; Matson's Laboratory, Manhattan, MT, USA, unpublished data). Each tooth type was randomly assigned a lab code, and ages were assigned independently by C. Nistler, after microscopic examination with a compound microscope (Model DM750; Leica Biosystems, Buffalo Grove, IL, USA).

Precision of age estimates

We assessed precision of age estimates using CAA for canines and incisors by calculating the mean of the absolute difference between paired samples for each tooth type and estimating the corresponding 95% confidence limits (CLs) using bootstrapping methods and the boot package (Davison and Hinkley 1997, Canty and Ripley 2019) in Program R (version 3.6.0; R Core Team 2019). We used a descriptive approach to evaluate estimates within tooth type and examined 95% CLs for a comparison between tooth types. For the latter, we assumed a difference existed if 95% CLs did not overlap.

We used a Bland-Altman approach modified for replicated measurements (Bland and Altman 1986, 1995, 1999; Carstensen 2004; Carstensen et al. 2008). The Bland-Altman approach is useful for comparing 2 measurement techniques, including through limits of agreement (i.e., interval within which 95% of the differences between measurements obtained by both methods lie) between the techniques to evaluate bias between mean differences (Giavarina 2015). In general, if the 95% CL for the mean difference does not contain zero there is evidence to suggest a difference (or a bias) between ages estimated using canines and incisors. The use of limits of agreement can only inform whether the 2 methods agree with each other, and not which method (if any) is more accurate. We used the MethComp package in Program R to calculate limits of agreement (Carstensen et al. 2017).

Factors affecting precision of age estimation among teeth

Cementum-line deposition and other dental characteristics may vary due to several factors, including by sex, and within and among populations (Harshyne et al. 1998, Costello et al. 2004, Asmus and Weckerly 2011, Matson's Laboratory 2021*a*), and therefore potentially affect precision of age estimates. Populations of widespread species in northern latitudes may have more distinct cementum annuli compared to those in southern latitudes, which may be associated with the former experiencing more prevalent seasonal resource availability, seasonal climatic conditions, and other factors affecting individual energetic requirements (Matson's Laboratory 2021*a*). Therefore, we hypothesized that, in addition to potential differences between sexes, precision associated with age estimation would vary based on geographic and environmental factors. For example, we hypothesized that precision would be lower in locations of lower productivity (e.g., low precipitation, high temperatures) and weaker seasonal patterns (e.g., lower elevations, lower latitudes). Given that precision may also vary geographically in populations, we also explored the potential of latitude and longitude affecting precision. Although the biological implications of geographic location (particularly longitude) may be unclear, if a relationship exists with precision, this knowledge may have management implications both within (e.g., age estimates are relatively poor within a particular management unit or portion of a state) and across (e.g., age estimates are relatively poor in ≥1 potentially unique area within the western USA) states. Based on our hypotheses, we developed a set of independent variables to explore factors that may affect precision of age estimates among teeth.

Location data for our samples were based on area (county or management unit within a state) of harvest. To incorporate location data, we calculated the centroid of each area and used each of latitude and longitude in decimal degrees as independent variables. We used annual minimum, mean, and maximum temperature data, where each was an average of all daily values within a given year from 2010 to 2017 (PRISM Climate Group, http://prism.nacse.org/recent/monthly.php). We also used total annual precipitation for the same time period (PRISM Climate Group, http://prism.nacse.org/recent/monthly.php). Each of the 4 basic climate elements were available in raster format at 800-m resolution. We calculated cell averages for each of the 4 basic elements over the 8-yr time period, which resulted in 1 raster/element. Then we calculated the mean value for each element within each area and used those values as our independent variables. Finally, we used elevation data (PRISM Climate Group, http://prism.nacse.org/normals/) in raster format (4-km resolution) and also calculated the mean value for each area. Additionally, we used independent variables associated with sex (male or female, based on DNA assignment), and the median value of the 4 age estimates for each individual. We used ArcMap (version 10.6; ESRI, Redlands, CA, USA) to organize and assess spatial data.

Our dependent variable was calculated based on a single measure of age estimates of 4 teeth (2 canines, 2 incisors) for each individual. We first calculated for each individual the standard deviation of the age estimates based on the 4 teeth obtained from each individual. We then performed a linear regression on the log-transformed standard deviations, by using $Y = \log(\mathrm{SD} + 1)$. We log-transformed the response variable to account for heteroscedasticity in the non-transformed data. To test for multicollinearity among independent variables, we used the Pearson product-moment correlation coefficient (r). If $|r| \geq 0.70$ for any pair of independent variables, we did not include both variables in a model. After excluding correlated variables, we fit models of all combinations of independent variables and ranked them using second-order Akaike Information Criterion (AIC_c; Burnham and Anderson 2002). We evaluated model performance via repeated 5-fold cross-validation with 100 repeats (Kohavi 1995, James et al. 2013) using the caret package (version 6.0-84; Kuhn 2008) in R. We used the MuMIn package (version 1.43.6; Barton 2019) in R to perform conditional model averaging (Burnham and Anderson 2002) on the set of all models within 2 AIC_c units of the model with the lowest AIC_c.

RESULTS

Accuracy of sex assignment

Furtaker-reported sex identification of harvested bobcats differed from the genetically determined classification (likelihood ratio $\chi^2 = 54.2$, df = 1, $P < 0.001$). Overall, field identification was 82.1% accurate (45 of 55 genetic females and 56 of 68 genetic males correctly classified by furtakers from a total of 123 individuals), with males incorrectly reported as females (21.1%; 12 males of 57 individuals) about as often as females were incorrectly reported as males (15.2%; 10 females of 66 individuals; likelihood ratio $\chi 2 = 0.72$, df = 1, $P = 0.40$). Of the 22 bobcats for which furtakers assigned incorrect sex, 50% (3 of 10 genetic females; 8 of 12 genetic males) were animals aged as 0–1 yr old.

Precision of age estimates

Mean estimated age of all paired canines was 2.6 yr (SE = 0.2, min–max = 0–15), whereas mean estimated age of all paired incisors was 2.4 yr (SE = 0.2, min–max = 0–12). The frequency distribution of absolute differences in estimated ages indicated a greater dispersion in estimates using paired incisors compared to canines (Figure 2A,B). For example, the absolute differences of paired canines included 0 (81.5% of total), 1 (17.9%), and 2 (0.7%) yr, whereas absolute differences of paired incisors was 0 (46.4%), 1 (32.5%), 2 (14.6%), and 3–6 yr (6.6%). The mean difference in estimated age using canines was 0.19 yr, whereas the mean difference in estimated age using incisors was 0.88 yr. Confidence limits for differences of age estimates from canines (95% CL = 0.13–0.26) and incisors (95% CL = 0.71–1.07) did not overlap, which suggested the precision of estimates from canines may be greater compared to incisors.

Limits of agreement for repeated measurements indicated that the difference in age estimates obtained using canines and incisors was not different from zero (Figure 3), although limits were relatively wide (standard deviation of bias = 1.27, confidence interval width = 5.07). The relationship between the estimation of age (yr) using canines (y) and incisors (x) was described by the following:

$$y = -0.03 + 1.1x,$$

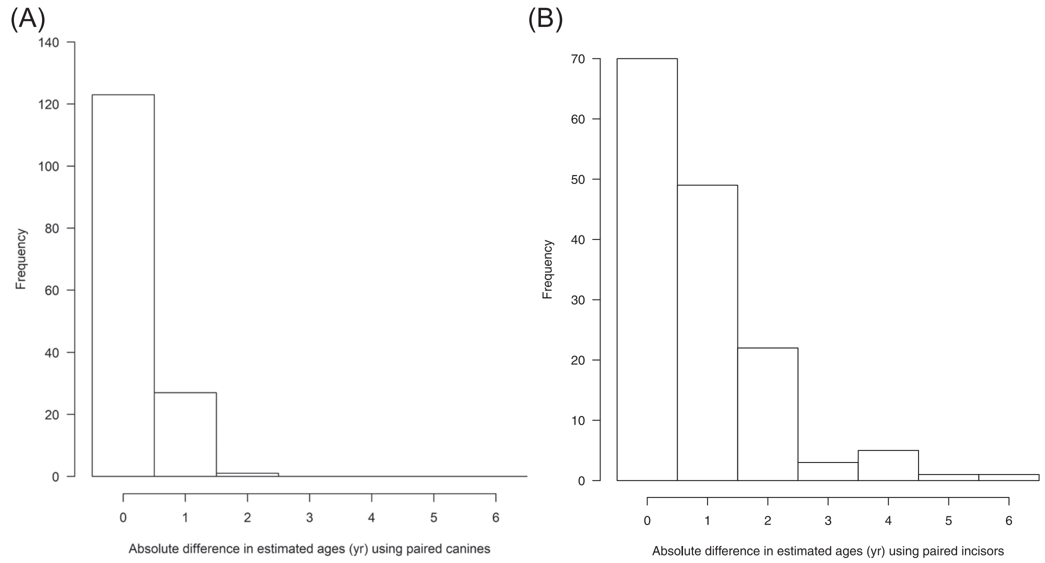

FIGURE 2 Frequency distributions of absolute differences in estimated ages of harvested bobcats (*Lynx rufus*) using cementum annuli analysis of A) paired canines and B) paired incisors, western USA, during 2017–2018.

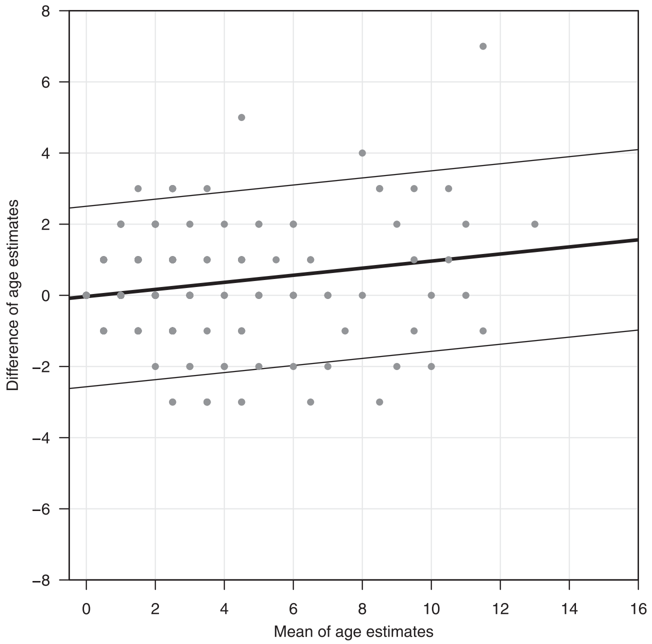

FIGURE 3 Bland-Altman plot of the limits of agreements for repeated measurements of age using paired canines and paired incisors of bobcats (*Lynx rufus*) harvested in western USA, during 2017–2018. Bold line is the mean difference and light solid lines are limits of agreement.

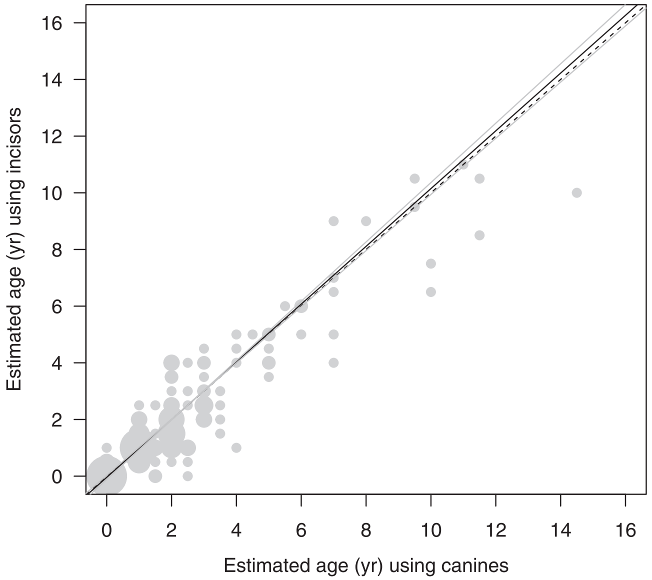

FIGURE 4 Relationship between the estimation of age (yr) using canines (*y*-axis) and incisors (*x*-axis) using cementum annuli analysis for bobcats (*Lynx rufus*) harvested in western USA, during 2017–2018. Symbol size is proportional to the square root of the number of data points at a given coordinate; dashed line is the 1:1 correspondence line, bold solid line is the regression line ($y = -0.03 + 1.1x$), and light solid lines are approximate 95% confidence limits.

which suggested that as mean estimated age increased, the difference between age estimates increased (Figure 4). Further, this resulted in estimated age based on canines being higher than estimates based on incisors for older-aged individuals. For example, an individual aged at 5.00 yr using incisors would be estimated to be 5.47 yr using canines; any individual aged ≥6 yr using incisors may be aged as one year older using canines, if rounded to the nearest year of age.

Factors affecting precision of age estimation among teeth

Based on information associated with residuals, we transformed the dependent variable according to log (SD + *c*), where SD = standard deviation of the 4 age estimates for an individual, and *c* = 1. We excluded all 3 independent variables associated with temperature due to multicollinearity with latitude. The highest-ranked model included the independent variables sex, median age, and mean elevation; however, there were 3 additional models with ≤2 ΔAIC_c suggesting a set of 4 competitive models (Table 1). Therefore, we used conditional model averaging with the independent variables sex (β = −0.11 [male]; 95% CL = −0.20 to −0.02), median age (β = 0.06; 95% CL = 0.05 to 0.08), mean elevation (β = −0.00007; 95% CL = −0.00015 to 0.00001), mean precipitation (β = 0.00007; 95% CL = −0.00005 to 0.00018), longitude (β = −0.001; 95% CL = −0.008 to 0.005), and intercept (0.34 [female]; 95% CL = 0.03 to 0.66). Repeated 5-fold, cross-validation results indicated that the top 4 models performed similarly, all explaining 28–29% of the variation present in our data. Furthermore, their comparable root-mean-square errors (0.29; SD = 0.03), compared to the range (0.00–1.41) of the response variable suggested that the models accurately predicted the response variable. Standard deviation of age estimates was lower for males (slope on the logarithmic scale = −0.11, 95% CL = − 0.20 to 0.02) than females, suggesting that age estimates for male bobcats

TABLE 1 Model selection results of 9 best-performing models from a set of 64 models based on second-order Akaike's Information Criterion (AIC_c; Burnham and Anderson 2002) to predict precision among age estimates of harvested bobcats ($n = 151$), western USA, 2017–2018. Dependent variable was log(SD +1) of age estimated for individual using cementum annuli analysis of 2 canines and 2 incisors per individual; K = number of model parameters, ΔAIC_c = difference in relation to best model within the set, $w = AIC_c$ weight. LL = log-likelihood, *r*-squared (SD) = cross-validation *r*-squared and associated standard deviation, RMSE (SD) = cross-validation root-mean-square error and associated standard deviation.

Model		*K*	ΔAIC_c	*w*	*LL*	*r*-squared (SD)	RMSE (SD)
1	Sex + median age + mean elevation	5	0.00	0.19	−24.40	0.29 (0.14)	0.29 (0.03)
2	Sex + median age + mean precipitation	5	0.91	0.12	−24.85	0.28 (0.14)	0.29 (0.03)
3	Sex + median age + mean elevation + mean precipitation	6	1.71	0.08	−24.17	0.28 (0.13)	0.29 (0.03)
4	Sex + median age + mean elevation + longitude	6	1.94	0.07	−24.28	0.28 (0.14)	0.29 (0.03)
5	Sex + median age	4	2.03	0.07	−26.48	0.28 (0.13)	0.29 (0.03)
6	Sex + median age + mean elevation + latitude	6	2.15	0.06	−24.39	0.28 (0.13)	0.29 (0.03)
7	Sex + median age + mean precipitation + longitude	6	2.79	0.05	−24.71	0.27 (0.14)	0.30 (0.03)
8	Sex + median age + mean precipitation + latitude	6	3.08	0.04	−24.85	0.27 (0.14)	0.30 (0.03)
9	Median age + mean elevation	4	3.08	0.04	−27.01	0.28 (0.13)	0.29 (0.03)

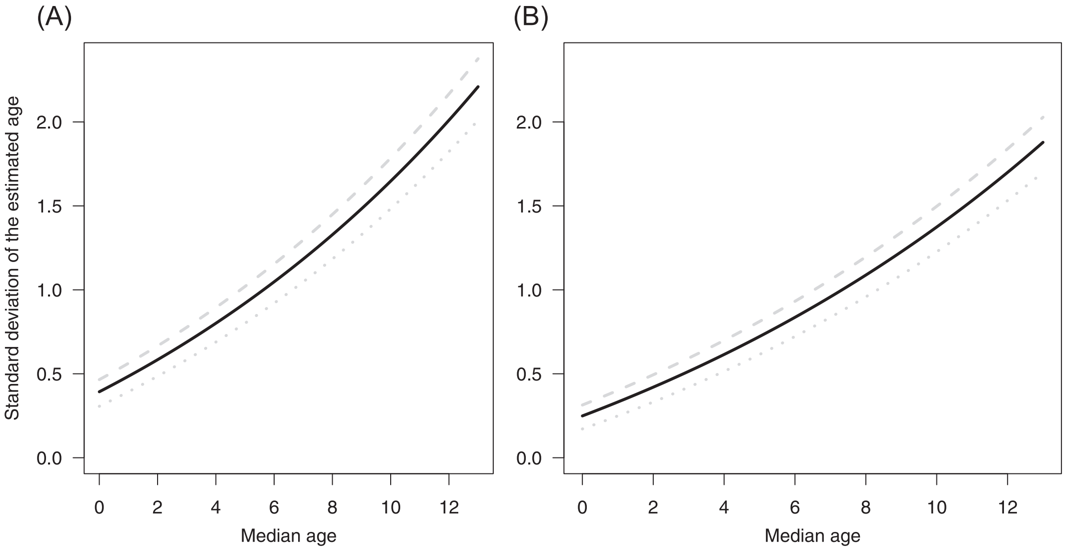

FIGURE 5 Standard deviation of age estimates obtained using cementum annuli analysis of canines and incisors of bobcats (*Lynx rufus*) harvested in western USA during 2017–2018, as a function of elevation and median age, for A) females and B) males. Dashed gray line represents minimum elevation (206 m), solid black line represents mean elevation (1,196 m), and dotted gray line represents maximum elevation (2,450 m).

may be more precise compared to females. Standard deviation of age estimates increased with median age of individuals (slope on the logarithmic scale = 0.06, 95% CL = 0.05 to 0.08). Standard deviation of age estimates tended to decrease with elevation (slope on the logarithmic scale = −0.000069, 95% CL = − 0.000148 to 0.000097; Figure 5).

DISCUSSION

Wildlife harvest models designed to support decisions for ensuring long-term population viability necessarily include demographics of harvest. For species that are selectively harvested, the sex and age of an individual can often be assessed prior to harvest in efforts to minimize unintentional or detrimental impacts at the population level (Miller et al. 2016). However, because of the methods commonly used by furtakers, harvest of bobcats is more likely to be nonselective and, as result, may include females and males of all ages (Allen et al. 2018). This is not always the case; however, and individuals assumed to be <1 yr old may often be released by trappers or not harvested by hunters, especially if pelt prices are high and a harvest limit is implemented in a given jurisdiction. When harvest is nonselective, the quality of post-mortem reporting of sex and age are crucial in monitoring population-level effects of harvest.

The degree of sexual dimorphism in bobcats varies regionally (Sikes and Kennedy 1993), and errors in reporting of sex can occur (Williams et al. 2011, Hiller et al. 2014). Genetic evidence confirmed that incorrect sex was reported in 18% of the harvested bobcats sampled in our study, assuming that genetic identification was 100% accurate. Errors were more common among the younger age classes, especially among genetically identified males. Similarly, Williams et al. (2011) reported that juvenile male bobcats harvested in Michigan had the highest rate (64%) of sex misidentification by furtakers (overall error rate = 23.6%, $n = 182$). The less conspicuous testes of young male bobcats (Crowe 1975) likely contributes to sex-assignment errors in that group (Williams et al. 2011). Older bobcats are easier to sex correctly because sexual dimorphism in body size is more pronounced in adults; e.g., by 1.5 yr of age, male bobcats in Wisconsin were on average larger and heavier than females of any age (Allen et al. 2018).

Correctly assigning sex of juvenile (0–1 yr old) bobcats may be difficult for furtakers and biologists. Accuracy of sex assignment, particularly for younger age classes, could be improved through specific training for those responsible for assignment of sex, or by using tooth measurements, although these measurements show significant overlap of the sexes, especially among bobcats ≤3.5 yr of age (Williams et al. 2011). Alternatively, genetic tests are decisive but costly and may not always be justified. We found direction of error in sex assignment to be similar (female to male vs. male to female). A 76% (Williams et al. 2011) to 82% accuracy rate (this study) in furtaker-reported sex may be sufficient for modeling purposes, although it may be prudent to initially confirm the degree of reporting accuracy for a given region.

The use of CAA is a common method of age estimation in carnivores (Klevezal and Kleinenberg 1967, Grue and Jenson 1979, Matson 1981), including bobcats (Crowe 1972). Because our sampled bobcats were of unknown ages, accuracy of CAA results among bobcats that we sampled could not be verified. However, for >30 years, Matson's Laboratory has relied on an aging model developed for bobcat canines at a deposition rate of one annuli line/yr based on >234,000 bobcats (Matson's Laboratory 2021*b*). Thus, we assumed that Matson's formula was accurate for purposes of testing precision among paired canines from bobcats and, therefore, appropriate for comparing the relative precision of paired incisors.

Our study confirmed that cementum annuli counts in the lower canine teeth of bobcats offered a higher level of precision than counts in incisors for estimating age. Previously, Crowe (1972) reported consistent patterns of annuli in paired upper canines of bobcats from Wyoming. However, cementum-line deposition is most obvious where food resources and breeding seasons are strongly seasonal (Matson 1981). Matson's Laboratory classifies CAA aging for bobcat canines as being moderately (80–90%) accurate, noting variability among populations, with accuracy being higher in northern than in southern populations (Matson's Laboratory 2021*a*). In Hawaii, CAA in paired canines differed in 8 of 22 feral cats (*Felis catus*; Danner et al. 2010). Similarly, intraspecific differences in cementum-line deposition have been documented in other carnivore species with wide geographic distributions, including black bears (*Ursus americanus*; McLaughlin et al. 1990, Costello et al. 2004) and African lions (*Panthera leo*; White and Belant 2016). Notwithstanding, our results for bobcat samples that originated from a broad range of latitudes (and longitudes) documented good precision among pairwise comparisons of canines.

Canine teeth are often better suited to CAA than other tooth types in most carnivores given the physically larger size of this tooth type, which may decrease compression of annuli layers at the root tip, thereby facilitating line detection (Matson 1981). Similarly, the small size of incisors results in less physical material available for subsequent laboratory processing and analysis, possibly factoring into lower levels of precision. In our study, incisors from bobcats were not as precise as canines in producing age estimates using CAA, with larger absolute differences between pairs. Precision of annuli counts in carnivores have been found to vary with tooth type in coyotes (*Canis latrans*; Roberts 1978). Incisors also produced lower age estimates than canines, which, depending on age-class assignments, could affect results of population modeling. A comparison of paired PM2 in African lions included discrepancies in line counts in 29 of 31 pairs (94%; White and Belant 2016), with differences sufficient to misclassify individuals to age classes relevant to sustainable harvest in 14 of 31 (45%) cases.

Lower age precision, as was obtained from female bobcats, may be the result of physical and physiological changes associated with reproduction (Asmus and Weckerly 2011). In southern populations of white-tailed deer (*Odocoileus virginianus*), CAA was found to be less reliable for females than males, a difference that was attributed to metabolic stressors associated with lack of synchronization between environmental conditions, such as forage, and parturition at lower latitudes (Asmus and Weckerly 2011). Although we found no effect of precipitation as a variable, it is possible that the long-term and widespread drought conditions in the western USA resulted in precipitation alone being an uninformative parameter during our study period. Elevation may more accurately describe temperature and precipitation (as both rain and snow) at a given centroid location, which, in turn, can impact vegetative cover and food resource availability important to bobcats (Svoboda et al. 2019). In the Black Hills, South Dakota, male bobcats utilized higher elevations and different microhabitats than female bobcats (Mosby et al. 2012), which presumably could differentially influence food resources, reproductive cycle, and CAA deposition between sexes.

Age precision of CAA also decreased in older individuals, similar to what has been reported from the oldest classes of gray wolves (*Canis lupus*; Gipson et al. 2000). Regardless, age estimates from CAA of bobcat incisors may prove sufficient for assignment to age classes, especially when used in conjunction with other definitive features indicative of age in *Lynx* spp., such as tooth wear (Marti and Ryser-Degiorgis 2018). The appropriateness of using incisors will depend on a combination of factors, including if the tooth being sampled is from a living or dead animal. Given their functional role in capturing and killing prey (Van Valkenburgh 1996), the loss of a canine may affect ability to successfully capture prey more so than the loss of an incisor. Moreover, age estimates which can be used to assign individuals to age classes may be sufficient depending on the specific research questions or management goals, especially if the rate of error has previously been determined.

MANAGEMENT IMPLICATIONS

Sex-age structure of harvested species has become a critical component for many population modeling efforts that support decision making by management agencies. Our assessment of the accuracy, and direction of error, associated with sex assignment by furtakers in the western USA may reveal a level of reporting error that is acceptable for specific management objectives. If accuracy of sex identification is determined to affect modeling results, then agencies may want to provide educational tools that will reduce errors of sex identification in the field. Alternatively, 100% accuracy in sex identification of individual pelts can putatively be achieved using genetic confirmation, although this method entails greater time and expense.

For age estimation via CAA, although the canine remains the preferred tooth type in most carnivores, the value of using the incisor for age estimation should not be discounted. In fact, the incisor may be more desirable for collection in research projects involving live capture and release to reduce discomfort and potential post-release effects (e.g., canine removal affecting ability to capture prey) to the study animals. Although lower precision associated with age estimation should be expected from incisors, the resultant estimates may be useful to establish a relative age index, or to group individuals into age classes. Managers may determine that identification of age class is sufficient for making informed decisions based on results of SPR or other population modeling approaches. Quantifying errors associated with sex identification and age estimation, in addition to identifying specific management goals, can assist managers in fully utilizing harvest data that are available. Finally, agencies may want to review their data-collection processes and make any revisions necessary to minimize errors associated with sample collection; e.g., proper labeling of individual mandibles and pelts to minimize mismatching samples.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

ETHICS STATEMENT

Our samples from Oregon were obtained and processed under Oregon Scientific Taking Permit No. 001-18.

DATA AVAILABILITY STATEMENT

Data available on request from the authors; permission from individual state agencies may be required.

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