USING PHOTOGRAMMETRY TO ESTIMATE POPULATION DEMOGRAPHICS OF ALASKAN STELLER SEA LIONS (*EUMETOPIAS JUBATUS*)

– By –

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ABSTRACT

Steller sea lions (*Eumetopias jubatus*) experienced a precipitous 80% decline in abundance over a 25-year period starting in the mid-1970s. The decline occurred at different rates over the range of the species, which is comprised of two Distinct Population Segments (DPS). The endangered western DPS stabilized in 2004, but stark regional differences have been observed within the six regions that comprise this DPS; increases in abundance in the eastern four regions of the range have been largely offset by significant declines in the two western regions. In contrast, the threatened eastern DPS, which occurs in southeast Alaska, is recovering and currently being considered for delisting under the Endangered Species Act. Aerial surveys of haul out and rookery sites (sites with >50 pups born annually) offer snapshots of abundance and population health, but ecological mechanisms driving population dynamics cannot be inferred from these surveys. Current methodologies employed to study vital rates (i.e., survival, recruitment, and natality) are limited to a relatively small number of rookeries, leaving gaps in age-structure information across the Alaskan range —most notably in the central and western Aleutian Island regions, which continue to experience significant declines.

In the present study, photogrammetric methodologies were developed which allowed the measurement of lengths of individual Steller sea lions from images captured during a 2008 aerial survey. These length data were then used to provide estimates of the proportion of different age and sex classes in various regions. Standard lengths of sea lions were measured from vertical digital images. All sea lions observed in close proximity to a pup or juvenile were considered adult females, thus providing a category of "known" adult females. All standard lengths assigned a Straightness Classification of 3 - lying straight along their long axis with only minor curvature at either the posterior or anterior portion of the body - were used in analysis. An altitude calibration flight was performed in Sitka, Alaska in which images of the runway number were obtained (for which true dimensions were known) and linear regressions were performed to correct for bias in altitude measurements collected from the radar altimeter. The resulting regression equations were combined to produce an equation to convert measured lengths (L_m; pixels) to "true" lengths of sea lions (L_P; m) using altitude measurements from the radar altimeter (H_m; ft): $L_p = (L_m)3.742E^{-3}H_m + 8.003E^{-3}$.

Converted length data were applied to a finite mixture distribution model to estimate the proportion of the population comprised of three age-sex classes—juvenile (males and females), adult female and adult male. To minimize bias due to the effects of sample size and site selection, broad regional comparisons of rookery, haul out, and combined sites were conducted for the eastern and western DPS, as well as a comparison of two areas within the range of the western DPS experiencing contrasting abundance trends. Females in the eastern DPS were significantly smaller than those in the western; and amongst the western DPS regions, females in the center portion of the range were larger than in two fringing regions. Range-wide estimates of vital rates and age structure of Steller sea lions may help to identify environmental or anthropogenic drivers that are impeding the recovery of the western DPS of Steller sea lions in Alaska.

Key words: age-structure, Alaska, finite mixture distribution, length-frequency analysis, photogrammetry, population demographics, Steller sea lion, *Eumetopias jubatus*

INTRODUCTION

Steller sea lions (*Eumetopias jubatus*) occur across the North Pacific rim from Japan to California. In 1997, the National Marine Fisheries Service (NMFS) identified two distinct population segments (DPS), the western and eastern, divided at 144°W longitude near Cape Suckling in the Gulf of Alaska, based on genetics, distribution, demography and phenotypic characteristics (Loughlin 1997; U.S. Federal Register 1997a). The decline of the western DPS began in the 1950s with a reduction of approximately 80% since the mid-1970s (Loughlin et al. 1992; Sease and Gudmundson 2002; Trites and Larkin 1996). The decline was first observed in the eastern Aleutian Islands in the mid-1970s followed by subsequent decreases in abundance continuing eastward towards Kodiak Island during the late 1970s and early 1980s (Braham et al. 1980; Merrick 1987). Documentation of these declines prompted the NMFS to list the entire US range of Steller sea lions as threatened under the U.S. Endangered Species Act (ESA; 1973) in 1990 (U.S. Federal Register 1990). The continued decline of the western DPS led NMFS to elevate its listing from threatened to endangered in 1997. In contrast, the eastern DPS remained listed as threatened (U.S. Federal Register 1997b).

The population decline of the western DPS continued from 1990 at about 5% per year until approximately 2000. Subsequently, this DPS stabilized from 2004 through 2008 (Fritz et al. 2008). The western DPS has remained relatively stable in recent years, although stark differences in population trends have been observed among its six regions: eastern (E-), central (C-), and western Gulf of Alaska (WGOA) and eastern (E-), central (C-), and western Aleutian Island (WAI) regions (FIG. 1—Fritz et al. 2008; NMFS 2010). Specifically, net increases observed in the four eastern regions - EGOA through EAI - have been largely offset by decreases within the two western regions - CAI and WAI (FIG. 2—Fritz et al. 2008; NMFS 2010).

Following the cessation of sea lion predator-control kills and commercial harvests in the early 1970s, the eastern DPS began to recover, increasing at approximately 3% per year (Pitcher et al. 2007) which eventually led to the consideration for delisting in 2008 (NMFS 2008). From 1980 through the 1990s, the breeding range for this DPS expanded to include several new rookery sites along the northern coast of southeast Alaska (SE AK; Pitcher et al. 2007). The NMFS delineated the two discrete DPS units based on population dynamics, tagging data, branding and radio-telemetry studies, phenotypic data, and genetics, (Loughlin 1997), but immigration and emigration has been observed between the two DPS units within the GOA—primarily between the EGOA (western DPS) region and SE AK (eastern DPS; Bickham et al. 1996; Raum-Suryan et al. 2002). Immigration of western DPS sea lions to the eastern DPS occurs at a negligible rate, but the two most northern rookeries in SE AK were colonized largely by western DPS females (Gelatt et al. 2007; O'Corry-Crowe et al. 2006).

Under the ESA and Marine Mammal Protection Act (MMPA), NMFS is charged with managing both DPS units (stocks) of Steller sea lions. Accordingly, NMFS conducts annual aerial abundance surveys of Steller sea lion rookeries (terrestrial sites at which more than 50 pups are born annually) and haul-out sites in Alaska. The objective of these surveys is to monitor trends in Steller sea lion abundance and natality by counting non-pups (adult and juvenile sea lions ≥ 1 y) and pups (newborn sea lions) hauled out during the breeding season (Fritz et al. 2008).

Abundance surveys capture a snapshot of a population, but do not allow inference regarding the specific drivers that could inhibit recovery (Holmes et al. 2007). Abundance can change gradually with simultaneous and sometimes offsetting changes in age-structure or vital rates (e.g., survival, recruitment, and natality; Holmes et al. 2007). Significant changes in vital rates can occur over short time frames but these changes can only be estimated when age-structure information is available (Holmes et al. 2007). This presents a major challenge for the management of long-lived species, such as the Steller sea lion, as an understanding of the primary causes of spatial and temporal variation in population demographics is required for population viability assessments and conservation of endangered populations (Holmes and York 2003; Koons et al. 2006; Tinker et al. 2006).

Current methods employed to study vital rates require many years of dedicated research and are limited because estimates derived from rookery sites may reflect those mechanisms driving abundance within a rookery area, or region. Length data collected from vertical images captured in aerial surveys can be used to derive vital rates estimates for areas where this information cannot be derived from currently implemented methods. Holmes and York (2003) and Holmes et al. (2007) applied length data measured from oblique survey film images to an age-structure model to estimate vital rates from the mid-1980s to 2004 in the CGOA. Unfortunately, this model could not be applied range-wide, as the CGOA region was the only region for which pre-decline age-structure and fecundity were known (Holmes et al. 2007; Holmes and York 2003).

The application of length data for disseminating growth rates, age-structure, and population demographics has been used for a variety of different taxa, including cetaceans (Perryman and Lynn 1993), mollusks (Diederich 2006; Orsi Relini et al. 2006), sea turtles (Bjorndal et al. 1995; Casale et al. 2011), and perhaps, most notably, for teleosts (Hilborn and Walters 1992; Pauly 1987). Vertical images have been used to estimate lengths of marine mammals in several cetacean species

(Gilpatrick 1996; Gilpatrick and Perryman 2008; Perryman and Lynn 1993; Perryman and Westlake 1998; Ratnaswamy and Winn 1993), but such methods have not been used for pinnipeds. Steller sea lions are a model species for the application of photogrammetric methods as they are sexually dimorphic, with adult males having almost three times the mass and lengths approximately 24% greater than that achieved in adult females (NMFS 2010).

Winship et al. (2001) described growth in length and mass of Steller sea lions from morphometric data collected from known-age animals sampled on rookeries and haul-outs from 1976 to 1989. The asymptotic length (approaching 90% of final length) is achieved around the time of sexual maturity for both females and males (Winship et al. 2001). Specifically, females reach asymptotic length at about 4 years of age, while males reach asymptotic length around 7.5 years of age (Winship et al. 2001). Laws (1956) reported that female pinnipeds at sexual maturity are a "remarkably constant" percentage of final length. Winship et al. (2001) found this to occur at 3 years of age in Steller sea lion females; coinciding with the earliest evidence of female sexual maturity. Sexually mature male sea lions can be categorized as adults (bulls) and sub-adults; males achieve sexually maturity at approximately 5 to 7 years (sub-adults), but social maturity is not reached until 10 to 11 years of age (bulls), when larger body mass is achieved (Winship et al. 2001). Thus, body length measurements are an appropriate metric for identifying three age-sex classes in Steller sea lions: juveniles (males and females), adult females, and adult males. The proportions of juvenile and female sea lions, coupled with pup estimates, are important for assessing population health in pinnipeds, in terms of reproduction and survivorship (Winship et al. 2001).

The present study presents an application of photogrammetric methods in which length data were used to estimate the proportion of three age and sex classes of Steller sea lions. A time series of such observations could provide estimates of vital rates that could help illuminate or eliminate ecological factors driving trends in abundance. For example, a declining or stable population with relatively high juvenile and adult survival suggests that direct mortality factors (e.g., predation, illegal shooting, and incidental take in fisheries) are less important than indirect factors that could affect reproduction (e.g., disease and pollutants; Holmes et al. 2007; Holmes and York 2003). This approach offers a non-invasive method for estimating vital rates by utilizing vertical digital images captured in aerial surveys. In addition, as the management of Steller sea lions has a long history of contention—especially in those areas where sea lions are believed to interact with commercial fisheries—knowledge from vital rates could lead to a better understanding of geographical variation in trends and, perhaps, the underlying ecological drivers of the demography of the western DPS.

MATERIALS AND METHODS

Data collection.—The focus of the 2008 aerial survey was to survey known haul out sites to estimate the abundance of adults and juveniles (non-pups). This was the first complete survey of the endangered western DPS in Alaska since 2004, and the first complete survey of the threatened eastern DPS in Alaska since 2002 (Fritz et al. 2008; Pitcher et al. 2007). The aerial survey was conducted from 7 June to 6 July 2008 with daily effort between 0900 and 1800 (Alaska time zone)—the optimal time window for surveying non-pups (Sease and Gudmundson 2002).

The 2008 non-pup survey was the first full aerial survey conducted with the single digital camera mount system, employing a Canon EOS 1Ds Mark III digital camera with a 50-mm (f1.2) lens oriented vertically with forward motion compensation (to match ground speeds to reduce blur of image) secured within the belly port of a Twin Otter aircraft (operated by NOAA, Aircraft Operations Center, Tampa FL). A radar altimeter (Sperry AA-300) was mounted in the belly port of the aircraft to collect altitude measurements for each image captured.

Of the 356 known terrestrial rookery and haul out sites in Alaska, 339 (95%) were surveyed in 2008, beginning at Dixon Entrance in southeast Alaska (SE AK; 134˚W), and heading towards Attu Island (172˚E) at the western end of the Aleutian Islands. Of all sites surveyed, 140 had no sea lions present; those with 15 individuals or more were photographed; sites with fewer than 15 sea lions were visually enumerated. Those sites photographed without a corresponding altitude measurement recorded from the radar altimeter (due to technical difficulties) were not considered for selection. In addition, as the proportion of sea lions eligible for measurement (lying along a straight axis) is significantly less than the total abundance at each site, those sites with less than 75 sea lions were not considered further. In an effort to measure at least 10% of the total non-pup abundance estimated from the 2008 census survey, those sites with the highest relative abundance of non-pups within the region were selected for further analysis (FIG. 3—$n = 68$). Proportion of the non-pup abundance measured amongst the seven regions ranged from 3 to 19% for haul out sites, 11 to 22% for rookery sites, and for combined sites 9 to 20% of total non-pup abundance was measured.

Using Image J, a free image processing and analysis program (rsbweb.nih.gov), standard lengths, in pixels, was measured for individual sea lions by drawing a straight line from the tip of the nose to the tail or the end of the body where the lanugo coat ends before the hind flippers (FIG. 4). Straightness classifications (SC), ranging from 1 to 4, were used to categorize the degree of straightness observed in individual sea lions, using the following criteria: animals lying flat with fully extended flippers (SC 1); animals lying flat and relaxed with no flippers tucked under body (SC 2); animals lying along a straight line axis with minor curvature, or flippers tucked under body, at either the posterior or anterior portion of the body (SC 3); and, finally, animals with curvature or flippers tucked under the body at both the posterior and anterior portion of the body (SC 4). All animals with SC ranging from 1 to 3 were measured at each selected site. There were very few samples of SC 1 and 2 measurements and SC 4 lengths could introduce significant error due to the exaggerated curvature of body posture, so only SC 3 lengths were used in the final analysis (TABLE 1). In addition, all females with a pup were identified, providing the ability to estimate the lengths of females that have reached sexual maturity (Perryman and Lynn 1993; Perryman and Westlake 1998). We assumed measurement bias across sites and regions was consistent throughout the range of the species (Holmes et al. 2007; Perryman and Westlake 1998).

Altitude corrections and image length conversions.—An altitude calibration flight was conducted on 7 June 2008 at the Rocky Gutierrez Airport in Sitka, Alaska where vertical images of the runway number were captured at four approximate altitudes—120, 180, 240, and 305 m. Actual survey altitudes ranged from 152 to 305 m, with survey speed ranging from 46 to 62 m/s (Fritz et al. 2008). Vertical digital images of the runway number, for which ground dimensions were known, were obtained to calibrate the single camera mount system (camera and lens) and correct for bias in measurements collected from the radar altimeter (Sperry AA-300). Ultimately, this was performed to produce the final conversion equation to convert lengths measured from images (px) to true lengths (m; Perryman and Lynn 1993). The relationship between known ground measurements and image measurements was determined using the following scale factor relationship (FIG. 5—Gilpatrick 1996; Perryman and Lynn 1993; Wolf 1983):

$$S = \frac{AB}{ab} = \frac{f}{H}$$

The photogrammetric scale (S) reflects the proportional relationship between ground lengths (AB) to image lengths (ab) equal to the focal length (f) over altitude (H; Wolf 1983). Ground target lengths (AB) were collected from four different dimensions of the runway number "11." All digital images that captured the runway number in full were used for the altitude calibration. The same four dimensions measured on the ground were collected from these images in pixels (px) then converted to cm (ab) using the cm to px ratio, determined by Canon ($6.4E^{-4}$ cm per px). Any bias associated with incorrect pixel size was assumed to be consistent for all measurements. Likewise, the focal length was assumed to be 5 cm (f; 50 mm lens), and any bias from differences in actual focal length from the 5 cm focal length was assumed to be consistent for all measurements, as the same camera and lens were used for the entire survey.

Linear regressions were performed to determine the relationship between calculated altitude derived from the scale factor relationship and altitude measurements collected from the radar altimeter and a second linear regression was performed to establish the relationship of the px ratio (cm per px) as a function of measured altitude (Gilpatrick 1996). For the px ratio regression, the line was fit through the origin for this calibration curve as the relationship between the two remains 0 cm per px at 0 feet altitude. Finally, to assess measurement precision, a multiple measure test was performed for each of the four known runway dimensions (Perryman and Lynn 1993). Each image of the runway number captured in full was measured 5 times for each dimension at the four approximate altitudes and the variance of measured lengths from the known ground lengths was determined.

In addition to errors in measuring, errors in altitude measurements from uneven terrain of the terrestrial haul out sites, image distortion from non-vertical aircraft orientation, and sea lion body orientation all impact the accuracy of length measurements from vertical images. Error from body orientation was addressed in assigning a SC as described above. In addition, the radar altimeter averages altitude over a small swath from the radar, so that changes in site elevation are averaged. As such, converted lengths collected from images are not directly comparable to lengths measured with the animal in-hand under anesthesia.

Data analysis.—To eliminate bias from the sample size and selection of sites, larger regional comparisons were examined for haul out, rookery, and combined sites for the eastern DPS (SE AK), western DPS, and two larger areas within the western DPS—eastern GOA through the eastern AI regions (EGOA-EAI; relatively stable or increasing in pup and non-pup abundance) and the central and western AI regions (CAI-WAI; experiencing significant declines in abundance).

To estimate composition of each age-sex class (juvenile, adult female, and adult male), an EM (expectation-maximization) algorithm was used under the finite mixture distribution (FMD) model to derive maximum likelihood of age-sex classes using R statistical software (Prager and Shertzer 2005). This method was first developed to identify size composition data into age-sex classes for fish stocks (Everitt and Hand 1981; Wolfe 1970). This method has also been used to individual stocks in a mixture of length data to estimate fish stock composition in mixed-stock mixtures (Millar 1987; Wood et al. 1987). FMD modeling differs from other maximum likelihood methods in that estimates are not derived for each individual, but rather estimates of individuals are used to identify the number of stocks in a mixture (Bhattacharya 1967; DeVries et al. 2002; Prager and Shertzer 2005). This allows the finite mixture distribution methods to be applied to a wide variety of metric data, especially since these methods do not require prior mixture composition estimates (Bhattacharya 1967; DeVries et al. 2002; Prager and Shertzer 2005). For this study, the different stocks are synonymous with the age-sex classes of Steller sea lions identified—juvenile, adult female, and adult males. Converted lengths (m) measured from vertical digital images of SC 3 were applied to an FMD model to estimate the mean length (μ), standard deviation (σ), and proportion (π) for each age-sex class from the distribution for haul out, rookery, and combined sites in the eastern DPS, the western DPS as a whole, and separately for the increasing (EGOA-EAI) and decreasing (CAI-WAI) portions of the western DPS.

RESULTS

Linear regression models.—Corrected altitude (H_c) was calculated for each of the known length runway number dimensions using an arrangement of the scale relationship: known ground measurements (AB), measured lengths from digital images of corresponding ground dimensions (ab), and focal length of the 50mm lens (f; Gilpatrick 1996; Wolf 1983):

$$H_c = \frac{AB}{ab} * f$$

A linear regression equation describing H_c as a function of altitude measurements (H_m) recorded from the radar altimeter was determined ($n = 140; r^2 = 0.998$) to correct for any bias from radar altimeter measurements (FIG. 6A—Gilpatrick 1996):

$$H_c = 0.966\, H_m + 20.669$$

To determine the relationship between the px ratio to altitude measurements, a second linear regression was performed (FIG. 6B). The regression equation describing the px ratio (L_t) as a function of the measured altitude to correct for bias in conversion factors caused by altimeter readings ($n = 140; r^2 = 0.997$) was determined:

$$L_t = 3.872E^{-3}\, H_m$$

The final resulting equation describing the 'true' length converted from image lengths (L_p; m) as a function of the measured length from digital images (L_m; px) and measured altitude recorded from the radar altimeter (H_m; ft) is shown below:

$$L_p = 3.742E^{-3} L_m H_m + 8.003E^{-3} L_m.$$

To test the precision of measurement collection to true lengths, a multiple measure tests of each of the four known runway number dimensions was performed for each altitude. The multiple measured lengths collected from vertical digital images were converted to true lengths (m; utilizing above conversion equation). Measured lengths were within 3.4% (or 10.689 cm) of the known ground length.

Known adult female comparisons.—Females observed in the presence of a pup or juvenile (nursing, touching, or in close vicinity to offspring) were identified in every photograph, allowing analysis of the proportion and size of "known" adult females between the eastern and western DPS, and within the western DPS, using Student's t-test (FIG. 7). Females in SE AK were significantly smaller than females in the entire western DPS ($p = 3.466E^{-29}$) and regionally, within the western DPS (all values $p \leq 2.716E^{-4}$). Mean adult female lengths were estimated for all six regions within the western DPS. Adult females in the EGOA and WAI were the smallest, relative to the CGOA ($p = 0.011$ and 0.034, respectively), WGOA ($p = 0.037$ and 0.087), EAI ($p = 0.007$ and 0.019), and CAI ($p = 0.140$ and 0.229). All other regional comparisons indicated adult females were not significantly different in mean length ($p > 0.080$). Additionally, observed known adult female mean lengths were pooled for the same broad regional comparisons applied to FMD modeling methods allowing for confirmation of the adult female age-sex class derived from modeling.

Finite mixture distribution modeling.—The finite mixture distribution (f) of L_P is expressed as a weighted sum of its i age-sex class distributions ($g_i, i = 1, \ldots i$), where $\pi = \pi_1, \pi_2, \pi_3$ are the independent mixing proportions for each age-sex classes—juvenile, adult female, and adult male (Bhattacharya 1967; Prager and Shertzer 2005). For each i age-sex class the mean length (μ_i) and standard deviation (σ_i) were estimated (Bhattacharya 1967; Prager and Shertzer 2005).

$$f(L_P|\pi, \mu, \sigma) = \sum_{i=1}^{I} \pi_i g_i\,(\pi|\mu_i, \sigma_i)$$

To limit bias from sites selected for measuring and small sample size, modeling was conducted for rookery, haul out, and combined sites for broader regional comparisons—eastern DPS, western DPS, EGOA-EAI, and the CAI-WAI (FIG. 8). An analysis of variance (ANOVA) was performed for each broad regional comparison and site type, with only significant differences observed for the eastern DPS distribution of lengths measured from haul out sites ($F_{22,195} =$

$43.749, P = 0.004$). This was likely due to small sample size, as evident by the lack of data for larger sea lions, or the presence of adult males.

The FMD model was able to clearly identify three age-sex classes for rookery and combined sites in the western DPS, EGOA-EAI, CAI-WAI, and for haul out sites in the western DPS and EGOA-EAI. However, three age-sex classes were not clearly discriminated in the eastern DPS (all site types) or at haul out sites in CAI-WAI. In particular, the eastern DPS and CAI-WAI haul out sites converged for two smaller components—likely, juvenile and adult female age-sex classes—however, the third component, estimated the variance of the total distribution rather than converging for the adult male age-sex class; this is likely due to small sample sizes of longer animals (i.e., adult males).

Due to the less exaggerated sexual dimorphism observed in the smaller eastern DPS sea lions, proportions derived for the three age-sex class components do not reflect similar trends observed in all proportions derived for haul out, rookery, and combined sites within the western DPS (FIG. 9). This is evident by the strong overlap observed in modeled age-sex class density distributions, indicating challenges with identifying adult females from longer juveniles or small sub-adult males. Based on comparisons with 2008 abundance counts—where sea lions were counted and individuals were subjectively classified into age-sex classes by independent counters—model derived proportion estimates correspond with western DPS classified abundance counts. Observed adult female mean lengths, as indicated by the presence of a pup or juvenile, for the same broad regional comparisons applied to the FMD model corroborates model derived demographic estimates for the adult female age-sex class component (TABLE 2).

DISCUSSION

Several studies have also documented the significantly smaller body size of eastern sea lions (Bickham et al. 1996; Loughlin 1997), but regional differences within the western DPS have not been described across the range since the 1980s (Calkins et al. 1998; O'Corry-Crowe et al. 2006). There is no strong evidence of poor body condition (i.e., starvation) observed in individual sea lions within the affected regions (NRCC 2003), but nutritional stress has been found to decrease body size in Steller sea lions (Calkins et al. 1998; Pitcher et al. 1998). This study shows adult female body size varied throughout the six regions within the western DPS—reproductive females in the WAI and EGOA regions were smaller than neighboring regions throughout western DPS. The WAI region is experiencing the most drastic declines relative to other regions in the western DPS—

declining at 7.2% per year from 2000 to 2008; approximately 40% in 8 years (NMFS 2010). NMFS (2010) reported in the 2010 Biological Opinion that in this affected area, no evidence of disease and contaminants could be found and that nutritional stress was thought to be the cause for significant decline in the CAI and WAI. Nutritional stress causing a decrease in birth rate and body size in female Steller sea lions (Calkins et al. 1998; Pitcher et al. 1998) could explain the decreased body size in females and relatively low pup to adult female ratio observed in the WAI region (NMFS 2010). As the EGOA neighbors areas which have reached stability or increased in abundance, nutritional stress does not seem likely to explain small body size, despite slight declines observed in the EGOA (NMFS 2010).

Demographic data were derived only for 2008, but with a longer time series of measurements, a time series of vital rates could be estimated allowing for more insight into demography of Steller sea lions throughout their Alaskan range. Further development of FMD modeling could also increase the accuracy of demographic estimates. The addition of model constraints such as maximum and minimum lengths of sea lion age-sex classes could aid in distinguishing adult females from large juveniles or small sub-adult males, especially for the smaller sea lions in the eastern DPS. Animals in the eastern DPS are relatively smaller, so sexual dimorphism is less exaggerated, creating difficulties in identifying age-sex classes. The mean lengths of females estimated from FMD modeling methods were confirmed with the observed lengths of adult females, but confirmation of the juvenile and adult male age-sex could further increase confidence in demographic estimates.

Asymptotic mass (approaching 90% of the final mass) for males and females is achieved at approximately 13 and 9 years of age, respectively. The inclusion of measurements of body girth, in conjunction with standard length measurements, could improve our ability to properly model age-sex classes with overlapping length frequency distributions—especially for smaller eastern DPS sea lions. This allometric relationship could also help to distinguish sub-adult males from bulls because of the significantly greater mass of the latter (Winship et al. 2001). In fact, variation in girth and length could further elucidate changes in body condition throughout the western DPS that are correlated with temporal and spatial variation in fecundity.

It would also be useful to develop a correction factor that corrects measurements of sea lions hauled out on sites with varying elevation. Placing known length markers at varying elevations upon haul out and rookery sites with steep or variable topography could be utilized to develop this correction factor thereby increasing confidence in demographic trend estimates. Furthermore, a systematic approach to selecting sites for measuring is necessary for consistency among measurers and length data attained across survey years, for future analysis.

In conclusion, the methods developed in this paper hold great promise for estimation of vital rates across the range of Steller sea lions. Furthermore, demographic trend data estimated from photogrammetric methods for all regions could be included in the NMFS age-structure model to illuminate mechanisms driving population abundance trends for all regions in Alaska. This is especially critical as NMFS evaluates the efficacy of the newly implemented groundfish fishery restrictions in the Aleutian Islands (NMFS 2010). Range-wide age-structure information would aid in illuminating environmental or anthropogenic causes for the continued regional decline of the endangered western DPS.

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Literature Cited

BHATTACHARYA, C.G. 1967. A simple method of resolution of a distribution into Gaussian components. Biometrics 23(1):115-135.

BICKHAM, J.W., J.C. PATTON, AND T.R. LOUGHLIN. 1996. High variability for control-region sequences in a marine mammal: Implications for conservation and biogeography of Steller sea lions (*Eumetopias jubatus*). Journal of Mammalogy 77(1):95-108.

BJORNDAL, K.A., A.B. BOLTEN, A.L. COAN JR, AND P KLEIBER. 1995. Estimation of green turtle (Chelonia mydas) growth rates from length-frequency analysis. Copeia 1995(1):71-77.

BRAHAM, H.W., R.D. EVERITT, AND D.J. RUGH. 1980. Northern sea lion population decline in the eastern Aleutian Islands. The Journal of Wildlife Management 44(1):25-33.

CALKINS, D.G., E.F. BECKER, AND K.W. PITCHER. 1998. Reduced body size of female Steller sea lions from a declining population in the Gulf of Alaska. Marine Mammal Science 14(2):232-244.

CASALE, P., A.D. MAZARIS, AND D. FREGGI. 2011. Estimation of age at maturity of loggerhead sea turtles Caretta caretta in the Mediterranean using length-frequency data. Endangered Species Research 13:123-129.

DEVRIES, D.A., C.B. GRIMES, AND M.H. PRAGER. 2002. Using otolith shape analysis to distinguish eastern Gulf of Mexico and Atlantic Ocean stocks of king mackerel. Fisheries research 57(1):51-62.

DIEDERICH, S. 2006. High survival and growth rates of introduced Pacific oysters may cause restrictions on habitat use by native mussels in the Wadden Sea. Journal of Experimental Marine Biology and Ecology 328(2):211-227.

EVERITT, B.S., AND HAND, D.J. 1981. Finite mixture distributions. Monographs on Applied Probability and Statistics, Chapman and Hall, London.

FRITZ, L., M. LYNN, E. KUNISCH, AND K. SWEENEY. 2008. Aerial, ship and land-based surveys of Steller sea lions (*Eumetopias jubatus*) in Alaska, June and July 2005-2007. U.S. Department of Commerce, National Oceanic and Atmospheric Administration Technical Memorandum, NMFS-AFSC-183 NMFS-AFSC, U.S. Department of Commerce, Washington, D.C. Pp. 70.

GELATT, T.S., A.W. TRITES, K. HASTINGS, L. JEMISON, K.W. PITCHER, AND G. O'CORRY-CROWE. 2007. Population Trends, diet, genetics, and observations of Steller sea lions in Glacier Bay National Park. Pp. 145-149 in Proceedings of the Fourth Glacier Bay Science Symposium (J.F. Piatt and S.M. Gende, eds.). United States Geological Survey Science Investigations Report. SIR 2007-5047, U.S. Geological Survey, Reston, VA. Pp. 260.

GILPATRICK, J.W. 1996. Calibration of radar altimeter readings used in aerial photogrammetry of eastern tropical Pacific dolphins 1992 and 1993. U.S. Department of Commerce, National Oceanic and Atmospheric Administration Technical Memorandum, NOAA-TM-NMFS-SWFSC-226, U.S. Department of Commerce, Washington, D.C. Pp. 24.

GILPATRICK, J.W., AND W.L. PERRYMAN. 2008. Geographic variation in external morphology of North Pacific and Southern Hemisphere blue whales (*Balaenoptera musculus*). Journal of Cetacean Research and Management 10(1):9-21.

HILBORN, R., AND C.J.WALTERS. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Reviews in Fish Biology and Fisheries 2:177-178.

HOLMES, E.E., L.W. FRITZ, A.E. YORK, AND K. SWEENEY. 2007. Age-structured modeling reveals long-term declines in the natality of western steller sea lions. Ecological Applications 17(8):2214-2232.

HOLMES, E.E., AND A.E. YORK. 2003. Using age structure to detect impacts on threatened populations: a case study with Steller sea lions. Conservation Biology 17(6):1794-1806.

KOONS, D.N., R.F. ROCKWELL, AND J.B. GRAND. 2006. Population momentum: implications for wildlife management. Journal of Wildlife Management 70(1):19-26.
LAWS, R.M. 1956. Growth and sexual maturity in aquatic mammals. Nature 178(4526):193-194.
LOUGHLIN, T.R. 1997. Using the phylogeographic method to identify Steller sea lion stocks. Pp. 159-171 in Molecular Genetics of Marine Mammals (A.E. Dizon, S.J. Chivers and W.F. Perrin, eds.). Special Publication Number 3, Society for Marine Mammalogy.
LOUGHLIN, T.R., A.S. PERLOV, AND V.A. VLADIMIROV. 1992. Range-wide Survey and Estimation of Total Number of Steller Sea Lions in 1989. Marine Mammal Science 8(3):220-239.
MERRICK, R.L. 1987. Behavioral and demographic characteristics of northern sea lion rookeries. Master's Thesis, Oregon State University, Corvalis, OR, U.S.
MILLAR, R.B. 1987. Maximum likelihood estimation of mixed stock fishery composition. Canadian Journal of Fisheries and Aquatic Sciences 44(3):583-590.
NMFS (NATIONAL MARINE FISHERIES SERVICE). 2008. Recovery Plan for the Steller sea lion (*Eumetopias jubatus*). Revision. National Marine Fisheries Service, Silver Spring, MD. 325 pp.
NMFS (NATIONAL MARINE FISHERIES SERVICE). 2010. Endangered Species Act - Section 7 Consulation Biological Opinion. National Marine Fisheries Service, Silver Spring, MD. 428 pp.
NRCC (NATIONAL RESEARCH COUNCIL COMMITTEE ON THE ALASKA GROUNDFISH FISHERY AND STELLER SEA LIONS). 2003. Decline of the Steller sea lion in Alaskan waters: untangling food webs and fishing nets. National Research Council of the National Academies: National Academies Press, Washington D.C.
O'CORRY-CROWE, G., TAYLOR, B.L., GELATT, T., ET AL. 2006. Demographic independence along ecosystem boundaries in Steller sea lions revealed by mtDNA analysis: implications for management of an endangered species. Canadian Journal of Zoology 84(12):1796-1809.
ORSI RELINI, L., MANNINI, A., FIORENTINO, F., PALANDRI, G., AND RELINI, G. 2006. Biology and fishery of Eledone cirrhosa in the Ligurian Sea. Fisheries research 78(1):72-88.
PAULY, D. 1987. A review of the ELEFAN system for analysis of length-frequency data in fish and aquatic invertebrates. Pp. 7-34 in Length-based models in fisheries research (D. Pauly and G.R. Morgan, eds.). ICLARM Congerence Proceedings 13.
PERRYMAN, W.L., AND LYNN, M.S. 1993. Identification of geographic forms of common dolphin (*Delphinus delphis*) from aerial photography. Marine Mammal Science 9(2):119-137.
PERRYMAN, W.L., AND WESTLAKE, R.L. 1998. A new geographic form of the spinner dolphins, *Stenella longirostris*, detected with aerial photogrammetry. Marine Mammal Science 14(1):38-50.
PITCHER, K.W., CALKINS, D.G., AND PENDLETON, G.W. 1998. Reproductive performance of female Steller sea lions: an energetics-based reproductive strategy? Canadian Journal of Zoology 76(11):2075-2083.
PITCHER, K.W., OLESIUK, P.F., BROWN, R.F., ET AL. Abundance and distribution of the eastern North Pacific Steller sea lion (*Eumetopias jubatus*) population. Fishery Bulletin 105(1):102-115.
PRAGER, M.H., AND SHERTZER, K.W. 2005. An Introduction to Statistical Algorithms Useful in Stock Composition Analysis. Pp. 499-516 in Stock Identification Methods: Applications in Fishery Science (S.X. Cadrin, K.D. Friedland, and J.R. Waldman eds.). Elsevier Academic Press, Burlington, MA.
RATNASWAMY, M.J., AND WINN, H.E. 1993. Photogrammetric estimates of allometry and calf production in fin whales, *Balaenoptera physalus*. Journal of Mammalogy 74(2):323-330.
RAUM-SURYAN, K.L., PITCHER, K.W., CALKINS, D.G., SEASE, J.L., AND LOUGHLIN, T.R. 2002. Dispersal, rookery fidelity, and metapopulation structure of Steller sea lions (*Eumetopias jubatus*) in an increasing and a decreasing population in Alaska. Marine Mammal Science 18(3):746-764.

SEASE, J.L., AND GUDMUNDSON, C.J. 2002. Aerial and land-based surveys of Steller sea lions (*Eumetopias jubatus*) from the western stock in Alaska, June and July 2001 and 2002. U.S. Department of Commerce, National Oceanic and Atmospheric Administration Technical Memorandum, NMFS-AFSC-131 NMFS-AFSC, U.S. Department of Commerce, Washington, D.C. Pp. 54.

TINKER, M.T., DOAK, D.F., ESTES, J.A., HATFIELD, B.B., STAEDLER, M.M., AND BODKIN, J.L. 2006. Incorporating diverse data and realistic complexity into demographic estimation procedures for sea otters. Ecological Applications 16(6):2293-2312.

TRITES, A.W., AND LARKIN, P.A. 1996. Changes in the abundance of Steller sea lions(Eumetopias jubatus) in Alaska from 1956 to 1992: How many were there? Aquatic Mammals 22(3):153-166.

U.S. FEDERAL REGISTER. 1990. Listing of Steller sea lions as threatened under the Endangered Species Act. Final Rule. FR 55:49203-49241 (26 Nov 1990). National Marine Fisheries Service, National Oceanic and Atmospheric Administration. Department of Commerce, Washington, D.C.

U.S. FEDERAL REGISTER. 1997a. Threatened Fish and Wildlife; Change in listing status of Steller sea lions under the Endangered Species Act. Final Rule. FR 62:24345-24355 (5 May 1997). National Marine Fisheries Service, National Oceanic and Atmospheric Administration. Department of Commerce, Washington, D.C.

U.S. FEDERAL REGISTER. 1997b. Listing of Steller sea lions as threatened under the Endangered Species Act. Final Rule. FR 62:30772-30773 (5 Jun 1997). National Marine Fisheries Service, National Oceanic and Atmospheric Administration. Department of Commerce, Washington, D.C.

WINSHIP, A.J., TRITES, A.W., AND CALKINS, D.G. 2001. Growth in body size of the Steller sea lion (*Eumetopias jubatus*). Journal of Mammalogy 82(2):500-519.

WOLF, P.R. 1983. Elements of Photogrammetry. McGraw-Hill, Inc, USA.

WOLFE, J.H. 1970. Pattern clustering by multivariate mixture analysis. Multivariate Behavioral Research 5(3):329-350.

WOOD, C.C., MCKINNELL, S., MULLIGAN, T.J., AND FOURNIER, D.A. 1987. Stock identification with the maximum-likelihood mixture model: sensitivity analysis and application to complex problems. Canadian Journal of Fisheries and Aquatic Sciences 44(4):866-881.

FIGURES

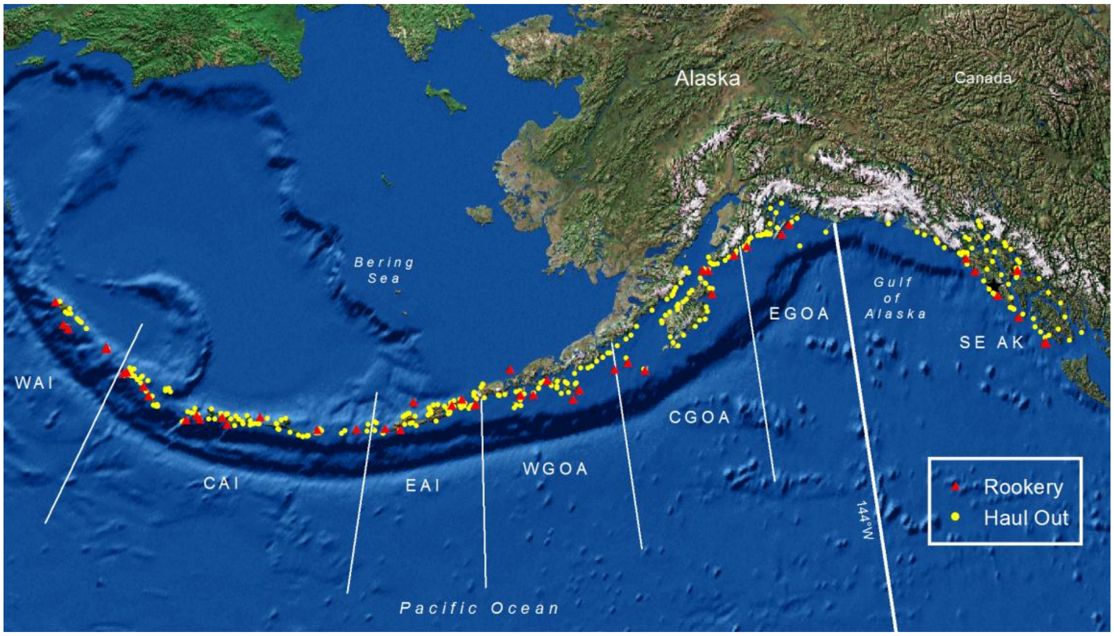

FIG. 1.–Distribution of Steller sea lion haul out and rookery sites throughout the Alaska range; eastern and western DPS divided at longitude 144°W.

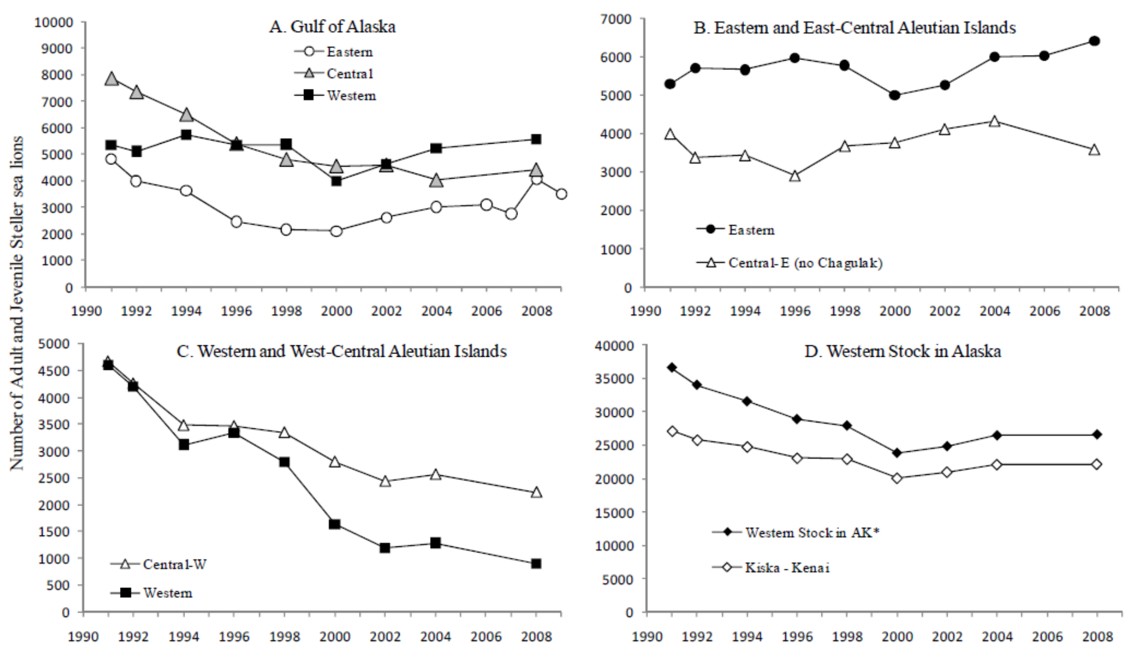

FIG. 2.–Abundance of non-pup Steller sea lions from 1991 to 2009, by region: A. GOA; B. EAI and east-CAI; C. WAI and west-CAI; and D. western DPS and the core of the western DPS range, Kenai to Kiska, which includes the CGOA through the CAI. Total in western DPS reflects adjustment to the eastern Gulf of Alaska total adjusted for movement, primarily from southeast Alaska in 2008 (*; NMFS 2010).

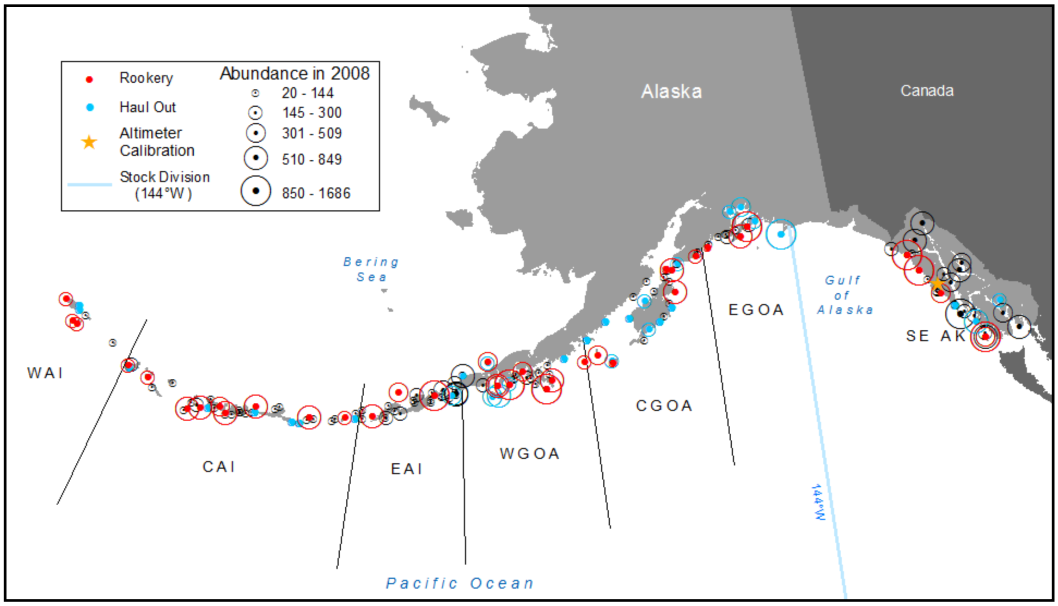

FIG. 3.–Steller sea lion rookery (red) and haul out (blue) sites selected for measuring shown in relation to 2008 abundance counts for all sites surveyed (circles), across the western (WAI), central (CAI) and eastern (EAI) Aleutian Island regions; western (WGOA), central (CGOA) and eastern (EGOA) Gulf of Alaska regions in the western DPS; and southeast Alaska (SE AK) region in the eastern DPS. Altitude calibration flight performed in Sitka, Alaska on 7 June 2008 (★).

FIG. 4.–Vertical digital image of Graves Rock rookery site in southeast Alaska (SE AK, eastern DPS); inset displays zoomed in region with individual sea lion standard lengths measured with a straight red line from the tip of the nose to the tail, or where the lanugo ends before the hind flippers begin.

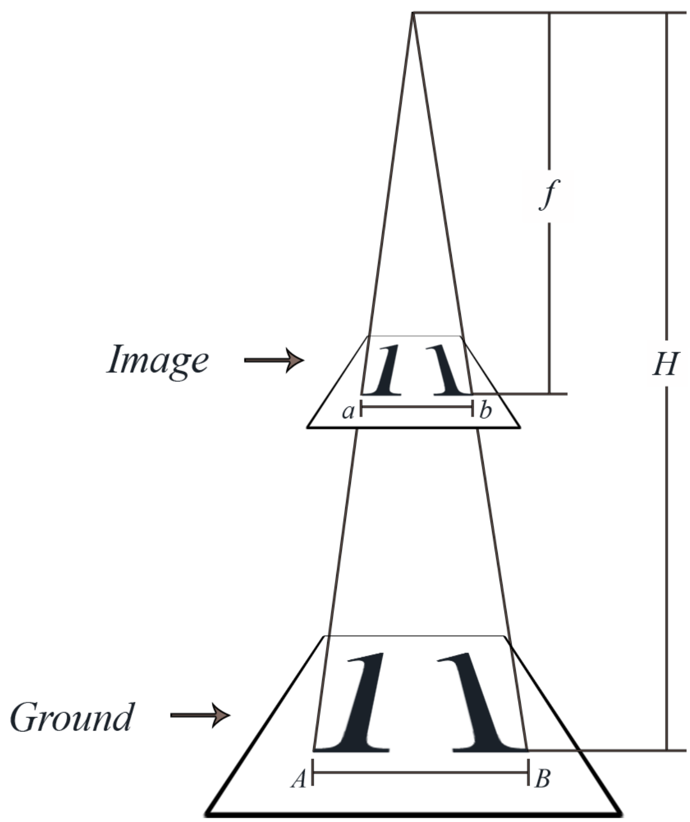

FIG. 5.—Depiction of the scale factor relationship between vertical aerial images captured of the runway number “11” in Sitka, Alaska captured during the altitude calibration flight (not to scale). The ground measurements (AB) at altitude (H) are proportional to lengths measured from vertical digital images (ab) captured at focal length distance (f; Gilpatrick 1996; Wolf 1983).

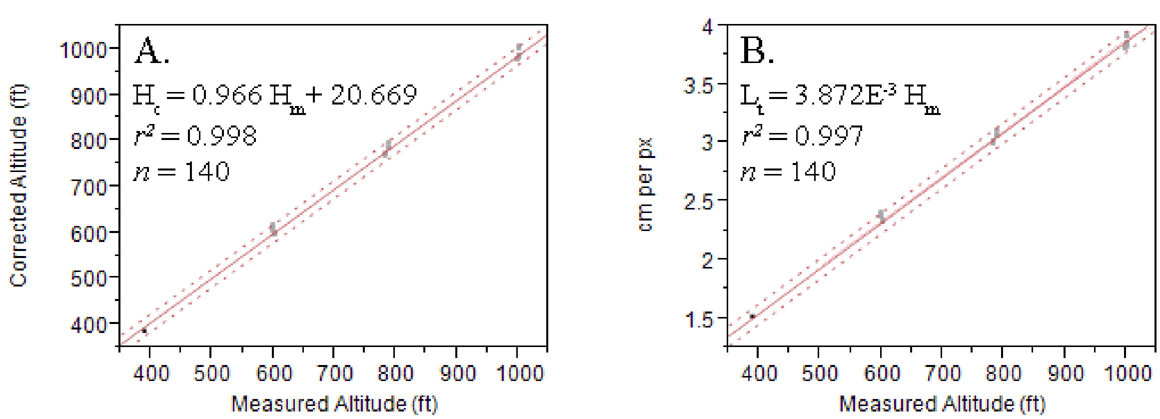

FIG. 6.—Linear regression (A) performed to determine the relationship between corrected altitude (H_c) and the measured altitude (H_m) recorded from the radar altimeter. The second linear regression (B) was conducted to find the relationship between the known pixel ratio (L_t) and measured altitude (H_m) measured from images captured during the altitude calibration flight performed on 7 June 2008 in Sitka, Alaska.

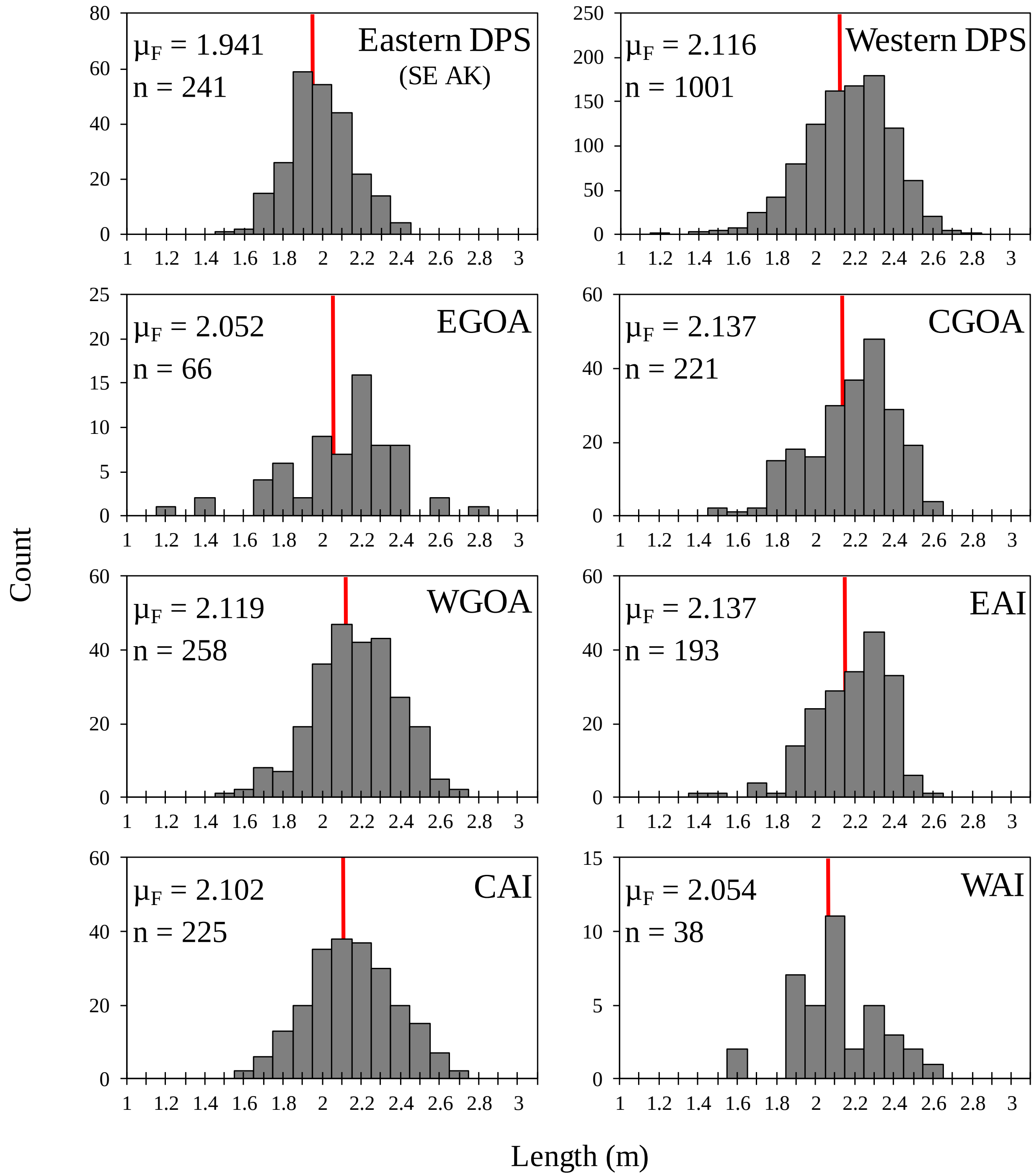

FIG. 7.—Histogram of observed adult female 'true' lengths (m; μ_F) measured from vertical digital images—as indicated by presence of pup or juvenile suckling, or in contact with female—for the eastern DPS (SE AK), western DPS, and the six regions comprising the western DPS—EGOA, CGOA, WGOA, EAI, CAI, and WAI regions.

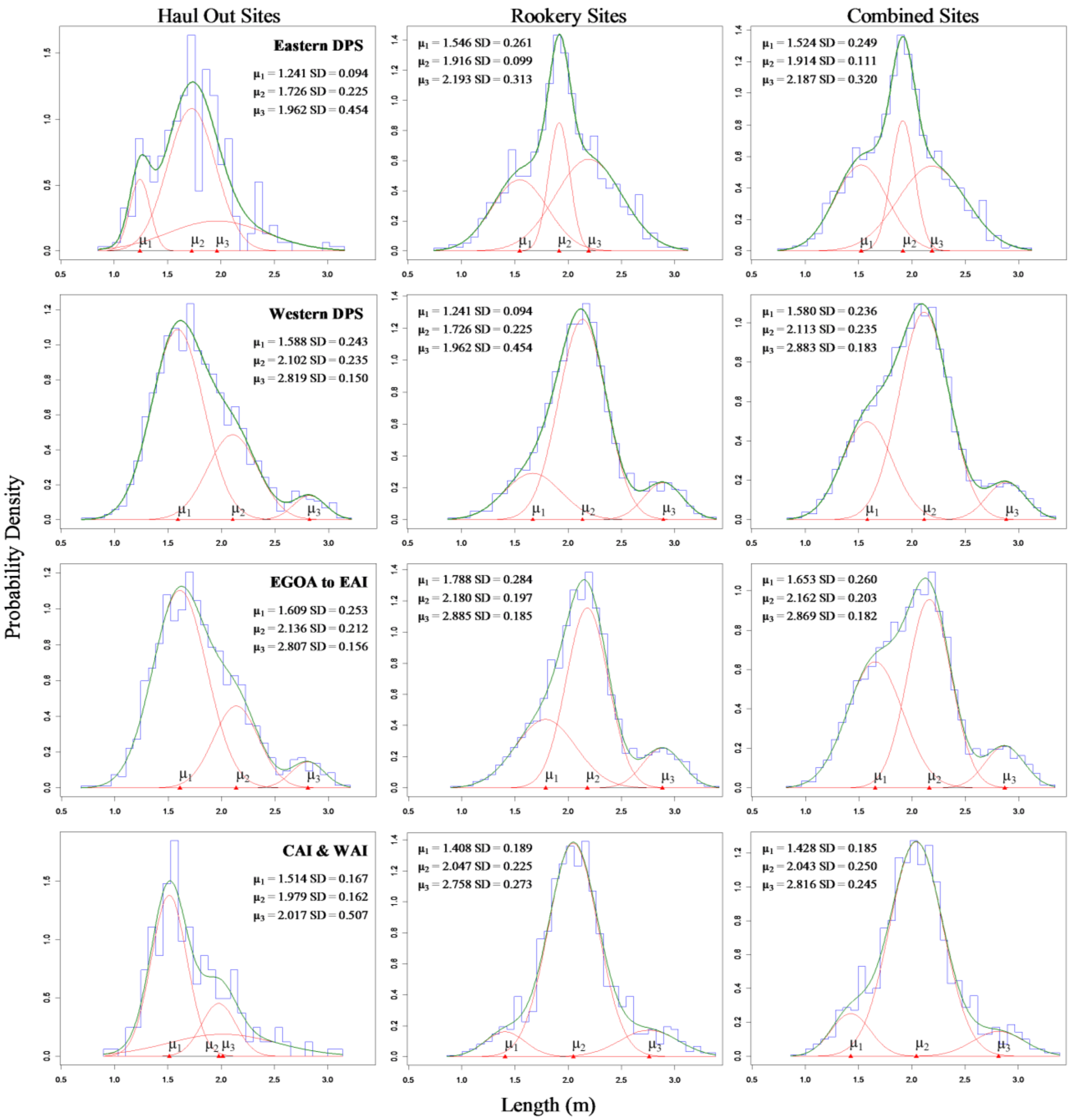

FIG. 8.—Probability density histograms of measured lengths (m) from rookery, haul out, and combined sites for the eastern DPS (SE AK), western DPS, EGOA-EAI regions—relatively stable or increasing abundance— and the CAI-WAI regions experiencing significant declines in pup and non-pup abundance. Mean length (m; μ) and standard deviation (m; SD) derived from FMD modeling for each age-sex class component (red distribution lines)—1, 2, and 3 for juvenile, adult female and male, respectively (note: probability density axes units vary).

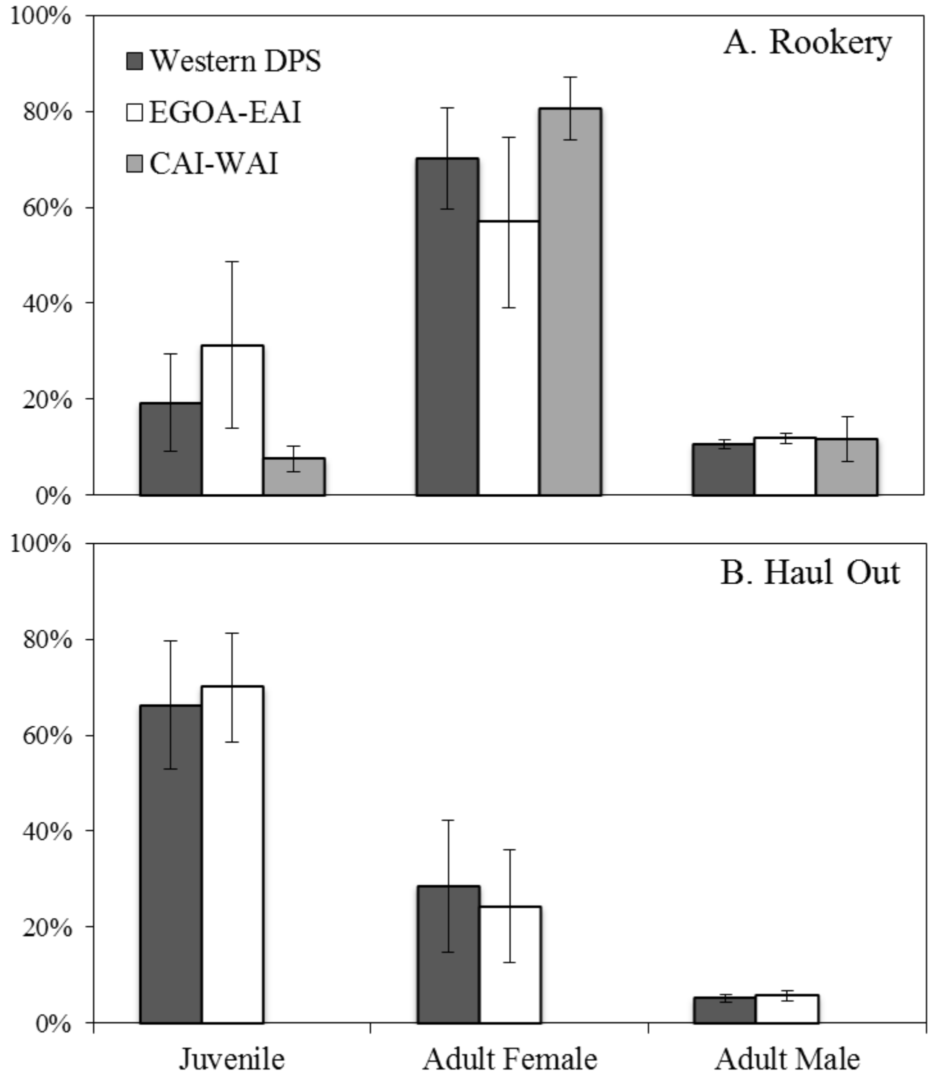

FIG. 9.—Percent of the total mixture (with standard error bars) estimated for each age-sex class component derived from FMD modeling for the broad regional comparisons—eastern DPS, western DPS, and EGOA-EAI regions for haul out and rookery sites; percent of mixture estimated for the CAI-WAI rookery only—proportion of mixture for eastern DPS haul out and rookery, as well as CAI-WAI haul out sites estimates not shown.

Tables

TABLE 1.—Number of sites selected for measuring, number of sea lions measured (of Straightness Classification 3), and number of observed known adult females indicated while measuring from haul out, rookery, and combined sites for the eastern DPS (SE AK), western DPS, and six regions comprising the western DPS.

		Haul Out Sites		Rookery Sites		Combined Sites		
	Region	Sites	Measured	Sites	Measured	Sites	Measured	Observed Female
Eastern DPS	SE AK	3	218	5	1066	8	1284	241
Western DPS	All Range	28	1479	32	3258	60	4737	1001
	EGOA	4	544	3	321	7	865	66
	CGOA	9	187	6	596	15	783	221
	WGOA	4	447	7	918	11	1365	258
	EAI	3	185	4	540	7	725	193
	CAI	6	105	9	756	15	861	225
	WAI	2	11	3	127	5	138	38
Total		31	1697	37	4324	68	6021	2243

TABLE 2.—Mean length (m) and standard deviation (SD; m) of juvenile and adult female and male age-sex classes derived from FMD modeling for rookery, haul out, and combined sites for the four broad regional comparisons—eastern DPS, western DPS, EGOA-EAI, and CAI-WAI regions. For the same broad regional comparisons, mean length and SD for combined sites estimated from observed known adult females—indicated by the presence of a pup or juvenile at close proximity—shown in parentheses.

Broad Regional Comparison		Haul Out Sites			Rookery Sites			Combined Sites		
		Juvenile	Adult Female	Adult Male	Juvenile	Adult Female	Adult Male	Juvenile	Adult Female	Adult Male
Eastern DPS	Mean	1.241	1.726	1.962	1.546	1.916	2.193	1.524	1.914 (1.941)	2.187
	SD	0.094	0.225	0.454	0.261	0.099	0.313	0.249	0.111 (0.167)	0.320
Western DPS	Mean	1.588	2.102	2.819	1.667	2.135	2.891	1.580	2.113 (2.116)	2.883
	SD	0.243	0.235	0.150	0.265	0.223	0.182	0.236	0.235 (0.221)	0.183
EGOA through EAI	Mean	1.609	2.136	2.807	1.788	2.180	2.885	1.653	2.162 (2.123)	2.869
	SD	0.253	0.212	0.156	0.284	0.197	0.185	0.260	0.203 (0.219)	0.182
CAI & WAI	Mean	1.514	1.979	2.017	1.618	2.050	2.725	1.600	2.057 (2.056)	2.692
	SD	0.167	0.162	0.507	0.270	0.196	0.228	0.236	0.184 (0.208)	0.245