Individual-based photogrammetric measures of length, growth and shape to infer body condition and reproductive status of southern resident killer whales

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Summary

The endangered population of southern resident killer whales (*Orcinus orca*) is hypothesized to be food limited, and declines in the availability of their primary prey of Chinook salmon have correlated with increased mortality, decreased fecundity and changes in social cohesion. However, a recent report on the effects of salmon fisheries on southern residents highlighted uncertainty about whether the abundance of Chinook salmon is low enough to cause nutritional stress, and recommended further evaluation using photogrammetry. Here we used aerial photogrammetry from a helicopter to provide measures of length, growth and shape of individually-identifiable whales to enable inference about body condition and reproductive status. Notably, we compared measurements from a previous field effort in 2008 to new data collected in 2013 to assess changes between years both at the individual and population levels.

We conducted 8 flights (8.5 hours total) in September 2013, using a helicopter based from Friday Harbor, WA. Aerial images were matched to a boat-based photo-identification catalog to provide individual identifications to whales of known age and sex. This resulted in 6974 aerial images of 69 different individuals from J, K and L pods (J=25, K=18; L=26), representing more than three quarters of the population (2013 population census of 82 whales). We also photographed a known-sized (6.4m) research boat on each day for calibration, revealing a high precision to our technique with median bias of just 4 cm (<1%).

Calculations of scale (altitude/focal length) were used to estimate total body lengths of 69 whales (40 females and 29 males) in 2013, ranging from 1.5 to 85.5 years of age, comparable to 68 individuals (38 females, 30 males) in 2008. In total between the two years we obtained 137 length-at-age measures for 86 different individuals; 51 individuals were measured in both years. The smallest whale measured in 2013 was J49, a 1.5yr old juvenile male of 3.5m, compared to the smallest whale measured in 2008, K42, 0.5yr male calf of 3.1m. The largest whale measured in both years was an adult male, L41 (31.5 and 36.5yr old), with a best length estimate of 7.3 m. For both years, adult males ranged from 6.2 m to 7.3 m (median = 6.9 m) and females of reproductive age or greater (>/= 10.5 years old) ranged from 5.1 m to 6.4 m (median = 6.0 m).

Head width (width at 15% of the distance between the blowhole and anterior insertion of the dorsal fin) was used the main indicator of body condition. We estimated head width for 66 individuals (38 females, 28 males) in 2013 and 59 individuals (32 females, 27 males) in 2008, assessing changes in 43 individuals (25 females, 18 males) common between both years. The age classes with the largest head width (proportional to blowhole-dorsal fin length) were young whales: immature males in 2013 and calves in 2008. In contrast, adult females had the smallest proportional head widths on average: post-reproductive females had the smallest in 2013 and reproductive females had the smallest in 2008 and the second smallest in 2013. Of the whales with measures in both years, 11 had significant declines in proportional head width compared to only five with increases. The average proportional head width decreased for all age classes, except for older males. This reduced body condition in 2013 is consistent with a declining trend in Chinook salmon returns through the core summer feeding range of the population.

Breadth (the width at the anterior insertion of the dorsal fin) was used as the main indicator of pregnancy. Breadth was measured for 44 individuals (27 females, 17 males) in 2013 and 47 individuals (28 females, 19 males) in 2008, with 23 individuals (17 females, 6 males) common across years. The only significant differences between years were for reproductive age females, with eight whales increasing in proportional breadth and five more having breadths comparable

to their pregnant measures in 2008. However, only two of these were documented later with a calf, suggesting a surprisingly high level of reproductive failure or neonatal mortality.

Background

The southern resident population of killer whales (*Orcinus orca*) was listed as "Endangered" under the Endangered Species Act in the U.S. in 2005 (National Marine Fisheries Service 2008) and the Species At Risk Act in Canada in 2002 (Fisheries & Oceans Canada 2008). This population is hypothesized to be food limited, and declines in the availability of their primary prey, Chinook salmon (*Oncorynchus tshawytscha*; Ford and Ellis 2006), have correlated with increased mortality, decreased fecundity and changes in social cohesion (Ford et al. 2009; Ward et al. 2009; Parsons et al. 2009; Foster et al. 2012b). However, a recent report of the independent science panel on the effects of salmon fisheries on southern resident killer whales highlighted uncertainty over the link between prey availability and population dynamics (Hilborn et al. 2012). Specifically, the panel cited a key data gap of whether the abundance of their preferred Chinook salmon prey is low enough to cause nutritional stress and, based on the success of our previous photogrammetric efforts in 2008 (see Durban et al. 2009, Fearnbach et al. 2011, and Durban et al. 2012), recommended the further use of photogrammetry to assess the nutritive status of the population. In response to these suggestions, we conducted a second round of aerial photogrammetry in 2013, with the aim of assessing growth (length-at-age), body condition and reproductive status of individuals within the southern resident population.

Here we report on the most recent photogrammetry effort in 2013, particularly in the context of evaluating changes in photogrammetric measures between the 2008 and 2013 samples, both at the level of individuals and the population. In both sampling periods we were able to successfully obtain measurements from more than three quarters of the population to fill key data gaps for monitoring health and status. These efforts would not have been possible without the long-term photo-identification monitoring by the Center for Whale Research (CWR), which allowed us to match aerial images to a current photo-identification catalog to link images to whales of known age and sex.

Methods

We used the same helicopter platform and followed the same survey methods as previously described for the 2008 photogrammetry effort (see Durban et al. 2009 and Fearnbach et al. 2011), with the exception of a few minor upgrades to equipment. Similar to 2008, we chartered a Robinson R44 Clipper helicopter, based out of Friday Harbor Airport, to fly all photogrammetry flights. The helicopter and pilot were on standby during the entire survey period (September 1st-15th) to allow for a quick response when whales were sighted and conditions allowed for photogrammetry efforts. Close communications were maintained between the aerial team (authors JWD and HOF) and boat team (authors DKE, KCB) to locate whales with a dedicated research boat (6.4m Boston Whaler) to minimize costly search time using the helicopter and assist with guiding the helicopter between specific individuals and groups of whales to maximize population coverage. Flight operations over whales were conducted between 230m (750ft) and 460m (1500ft), and approaches below 1000 ft were conducted under National Marine Fisheries Service Permit #155569 in the U.S. and Species-At-Risk Act Permit # 13-278 in Canada.

In-flight operations were also the same as 2008 (see Durban et al. 2009 and Fearnbach et al. 2011). JWD acted as the onboard guide to the helicopter pilot and maintained communications between the aerial team and boat team (DKE, KCB); HOF was the aerial photographer. Gear modifications included upgrading in the digital SLR camera and lens used for collecting photogrammetry images to a Nikon D800E with a fixed focal length 300mm f4 Nikkor lens to collect images with a resolution of 7360 X 1412 pixels (36.3 effective Megapixel resolution). We also changed our the primary GPS used for altitude recording to a Bad Elf Pro that was SBAS/WAAS/EGNOS/MSAS enabled with an estimated precision of 2.5 m.

Photo processing post-flights was also the same as 2008 (see Durban et al. 2009 and Fearnbach et al. 2011). Individual identifications were assigned to all photographs of whales in usable images by DKE, and all identifications were checked by HOF. Individual identifications were made by comparing to the Center for Whale Research's most current boat-based photo-identification catalog, and also by reviewing boat-based identification images that were collected simultaneously with aerial efforts. Images collected during the survey period proved to be important for showing temporary and natural marks that were apparent in the aerial images (see Figure 1).

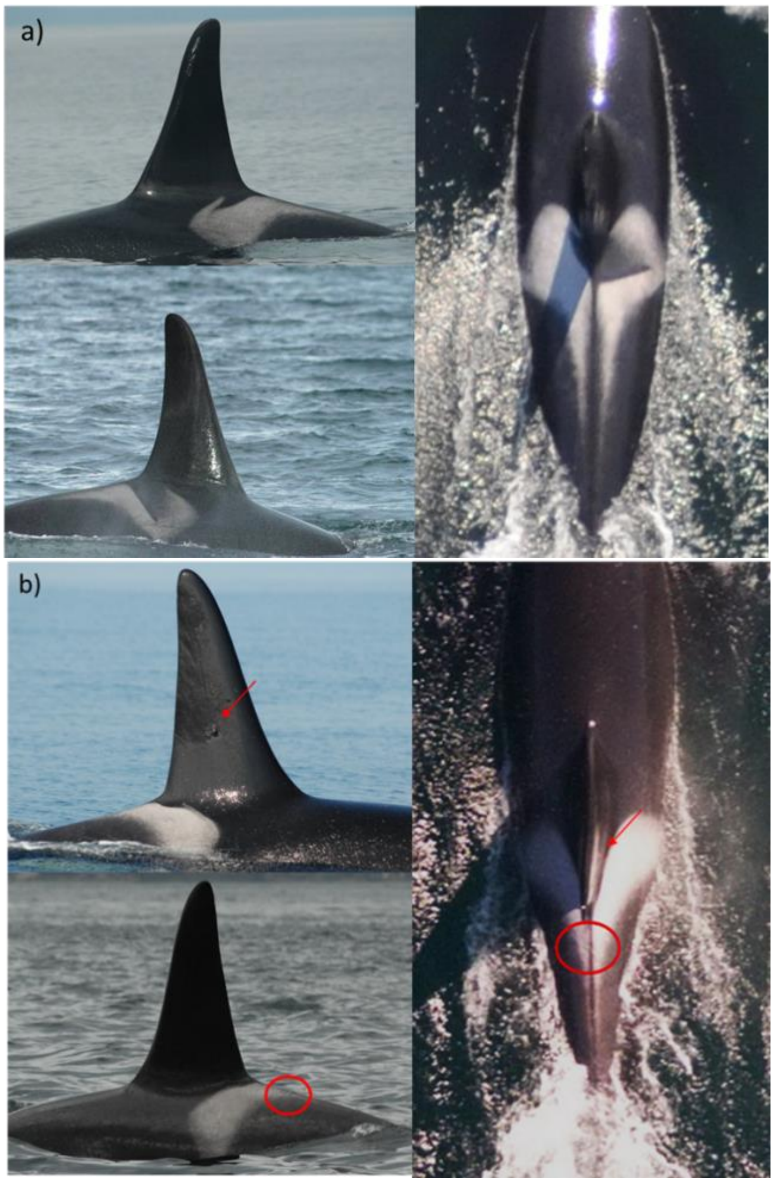


Figure 1: Left and right side identification photographs obtained from a boat (left) and helicopter (right) showing distinct patch pigmentation patterns and pigmentation patterns of individuals and demonstrating the utility of also using temporary marks to assist in aerial identification. **a)** L78, a male born in 1989, has distinctive asymmetrical saddle patch pigmentation used to confirm identification. **b)** K25, a male born in 1991, does not have an overly distinct saddle pigmentation pattern, but does have number of temporary marks (scratches and behind saddle and tagging wound on the fin) that are visible from both the water and the air.

Ages of whales were assigned based on the established method outlined in Fearnbach et al. (2011). The ages of individually identifiable whales born since the start of the photo-identification study in the 1970s were based on long-term longitudinal birth and sighting records (Ford et al. 2000, Balcomb unpublished data), and the age estimates of whales born prior to the start of the photo-identification study were based on the size development of dorsal fins for males and the age of oldest offspring for females, as described by Olesiuk et al. (1990, 2005) and presented in Ford et al. (2000). Following Olesiuk et al. (1990), ages were standardized by considering whales to be 0.5yrs old in their first summer (May to September) census period. Sex was determined by visual observation of genital anatomy and pigmentation (e.g. Ford et al. 2000), by the development of sexual secondary characteristics in males (particularly the dorsal fin), or by the birth of a calf in females (Ford et al. 2000, K. C. Balcomb unpublished data). To facilitate between year comparisons, individuals were assigned to age classes in each year as follows: C (calf, 0.5 years), J (juvenile, 1.5- 9.5 years), MI (male immature, 10.5-21.5 years), MO (male old, 22.5+ years), RF (reproductive female, 10.5-42.5 years), and SF (senescent female, 43.5+ years).

Photogrammetric measurements were obtained using the same methods as previously (see Durban et al. 2009 and Fearnbach et al. 2011). Only images where the whales were directly below the helicopter and where the whale was in straight orientation (i.e. no tilt in the body axis) were selected for measurement and included in analysis. The freely available photo processing software Image J (http://rsb.info.nih.gov/ij/) was used to measure the distance (in pixels) between points along the body axis including: the tip of the rostrum to the anterior insertion of the dorsal fin (SNDF), the blowhole to the anterior insertion of the dorsal fin (BHDF), the anterior insertion of the dorsal fin to the fluke notch (DFFL), body length (L = the tip of the rostrum to the fluke notch, L), head width (HW = the width of the head at a distance of 15% of the total distance between the blowhole and the anterior insertion of the dorsal fin), breadth (B= width at the anterior insertion of the dorsal fin), and fluke width (FL).

In an update to our previous methods, we used two approaches to estimate body length L and chose the maximum measurement from either the two methods as the best; this is based on the assumption that length estimates are inherently negatively biased for true length due to a degree of arching to the whales' bodies during surfacing. Similar to 2008, we estimated L from photos where the whale was in an apparently "flat" position and we could measure from tip of the rostrum and to the fluke notch, defined this as L_m (m = "measured"). We also estimated L from a combination of the maximum (least biased) measurement of SNDF and DFFL, defined as L_d (d = "derived"). Measurements in pixels were converted to a true measurement on the sensor using information on the real sensor width of the camera and the number of pixels comprising this width. Measurements were then scaled to true lengths using the measured altitude and the lens focal length (scale = altitude / focal length).

Also similar to 2008, we used two indices to evaluate body shape: head width (HW = the width at 15% of the distance between the blowhole and anterior insertion of the dorsal fin) and breadth (B = the width at the anterior insertion of the dorsal fin); both were measured in pixels and expressed as a proportion of the BHDF pixels in the same image. For all metrics, we required a minimum of at least three estimates in order to include an individual in the subsequent data analyses.

Results

Effort summary

Eight flights (8.5 hours total) were flown over five days between September 3rd -11th, 2013 (Table 1), with an average flight time of 64 min (min=30 mins; max=114 mins). Photographs were taken from an average altitude of 337 m in 2013 (range: 220-460 m) compared to 302 m (range: 220–407m) in 2008. Whales were primarily encountered in U.S. waters, to the west and south of San Juan Island, WA, but one encounter occurred in Canada off the southeast end of Vancouver Island, British Columbia, off Discovery Island (Figure 2). We collected 6974 aerial photographs during encounters, including images of the Center for Whale Research boat "Orca", a 6.4 m Boston Whaler that was used as calibration to measure an object of known size (see Fearnbach et al. 2011). Multiple copies of photographs were made when more than one whale was present in the image, resulting in 12624 whale images, and 9557 of these passed the quality standards for measuring. Pooling data from 2008 and 2013, a total of 16316 whale images have been databased and evaluated for measurements.

Table 1: Summary of the eight helicopter flights during which aerial photographs of whales were obtained including the date of survey, the duration of the flight in minutes (including transit to the whales), the southern resident killer whale (SRKW) pods photographed and the location where the whales were encountered off San Juan Island (SJI), WA, and Vancouver Island, British Columbia (BC).

Date	Flight Minutes	SRKW Pods	Location
03-Sept-2013	114	J, L	Strait of Juan de Fuca, Salmon Bank
04-Sept-2013	70	J, K, L	Haro Strait, off False Bay, W side of SJI
08-Sept-2013	65	J, K (+L87)	S Haro Strait
10-Sept-2013	61	J, K (+L87)	Haro Strait, off the W side of SJI
10-Sept-2013	69	J, K, (+L87)	Strait of Juan de Fuca, Salmon Bank
10-Sept-2013	30	J, K, (+L87)	Strait of Juan De Fuca, S of Salmon Bank
11-Sept-2013	47	J, K, L	Strait of Juan De Fuca, off Discovery Island, BC
11-Sept-2013	58	J, K, L	S Haro Straight

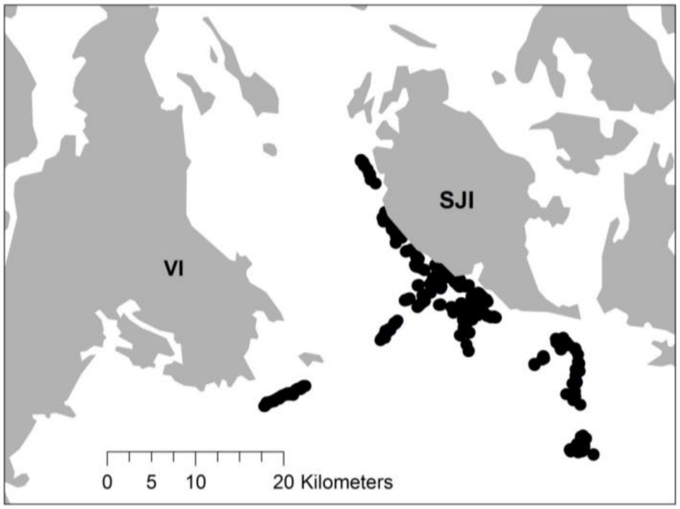


Figure 2: Map showing the locations where 6974 aerial photographs were obtained of Southern Resident killer whales (black dots) during the 8.5 hours of photogrammetry flights between San Juan Island (SJI), Washington State and Vancouver Island (VI), Canada in September 2013.

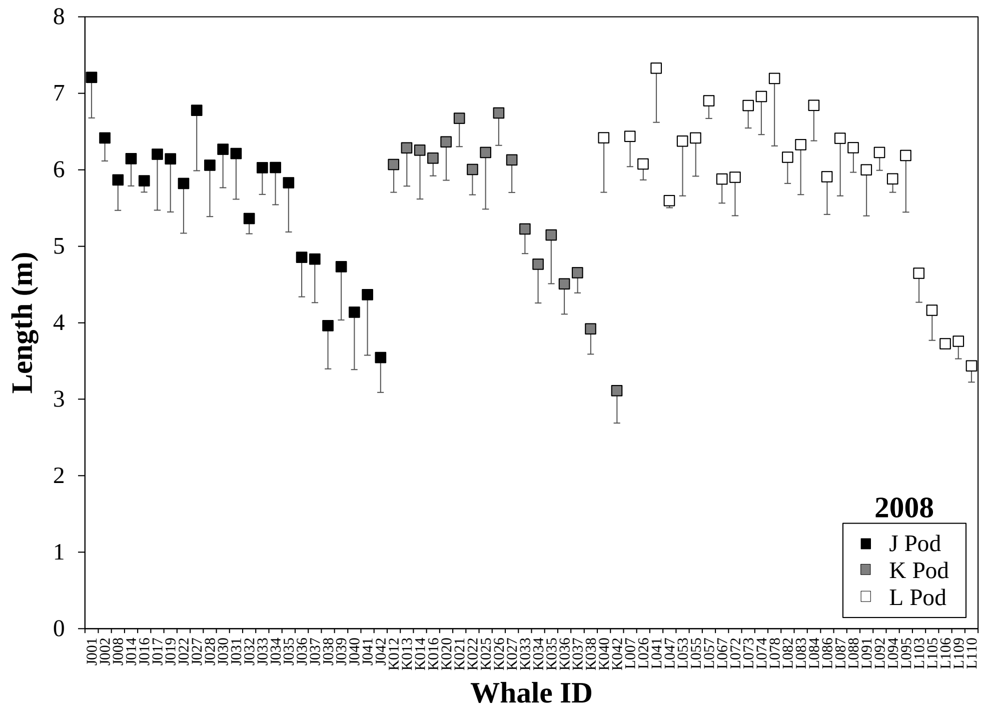
Calibration

We used our research boat, a 6.4m Boston Whaler in a calibration experiment to measure an object of known size (see Fearnbach et al. 2011). The boat was photographed at least once during each of the 8 flights and was always photographed in the same location and time period as the whales. We were able to measure 75 photographs that were deemed to be taken from directly overhead, and used the maximum estimate for the boat on each day. These daily estimates had a median of 6.36 m (range = 6.27 - 6.46), representing a bias of just 0.04 m (range = 0.03–0.13m) equating to just 0.63 % (range = 0.47–2.0%) of the true length of the boat.

In addition, we were able to use the measurement of J32, a whale that was photographed when alive in 2013, but subsequently died in 2014, as a second calibration. Our maximum free-swimming estimate (L_d) of J32 was 5.59 m and her necropsy measurement on December 6, 2014 was 5.62 m, a difference of only 0.03 m, representing 0.53% of her total length.

Length estimates

For those individuals for which we obtained three or more measurements, we estimated body lengths of 69 individuals (40 females and 29 males) in 2013, ranging from 1.5 to 85.5yrs old, compared to 68 individuals (38 females, 30 males) in 2008, ranging from 0.5 to 97.5yrs (Appendix Table 1, Figure 3). In total between the two years we obtained 137 length-at-age measures (Figure 4) for 86 different individuals; fifty-one individuals were measured in both years (Figure 5). The smallest whale measured in 2013 was J49, a 1.5yr old juvenile male of 3.5m, compared to the smallest whale in 2008, K42, a 0.5yr old neonate of 3.1m. We were able to monitor growth in 25 immature whales between 2008 and 2013. The largest whale measured in both years was an adult male L41 (31.5 and 36.5yrs old in 2008 and 2013, respectively), with a best length estimate of 7.3 m. For both years, adult males (defined for consistency as >/= 22.5yrs) ranged from 6.2 m to 7.3 m (median: 6.9 m) and females of reproductive age or greater (>/= 10.5yrs) ranged from 5.1 m to 6.4 m (median: 6.0 m). Length distributions for each age class were similar across year (Figure 6).



8
7
6
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4
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2
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Length (m)
2008
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Whale ID

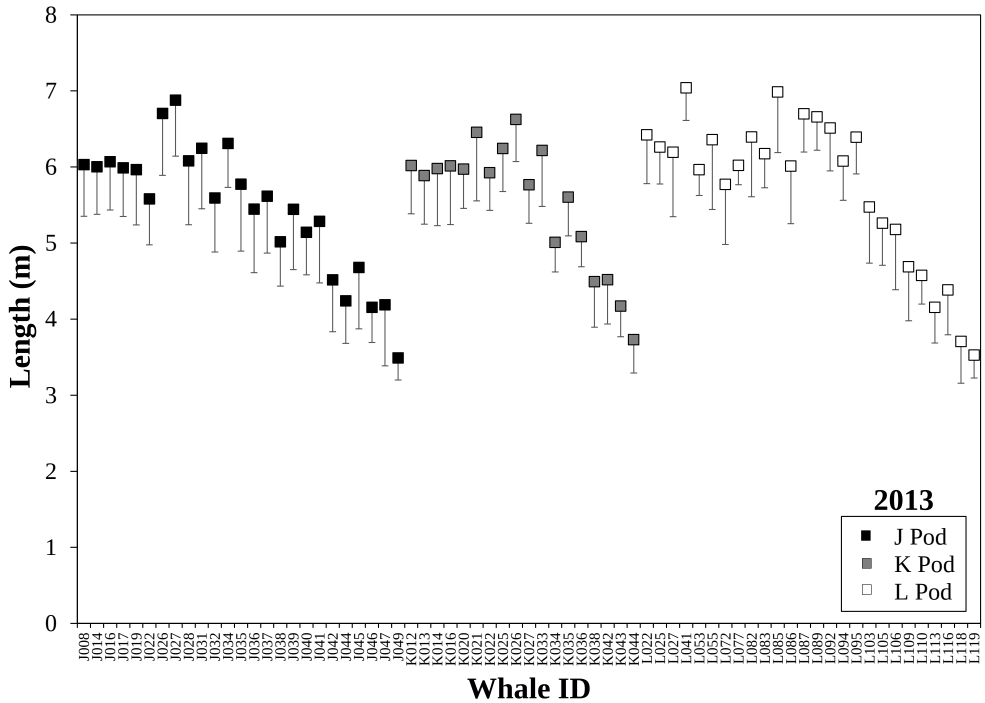


Figure 3: Length estimates for individuals from J (black square), K (gray square) and L (white square) pods within the southern resident killer whale population from 2008 (top, 68 individuals) and 2013 (bottom, 69 individuals). Squares represent the best (maximum) length estimate for each whale, vertical lines represent the extent of the variability between estimates of the same whale.

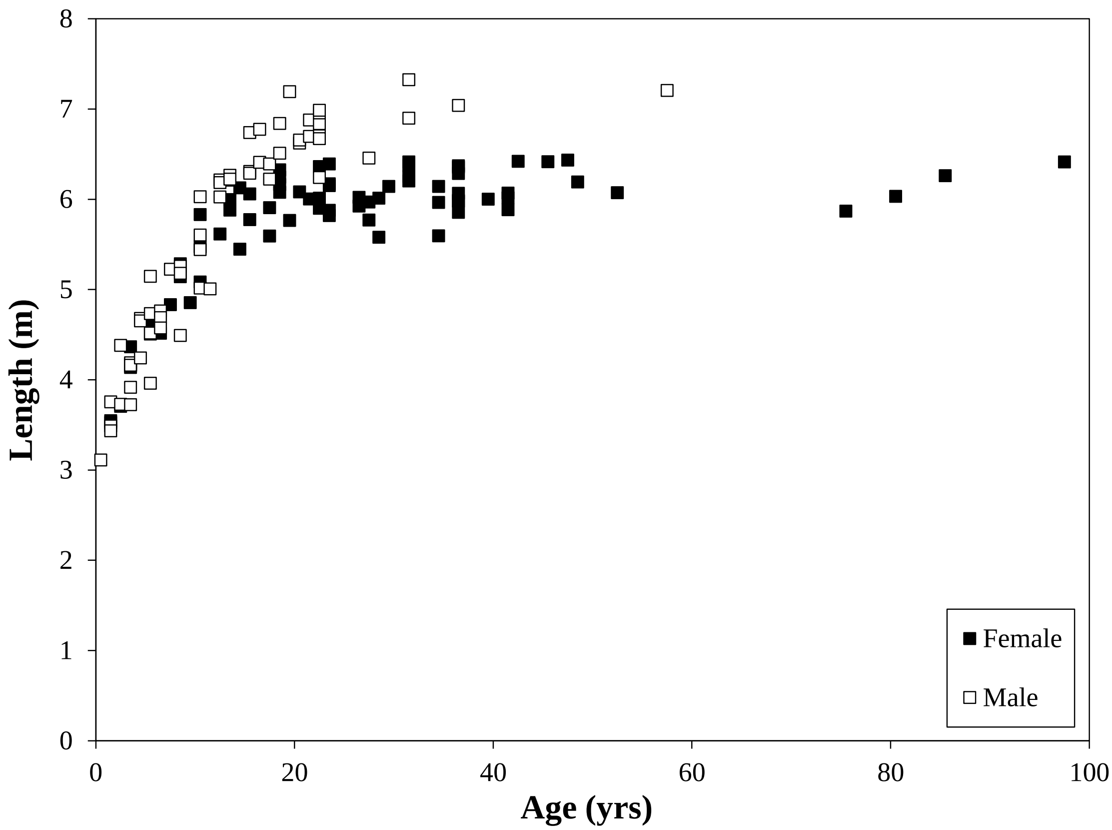


Figure 4: Maximum length estimates for 86 individuals from J, K and L pods within the southern resident killer whale population plotted against their observed or estimated ages. Estimates were combined from both years 2008 and 2013, resulting 137 size-at-age estimates (51 individuals were measured in both years) for ranging from 0.5 years to 97.5 years. Individuals were required to have with ≥3 measurements during each sampling period to be included.

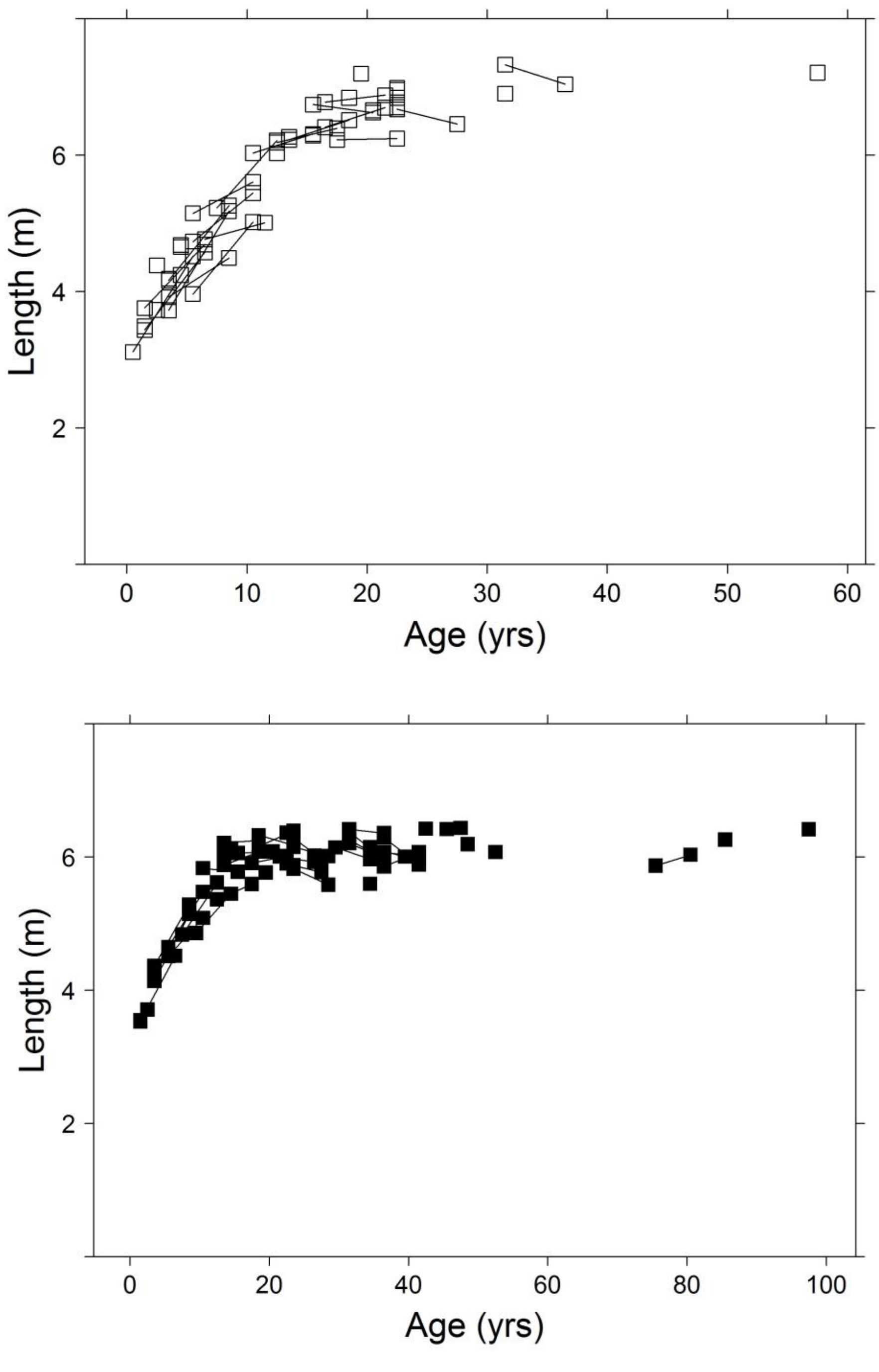


Figure 5: Best (maximum) estimates of length against age, for southern resident killer whale individuals. Estimates are combined for 2008 and 2013, and individuals were required to have with ≥3 measurements during a sampling period to be included. Males (*n*=30, 2008; *n*=29, 2013) are represented by white squares (top); females (*n*=38, 2008; *n*=40, 2013) are represented by black squares (bottom). Solid lines join estimates of the same individual from both years (20 males, 31 females).

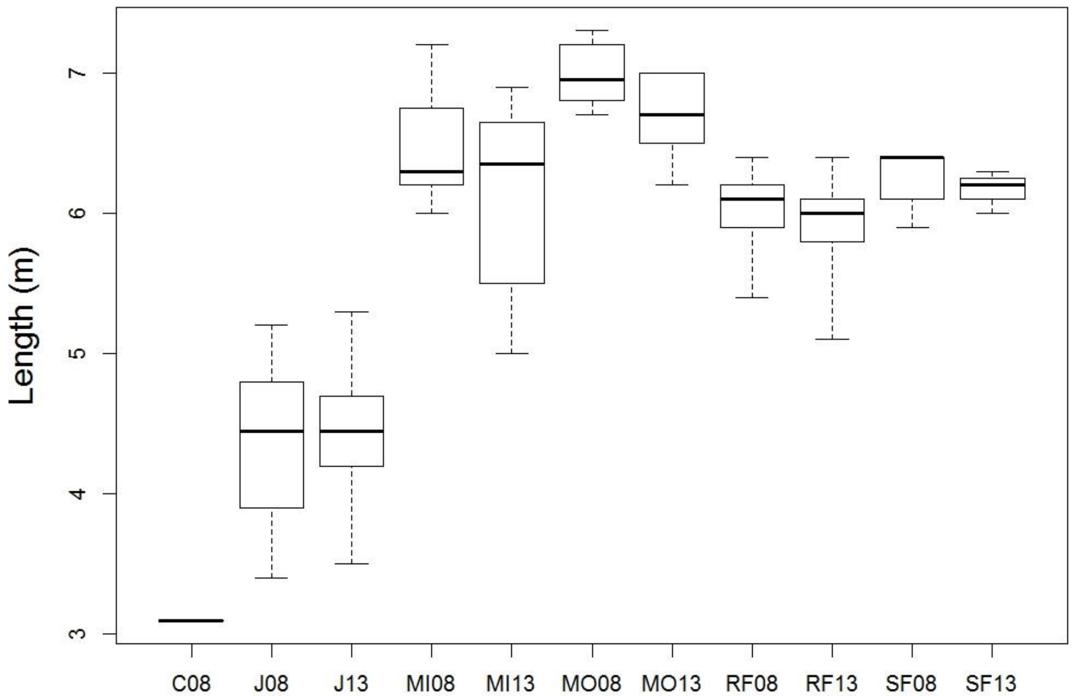
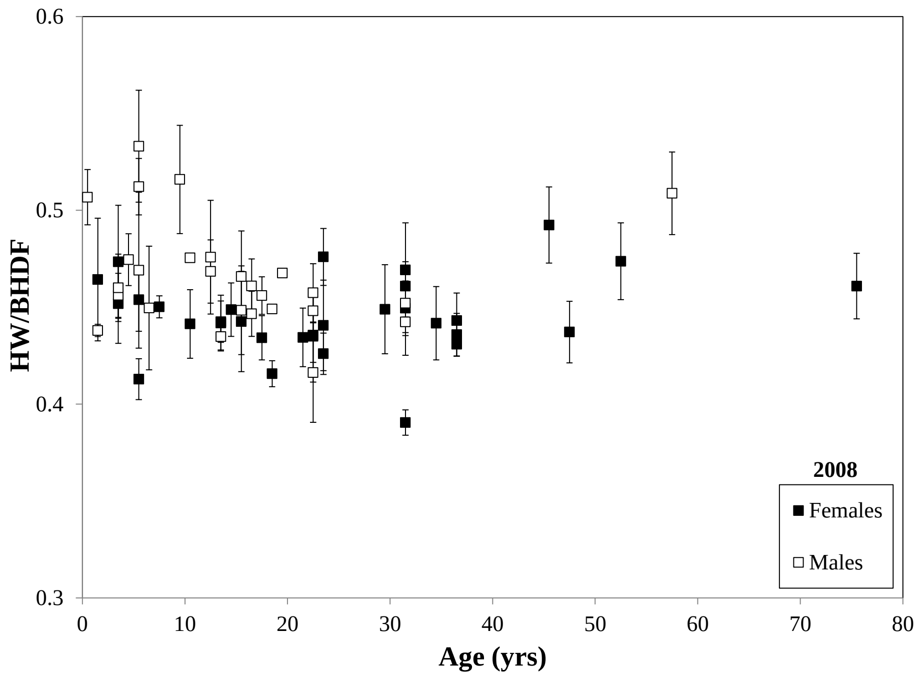


Figure 6. Box plots showing the distribution of best (maximum) estimates of lengths for individual southern resident killer whales in different age classes age classes: C = calves (</= 0.5 yrs), J = juveniles (1.5 - 9.5 yrs), RF = reproductive females (10.5 - 42.5 yrs), SF = senescent or post-reproductive females (>/= 43.5 yrs), MI = immature male (10.5-21.5 yrs), and MO = old males (>/= 22.5 yrs). The numbers "08" and "13" in age class labels represent the year (2008 or 2013). Estimates are presented as posterior medians (horizontal solid lines within the bars), with 75% (white bars) and 95% (vertical lines).

Body condition measurements: *Head Width*

We measured the HW/BHDF proportion for 66 individuals (38 females and 28 males) in 2013 and 59 individuals (32 females and 27 males) in 2008 (Figure 7) and were able to evaluate changes in HW/BHDF for 43 individuals (25 females and 18 males) between the two sampling periods (Figure 8). The individual whales with the smallest heads were reproductive females, L55 in 2008 and L94 in 2013; the whale with the largest head width in both years was J38, a juvenile male (Figures 7 and 8). In general, the age classes with the largest HW/BHDF were young whales: immature males in 2013 and calves in 2008; in contrast, adult females had the smallest head widths on average: post-reproductive (senescent) females had the smallest HW/BHDF in 2013 and reproductive females had the lowest HW/BHDF proportion for in 2008 and second lowest in HW/BHDF proportion in 2013 (Figure 9). Of the 44 with longitudinal measurements, 26 decreased (11 of these significantly; t-test, $p<0.05$) and only 11 increased (5 of these significantly) (Figure 8). Notably, 7 of the 11 whales with significant decreases were reproductive age females (10.5 - 42.5 yrs). In general, therefore, the average HW/BHDFL decreased for each all age class between 2008 and 2013, except for older males (Figure 9).



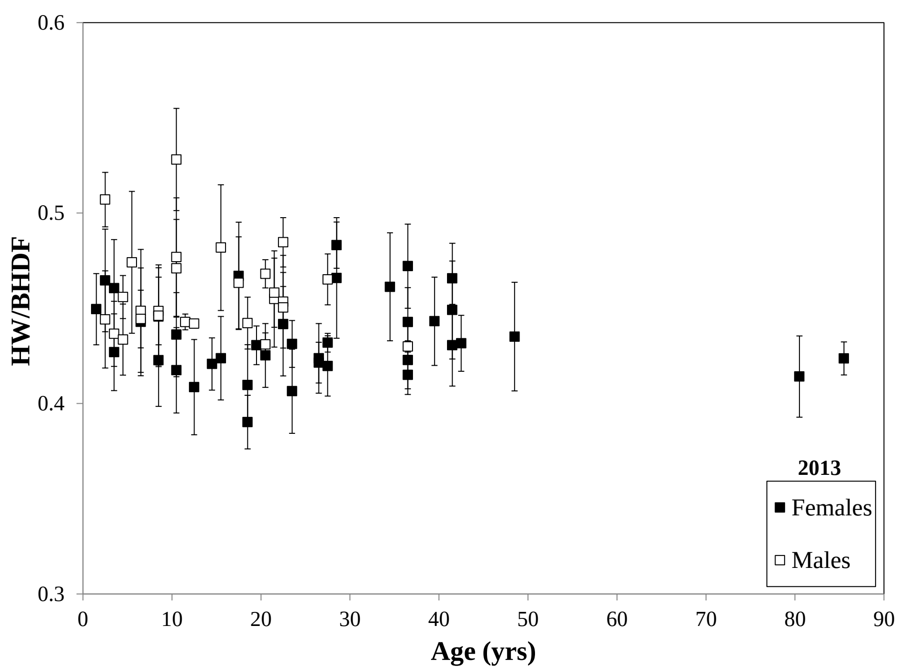


Figure 7. The head width (HW = width 15% posterior to the blowhole) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin), plotted against age for individuals from J, K and L pods in 2008 (*n*=59 individuals, top) and 2013 (*n*=66 individuals, bottom). Individuals were required to have ≥3 measurements to be included in each sampling period. The mean estimates across measurement photographs for each individual is shown by a square (black for females and white for males) and the vertical line is +/- one standard deviation.

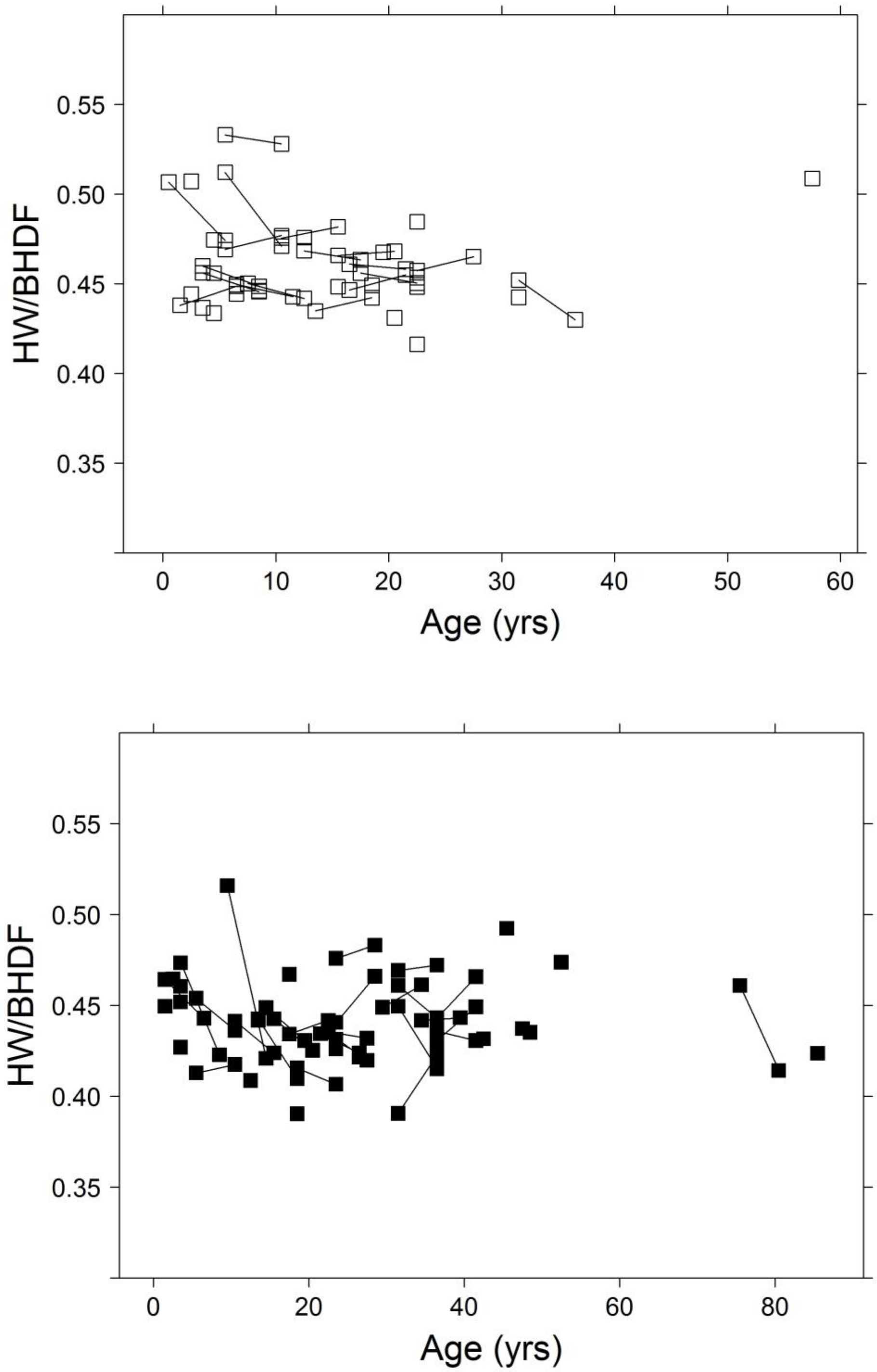


Figure 8: Best (mean) estimates of head width (HW = width at 15% posterior to the blowhole) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin) plotted against age for southern resident killer whale individuals. Measurements are presented for both 2008 and 2013, and individuals were required to have with ≥3 measurements during a sampling period to be included. Males (*n*=27, 2008; *n*=28, 2013) are represented by white squares (top); females (*n*=32, 2008; *n*=38, 2013) are represented by black squares (bottom). Solid lines join estimates of the same individual from both years (18 males, 25 females).

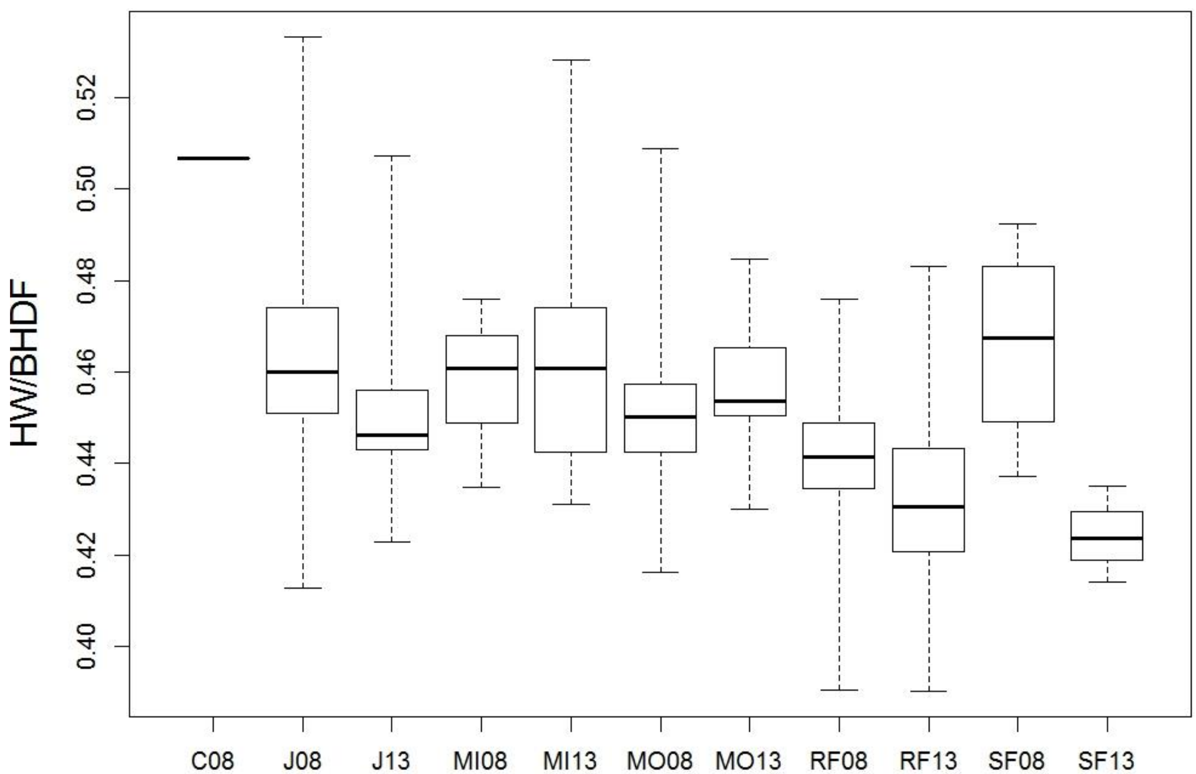


Figure 9: Box plots showing the distribution of average head width (HW = width at 15% posterior to the blowhole) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin) individual southern resident killer whales in different age classes age classes: C = calves (</= 0.5 yrs), J = juveniles (1.5 - 9.5 yrs), RF = reproductive females (10.5 - 42.5 yrs), SF = senescent or post-reproductive females (>/= 43.5 yrs), MI = immature male (10.5-21.5 yrs), and MO = old males (>/= 22.5 yrs). The numbers "08" and "13" in age class labels represent the year (2008 or 2013). Estimates are presented as posterior medians (horizontal solid lines within the bars), with 75% (white bars) and 95% (vertical lines).

Body condition measurements: *Breadth*

We estimated the B/BHDF proportion for 44 individuals (27 females, 17 males) in 2013 and 47 individuals (28 females and 19 males) in 2008 (Figure 10) and were able to evaluate changes in breadth for 23 individuals (17 females, 6 males) between the two sampling periods (Figure 11). Breadths were more difficult to measure than head widths, because water flow often obscured the edges of the animal during surfacing (Durban et al. 2009), as a result we obtained fewer whales with repeat measurements across years for breadth than for head width, and the age class summaries for breadth (Figure 12) reflect individual differences in body shape to a larger extent. However, if we examine changes in breadth for those specific individuals with repeat measurements in both years (Figure 13), significant differences ($p<0.05$, t-test) between years were found only for reproductive age females (10.5 - 42.5yrs) and not for any other age classes. This suggests that breadth is not a sensitive indicator of general change in body condition (as we suggested in Durban et al. 2009), but likely reflects differences in shape due to pregnancy. At least six females measured in 2008 are now known to have been pregnant at that time due to the documentation of calving within 17.5 months (gestation period) of the September photographic effort, and four of these were in relatively late stages of pregnancy (>9 months). In 2013, all of these females were either similarly wide in breadth (five whales; $p>0.05$ for null hypothesis of no between-year differences) or even wider (1 whale; $p<0.05$), suggesting that they may have been pregnant again. A further eight females that were not known to be pregnant in 2008 also had significantly wider breadths in 2013. Surprisingly, and notably, only two of these candidate pregnant animals were documented with a calf within gestation period of the September 2013 monitoring (J16, L86), and these did not include the whale with the widest breadth measured in either year (J22 in 2013). This strongly suggests a high level of reproductive failure or neonatal mortality before monitoring was able to document calves.

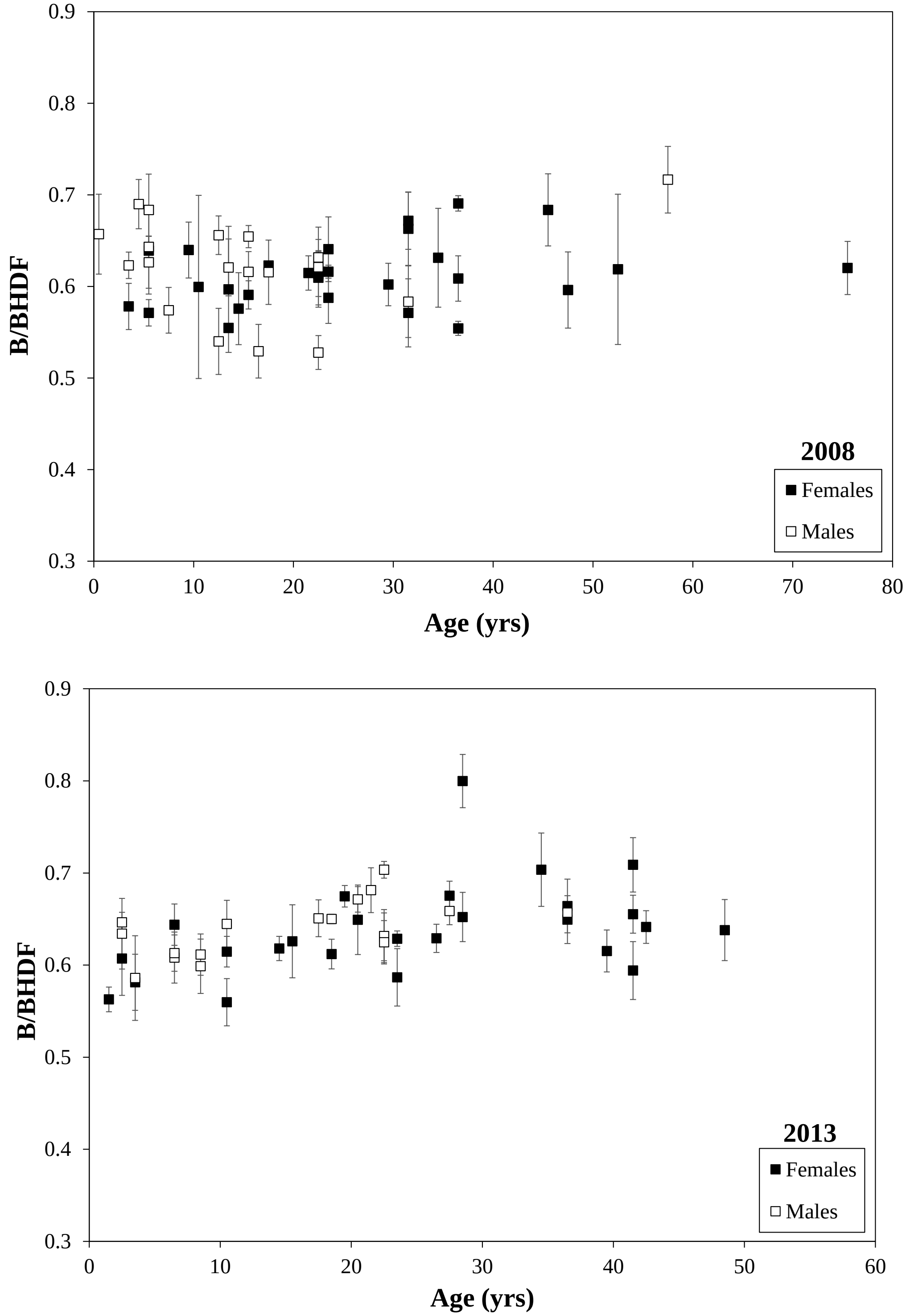
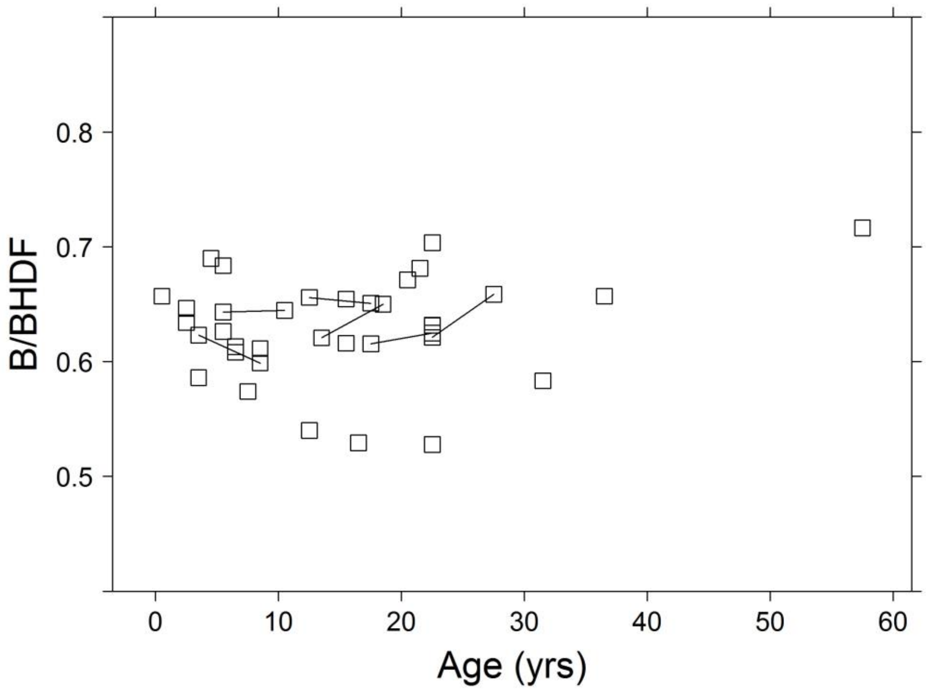


Figure 10. The breadth (B = width at anterior insertion of dorsal fin) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin), plotted against age for individuals from J, K and L pods in 2008 (*n*=47 individuals, top) and 2013 (*n*=44 individuals, bottom). Individuals were required to have ≥3 measurements to be included in each sampling period. The mean estimate across measurement photographs for each individual is shown by a square (black for females and white for males) and the vertical line is +/- one standard deviation.



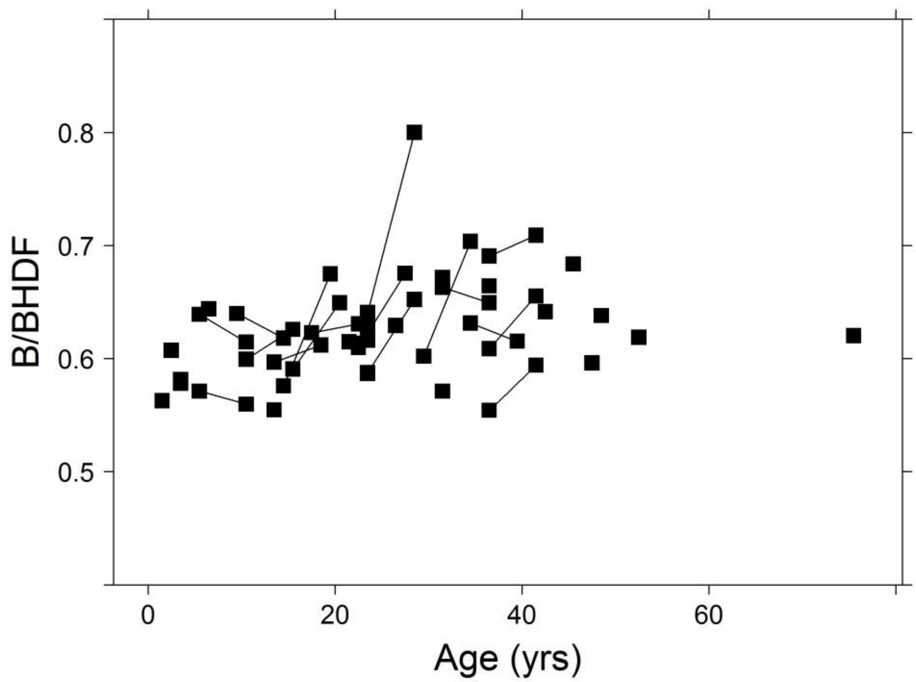


Figure 11: Best (mean) estimates of breadth (B = width at anterior insertion of dorsal fin) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin) plotted against age for southern resident killer whale individuals. Measurements are presented for both 2008 and 2013, and individuals were required to have with ≥3 measurements during a sampling period to be included. Males (*n*=19, 2008; *n*=17, 2013) are represented by white squares (top); females (*n*=28, 2008; *n*=27, 2013) are represented by black squares (bottom). Solid lines join estimates of the same individual from both years (6 males, 17 females).

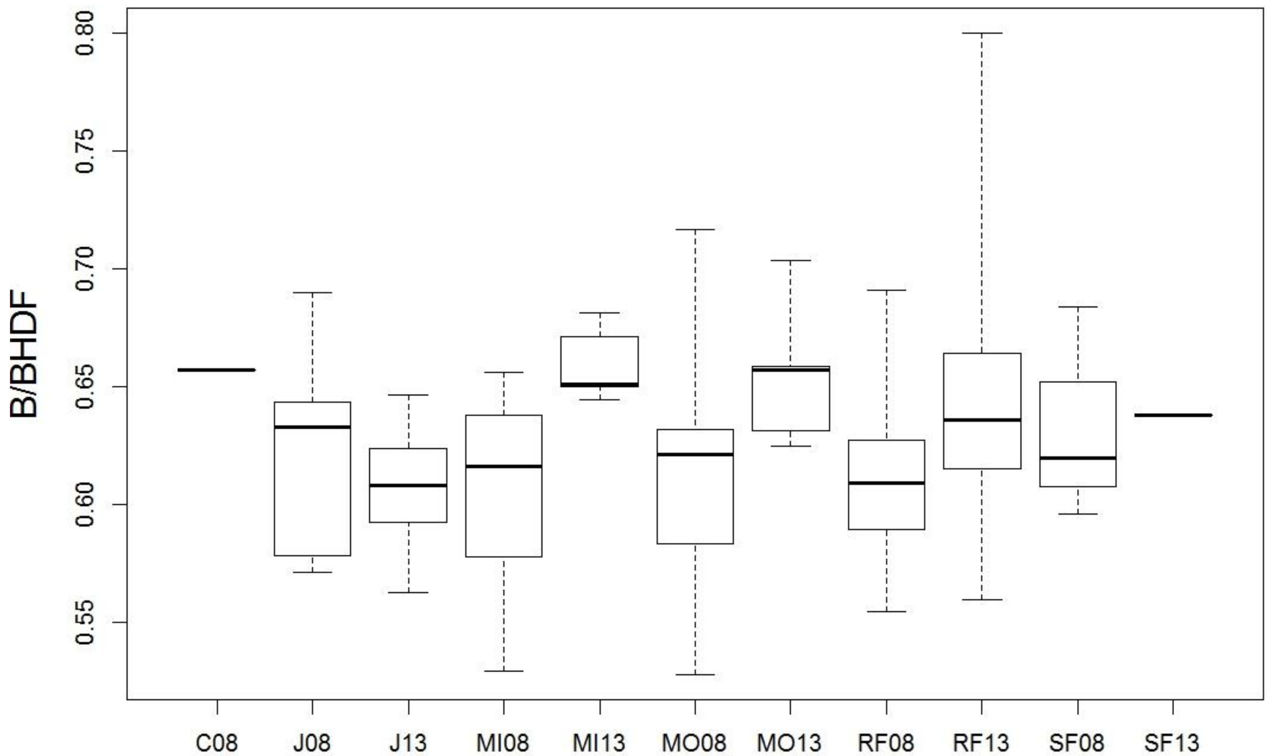


Figure 12: Box plots showing the distribution of breadth (B = width at anterior insertion of the dorsal fin) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin) individual southern resident killer whales in different age classes age classes: C = calves (</= 0.5 yrs), J = juveniles (1.5 - 9.5 yrs), RF = reproductive females (10.5 - 42.5 yrs), SF = senescent or post-reproductive females (>/= 43.5 yrs), MI = immature male (10.5-21.5 yrs), and MO = old males (>/= 22.5 yrs). The numbers "08" and "13" in age class labels represent the year (2008 or 2013). Estimates are presented as posterior medians (horizontal solid lines within the bars), with 75% (white bars) and 95% (vertical lines).

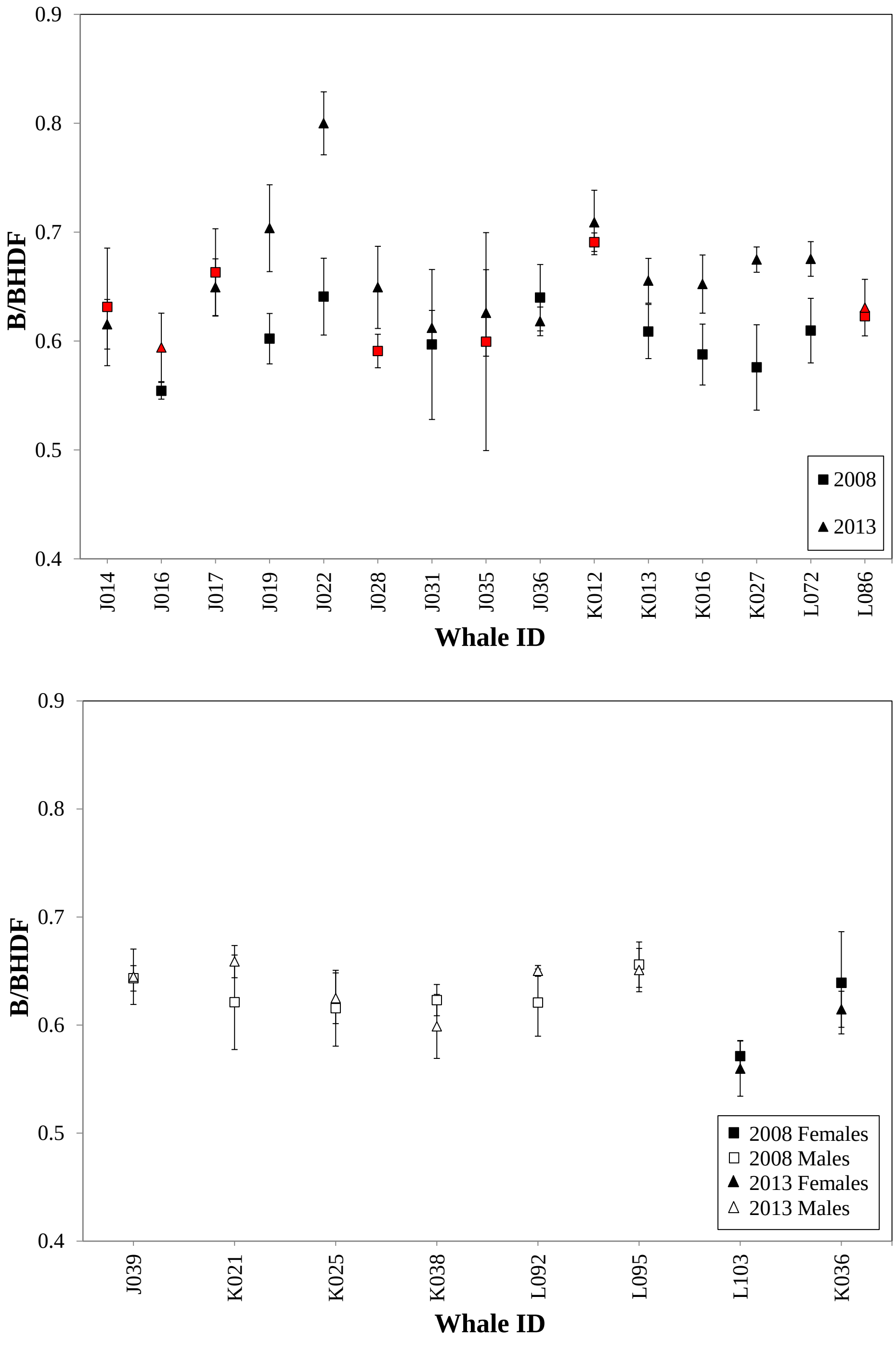


Figure 13. The breadth (B = width at anterior insertion of dorsal fin) proportional to BHDF (the length between the blowhole and anterior insertion of the dorsal fin) for reproductive age females (10.5 - 42.5yrs) with measurements in both 2008 (square symbols) and 2013 (triangle symbols; *n*=15 individuals, top); those females known to be pregnant at the time due to the documentation of subsequent calves are shown in red (all but two of the pregnancies from 2008 [J35 and K12] were relatively late stage at >9 months). Bottom panel shows proportional breadths for whales of other age/sex classes with measurements in both 2008 and 2014, comprising both males (open symbols) and non-reproductive females (closed symbols). Individuals were required to have ≥3 measurements to be included in each sampling period; the mean estimate over measurement photographs for each individual is shown and the vertical line is +/- one standard deviation.

Additional Observations

Analysis of our photographs demonstrated the additional utility of aerial photogrammetry beyond monitoring body condition and estimating size. Two examples are using high definition photographs for gender determination (Figure 14) and identification of the species and size of prey that are being chased (Figure 15). The quantitative measurements possible by knowing scale (altitude/focal length) also permits the analysis of behavior by enumerating whale spacing, and more dynamic analysis of behavior would be possible by collecting video rather than just capturing still photographs.

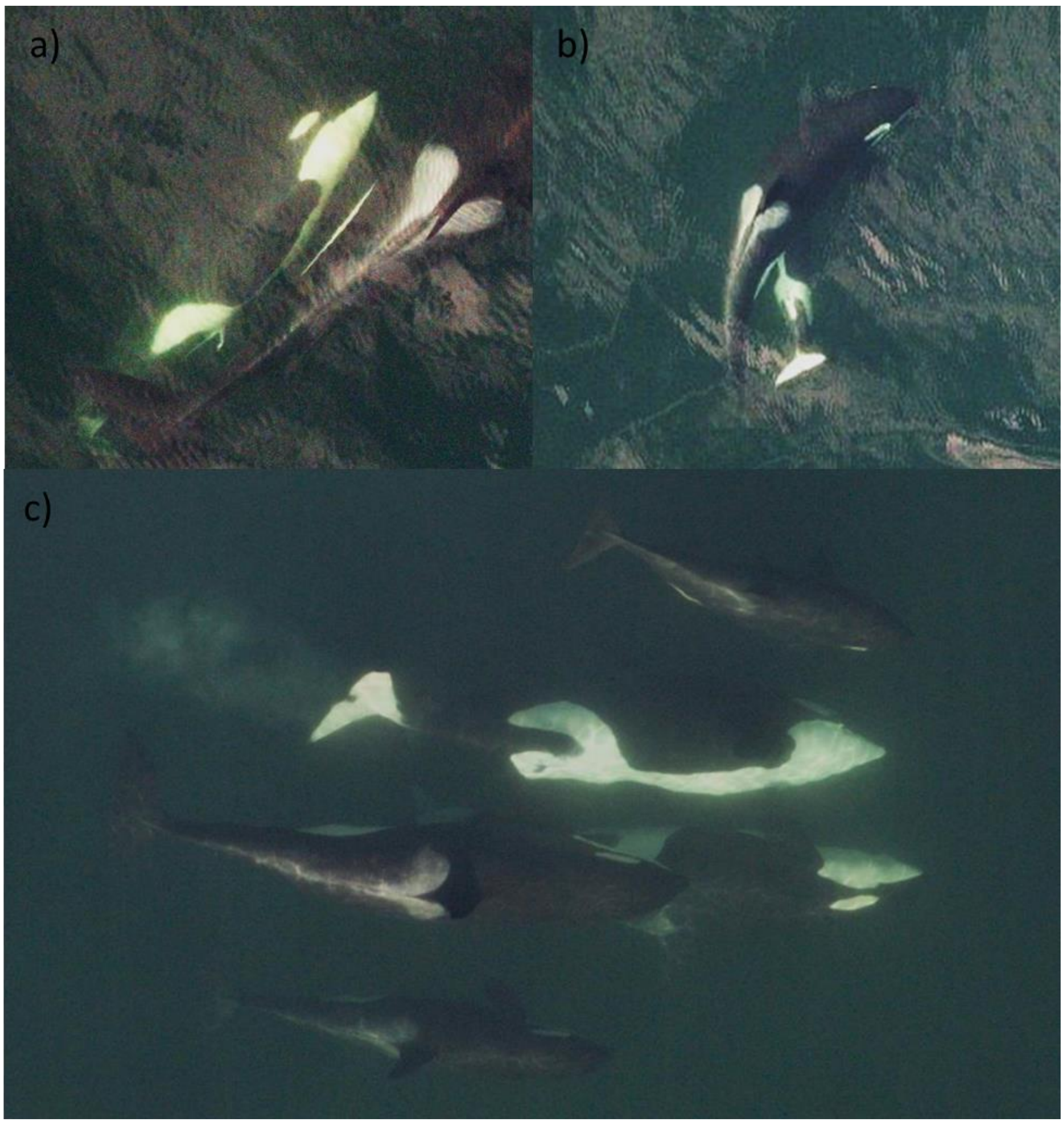


Figure 14. Examples of the utility of photogrammetry for the gender determination of individual whales. a) photo of J49 with penis showing; b) photo of the genital region of J49; c) photo of the genital region of J37, also note milk from nursing.

Figure 15. Aerial images showing an unknown whale with a ~0.7 m salmon in its mouth and K25 (right) unsuccessfully chasing a 0.8 m salmon.

Conclusions

Key Findings

We successfully coupled long-term photo-identification monitoring with aerial photogrammetry to provide measures of length, growth and shape that could be linked to individuals of known age and sex within the endangered population of southern resident killer whales.

Our photogrammetry approach was precise: photographs of a known-sized (6.4m) research boat revealed a median bias of just 4 cm (<1%) for a target that was approximate whale size.

Our approach was efficient: we obtained three or more repeat sets of measurements of 69 individuals in 2013, compared to 68 individuals in a previous field effort in 2008; more than three quarters of the population in both years despite a limited flight budget.

Length estimates were consistent, with similar length-at-age relationships in both 2008 and 2013. Growth in the lengths of 25 immature whales between 2008 and 2013 were comparable, and length distributions for each age class were similar in both years. For both years, adult males ranged from 6.2 m to 7.3 m (median = 6.9 m) and females of reproductive age or greater (>/= 10.5 years old) ranged from 5.1 m to 6.4 m (median = 6.0 m). Notably, K25, a 22.5yr old male in 2013, was the smallest adult male, the only adult male to overlap in size with adult females, and no change in best length estimate was recorded between 2008 and 2013. Interestingly, K25 is the only whale to have recovered from apparently poor body condition ("peanut head") following an injury in 2005 when he was 14 years old (see Durban et al. 2009), suggesting that the trauma and subsequent recovery during important growth years may have limited his growth to adult size.

Head widths proportional to body length were powerful for resolving body condition, with variability across age classes indicating key differences. In both years, the age classes with the largest head widths were young whales, and adult females had the smallest proportional head widths on average. This is indicative of the high level of food support received by young whales, in the form of nursing and provisioning by their mothers and other females within their matriline, and the high demand that is placed upon the providing females (both reproductive and senescent) (Ward et al. 2009; Foster et al. 2012a, 2012b).

There was also evidence of declining body condition between 2008 and 2013. Of the whales with measures in both years, 11 had significant declines in proportional head width compared to only five with increases. The average proportional head width decreased for all age classes, except for older males. This reduced body condition in 2013 is consistent with a declining trend in Chinook salmon returns through the core summer feeding range of the population (http://www.pac.dfo-mpo.gc.ca/fm-gp/fraser/docs/commercial/albionchinook-quinnat-eng.html).

Breadth (width at the anterior insertion of dorsal fin) was only variable for reproductive age females, indicating that is a useful indicator of pregnancy. Eight whales increased significantly in proportional breadth between the years and five more had breadths comparable to their pregnant measures in 2008. That at least several of these whales were likely pregnant in both years with a five-year separation is not surprising, given the average 4-5-year calving interval for reproductive females in this population (Olesiuk et al. 1990). However, only three of these were documented later with a calf, suggesting a surprisingly high level of reproductive failure or neonatal mortality. We suggest this is linked to poor overall condition: notably, 7/11 whales with significant declines in condition (head width) were reproductive-age females that have higher energetic demands.

A note on "shrinking whales"

There were some adult whales that had marginally decreased maximum (best) length estimates between the two years. However, these changes were within the ranges of the variability in length estimates for each of these whales in the 2008 sample, and this effect was therefore considered to represent sampling variability. This may have occurred because of the reduced number of different days on which different whales were photographed on average in 2013 (due to funding constraints on helicopter time), and therefore we may not have sampled behavioral variability as completely and may not have captured that whale in as "flat" (long) a surfacing position as a result. This effect could be minimized by collecting more images over a greater range of days and behaviors, and we propose an unmanned aerial system as a cost-effective method for doing this in the future (see below). However, we suggest this variability in the length estimates was more likely the result of changes in the condition of the whales. Fifteen of the 17 individuals that had marginal decreases in length estimates were reproductive age females, and head width measurements have demonstrated that many of these whales were likely in depleted body condition (see above). Similarly, several more reproductive females were confirmed and/or likely to be pregnant at the time of sampling (see above). Both conditions likely affect the buoyancy and resultant surfacing behavior of the whales and probably impacted the measureable dimension of these whales.

Future Monitoring

These quantitative data provide photogrammetric measures of growth trends, body condition and reproductive success that can serve as baselines for future monitoring. We have documented precision that allowed significant changes to be detected between years, even at the level of the individual. Recently, we have demonstrated that small unmanned aerial platforms are a cost-effective, non-invasive and precise alternative method for collecting aerial photogrammetry images of killer whales (http://www.fisheries.noaa.gov/podcasts/2014/10/aerial_vehicle_killer_whale.html#.VR8YtPnF8gk) and future work will use this approach to collect longitudinal samples from the southern resident population to monitor changes in growth and condition between years and across seasons to identify significant covariates for management attention.

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Appendix Table 1. Summary of measurements from 2008 and 2013 aerial photogrammetry of southern resident killer whales. L_m is the direct measure of length from tip of the rostrum to the fluke notch in the same photograph; L_d is the combination measurement for the distances tip of snout to anterior insertion of dorsal fin and anterior insertion of dorsal fin and fluke notch, combined across photographs. HW/BHDF is the proportion of HW (head width 15% posterior to the blowhole) relative to BHDF (the length between the blowhole and anterior insertion of the dorsal fin) in each picture; B/BHDF is the proportion of B (breadth at the anterior insertion of the dorsal fin) relative to BHDF in each picture. Individuals were required to have with ≥3 measurements during each sampling period to be included for each metric.

Whale	**Age** (yrs)	**Sex**	**Year**	**L_m** max (m)	min (m)	*n*	**L_d** max (m)	min (m)	*n*	**HW/BHDF** mean	sd	*N*	**B/BHDF** mean	sd	*n*
J1	57.5	M	2008	6.8	6.8	3	7.2	6.7	13	0.51	0.02	7	0.72	0.04	5
J2	97.5	F	2008	6.4	6.2	2	6.4	6.1	4	---	---	0	---	---	0
J8	75.5	F	2008	5.6	5.5	2	5.9	5.6	3	0.46	0.02	3	0.62	0.03	4
J8	80.5	F	2013	5.8	5.4	3	6.0	5.5	8	0.41	0.02	8	0.60	---	1
J14	34.5	F	2008	6.1	5.8	5	6.1	5.8	14	0.44	0.02	12	0.63	0.05	5
J14	39.5	F	2013	5.8	5.5	7	6.0	5.4	26	0.44	0.02	23	0.62	0.02	12
J16	36.5	F	2008	---	---	0	5.9	5.7	14	0.44	0.01	9	0.55	0.01	4
J16	41.5	F	2013	5.8	5.5	13	6.1	5.4	19	0.43	0.02	21	0.59	0.03	6
J17	31.5	F	2008	5.7	5.5	6	6.2	5.5	19	0.46	0.01	14	0.66	0.04	13
J17	36.5	F	2013	5.6	5.3	25	6.0	5.4	25	0.44	0.02	18	0.65	0.03	9
J19	29.5	F	2008	5.8	5.4	4	6.1	5.8	34	0.45	0.02	21	0.60	0.02	12
J19	34.5	F	2013	5.5	5.3	5	6.0	5.2	34	0.46	0.03	22	0.70	0.04	11
J22	23.5	F	2008	5.4	5.2	7	5.8	5.5	11	0.48	0.01	8	0.64	0.04	5
J22	28.5	F	2013	5.3	5.1	7	5.6	5.0	21	0.48	0.01	14	0.80	0.03	4
J26	17.5	M	2008	---	---	0	---	---	0	---	---	0	---	---	0
J26	22.5	M	2013	6.5	6.1	8	6.7	5.9	51	0.45	0.02	27	0.63	0.03	3
J27	16.5	M	2008	6.5	6.1	16	6.8	6.0	39	0.45	0.01	15	0.53	0.03	8
J27	21.5	M	2013	6.5	6.3	16	6.9	6.1	35	0.45	0.03	20	0.61	---	1
J28	15.5	F	2008	6.0	5.8	2	6.1	5.4	14	0.44	0.03	12	0.59	0.02	4
J28	20.5	F	2013	5.7	5.2	23	6.1	5.3	51	0.43	0.02	20	0.65	0.04	8
J30	13.5	M	2008	6.1	5.8	5	6.3	5.8	6	0.49	0.01	2	0.65	---	1
J31	13.5	F	2008	6.0	5.8	18	6.2	5.6	30	0.44	0.01	4	0.60	0.07	8
J31	18.5	F	2013	5.9	5.7	14	6.2	5.5	35	0.41	0.02	15	0.61	0.02	6
J32	12.5	F	2008	---	---	0	5.4	5.1	3	0.42	0.00	2	0.65	0.01	2
J32	17.5	F	2013	5.4	5.2	11	5.6	4.9	25	0.47	0.03	13	---	---	0
J33	12.5	M	2008	5.9	5.7	5	6.0	5.7	12	0.48	0.03	13	0.54	0.04	4
J34	10.5	M	2008	5.7	5.6	4	6.0	5.5	10	0.48	0.00	4	---	---	0
J34	15.5	M	2013	6.1	5.9	7	6.3	5.7	18	0.48	0.03	6	---	---	0
J35	10.5	F	2008	5.5	5.2	3	5.8	5.4	16	0.44	0.02	10	0.60	0.10	3
J35	15.5	F	2013	5.5	5.2	8	5.8	4.9	39	0.42	0.02	45	0.63	0.04	9
J36	9.5	F	2008	4.6	4.3	11	4.9	4.3	13	0.52	0.03	3	0.64	0.03	3
J36	14.5	F	2013	5.2	4.8	10	5.4	4.6	36	0.42	0.01	28	0.62	0.01	10
J37	7.5	F	2008	4.5	4.3	4	4.8	4.7	1	---	---	0	---	---	0

J37	12.5	F	2013	5.4	5.2	7	5.6	4.9	18	0.41	0.02	7	0.58	0.03	2
J38	5.5	M	2008	3.9	3.4	14	4.0	3.4	12	0.53	0.03	6	0.68	0.04	3
J38	10.5	M	2013	4.8	4.4	9	5.0	4.4	17	0.53	0.03	10	0.63	---	1
J39	5.5	M	2008	4.3	4.3	3	4.7	4.0	14	0.51	0.01	4	0.64	0.01	3
J39	10.5	M	2013	5.1	4.8	11	5.4	4.7	33	0.47	0.03	21	0.64	0.03	9
J40	3.5	F	2008	3.7	3.7	1	4.1	3.4	4	0.47	0.03	5	0.62	0.00	2
J40	8.5	F	2013	5.0	4.7	19	5.1	4.6	29	0.42	0.02	17	0.53	0.02	2
J41	3.5	F	2008	3.8	3.6	5	4.4	3.8	5	0.45	0.02	9	0.58	0.03	7
J41	8.5	F	2013	4.9	4.6	6	5.3	4.5	15	0.46	---	1	---	---	0
J42	1.5	F	2008	3.3	3.3	1	3.5	3.1	7	0.46	0.03	5	0.56	0.01	2
J42	6.5	F	2013	4.3	3.8	11	4.5	4.0	18	0.44	0.03	12	0.64	0.02	5
J44	4.5	M	2013	3.9	3.6	2	4.2	3.7	8	0.46	0.01	5	0.57	---	1
J45	4.5	M	2013	4.1	3.9	16	4.7	3.9	21	0.43	0.02	9	---	---	0
J46	3.5	F	2013	4.0	3.7	11	4.2	3.7	16	0.46	0.03	13	0.67	0.03	2
J47	3.5	M	2013	4.0	3.5	22	4.2	3.4	34	0.44	0.02	18	0.59	0.05	4
J49	1.5	M	2013	3.4	3.3	5	3.5	3.2	6	0.41	---	1	---	---	0
K12	36.5	F	2008	---	---	0	6.1	5.7	9	0.44	0.01	10	0.69	0.01	7
K12	41.5	F	2013	5.6	5.4	5	6.0	5.4	11	0.47	0.02	10	0.71	0.03	4
K13	36.5	F	2008	6.2	5.9	7	6.3	5.8	17	0.43	0.01	12	0.61	0.02	11
K13	41.5	F	2013	5.8	5.5	7	5.9	5.2	15	0.45	0.03	12	0.66	0.02	5
K14	31.5	F	2008	---	---	0	6.3	5.6	36	0.47	0.02	30	0.67	0.03	19
K14	36.5	F	2013	---	---	0	6.0	5.2	4	0.47	0.02	7	0.59	0.02	2
K16	23.5	F	2008	---	---	0	6.2	5.9	9	0.44	0.02	12	0.59	0.03	7
K16	28.5	F	2013	5.8	5.4	36	6.0	5.2	52	0.47	0.03	18	0.65	0.03	9
K20	22.5	F	2008	6.2	5.9	8	6.4	5.9	24	0.43	0.02	18	0.61	0.02	8
K20	27.5	F	2013	5.7	5.5	12	6.0	5.7	6	0.42	0.02	4	0.65	---	1
K21	22.5	M	2008	6.3	6.3	2	6.7	6.5	5	0.46	0.02	4	0.62	0.04	3
K21	27.5	M	2013	6.3	5.6	67	6.5	5.6	29	0.47	0.01	12	0.66	0.01	3
K22	21.5	F	2008	5.7	5.7	1	6.0	5.8	3	0.43	0.02	3	0.61	0.02	3
K22	26.5	F	2013	5.6	5.4	3	5.9	5.5	8	0.42	0.02	4	---	---	0
K25	17.5	M	2008	6.0	5.6	18	6.2	5.5	25	0.46	0.01	7	0.62	0.04	3
K25	22.5	M	2013	6.0	5.8	3	6.2	5.7	27	0.45	0.01	15	0.62	0.02	4
K26	15.5	M	2008	6.5	6.4	5	6.7	6.3	14	0.47	0.02	13	0.62	0.02	7
K26	20.5	M	2013	6.4	6.1	5	6.6	6.1	10	0.47	0.01	3	---	---	0
K27	14.5	F	2008	6.0	5.8	3	6.1	5.7	8	0.45	0.01	7	0.58	0.04	3
K27	19.5	F	2013	5.5	5.3	18	5.8	5.3	23	0.43	0.01	6	0.67	0.01	5
K33	7.5	M	2008	5.1	4.9	3	5.2	4.9	6	0.45	0.01	4	0.57	0.02	5
K33	12.5	M	2013	6.0	6.0	1	6.2	5.5	4	0.44	0.00	4	---	---	0
K34	6.5	M	2008	4.4	4.3	6	4.8	4.3	14	0.45	0.03	3	0.61	0.02	2
K34	11.5	M	2013	4.8	4.7	2	5.0	4.6	6	0.44	0.00	3	0.59	---	1
K35	5.5	M	2008	4.8	4.5	3	5.1	4.6	18	0.47	0.04	12	0.63	0.03	4
K35	10.5	M	2013	5.4	5.1	35	5.5	5.1	43	0.48	0.03	12	0.62	0.04	2
K36	5.5	F	2008	4.2	4.1	3	4.5	4.2	10	0.45	0.02	5	0.64	0.05	4
K36	10.5	F	2013	4.9	4.7	17	5.1	4.7	20	0.44	0.02	8	0.61	0.02	3

K37	4.5	M	2008	---	---	0	4.7	4.4	3	0.47	0.01	4	0.69	0.03	4
K38	3.5	M	2008	3.9	3.6	7	3.9	3.7	5	0.46	0.01	3	0.62	0.01	3
K38	8.5	M	2013	4.4	4.0	16	4.5	3.9	15	0.45	0.03	10	0.60	0.03	6
K40	45.5	F	2008	6.0	5.8	3	6.4	5.7	12	0.49	0.02	11	0.68	0.04	5
K42	0.5	M	2008	2.8	2.7	4	3.1	2.7	22	0.51	0.01	6	0.66	0.04	7
K42	5.5	M	2013	4.3	4.1	18	4.5	3.9	18	0.47	0.04	12	0.67	0.09	2
K43	3.5	F	2013	3.8	3.8	2	4.2	3.9	1	0.47	0.01	2	0.59	---	1
K44	2.5	M	2013	3.6	3.4	17	3.7	3.3	23	0.51	0.01	10	0.65	0.01	6
L7	47.5	F	2008	6.2	6.1	4	6.4	6.0	23	0.44	0.02	20	0.60	0.04	12
L22	42.5	F	2013	6.0	5.8	12	6.4	5.8	12	0.43	0.01	6	0.64	0.02	3
L25	85.5	F	2013	6.0	5.8	5	6.3	6.0	7	0.42	0.01	5	---	---	0
L26	52.5	F	2008	---	---	0	6.1	5.9	5	0.47	0.02	9	0.62	0.08	5
L27	48.5	F	2013	6.0	5.6	81	6.2	5.3	87	0.44	0.03	55	0.64	0.03	26
L41	31.5	M	2008	7.2	6.6	13	7.3	6.7	24	0.45	0.02	4	0.63	0.01	2
L41	36.5	M	2013	6.8	6.6	9	7.0	6.7	3	0.43	0.00	4	0.66	0.00	3
L47	34.5	F	2008	5.5	5.5	1	5.6	5.5	2	---	---	0	---	---	0
L53	31.5	F	2008	---	---	0	6.4	5.9	20	0.45	0.01	22	0.57	0.04	7
L53	36.5	F	2013	5.8	5.8	2	6.0	5.6	12	0.41	0.01	3	---	---	0
L55	31.5	F	2008	6.2	5.9	8	6.4	6.0	21	0.39	0.01	6	0.55	0.06	2
L55	36.5	F	2013	6.2	5.7	82	6.4	5.4	141	0.42	0.02	89	0.66	0.03	51
L57	31.5	M	2008	6.7	6.7	2	6.9	6.7	6	0.44	0.02	6	0.58	0.04	5
L67	23.5	F	2008	5.8	5.6	15	5.9	5.6	11	0.43	0.01	7	0.62	0.01	10
L72	22.5	F	2008	5.6	5.5	4	5.9	5.6	5	0.44	0.01	5	0.61	0.03	4
L72	27.5	F	2013	5.5	5.2	13	5.8	5.0	24	0.43	0.00	10	0.68	0.02	7
L73	22.5	M	2008	6.7	6.5	4	6.8	6.6	5	0.42	0.03	5	0.53	0.02	5
L74	22.5	M	2008	6.7	6.5	6	7.0	6.5	17	0.45	0.01	11	0.63	0.02	5
L77	26.5	F	2013	6.0	5.8	11	6.0	5.8	15	0.42	0.01	4	0.63	0.02	5
L78	19.5	M	2008	7.0	6.7	17	7.2	6.3	32	0.47	0.00	3	0.62	0.00	2
L82	18.5	F	2008	6.1	5.9	4	6.2	5.8	6	0.42	0.01	3	---	---	0
L82	23.5	F	2013	6.2	5.7	68	6.4	5.6	87	0.41	0.02	47	0.59	0.03	24
L83	18.5	F	2008	5.8	5.7	6	6.3	6.2	3	---	---	0	---	---	0
L83	23.5	F	2013	6.0	5.7	30	6.2	5.7	9	0.43	0.01	10	0.63	0.01	3
L84	18.5	M	2008	6.6	6.5	3	6.8	6.4	4	0.45	0.00	3	0.59	0.00	2
L85	22.5	M	2008	6.8	6.3	13	7.0	6.2	30	0.48	0.01	18	0.70	0.01	9
L86	17.5	F	2008	5.4	5.4	3	5.9	5.8	1	0.43	0.01	3	0.62	0.00	3
L86	22.5	F	2013	5.7	5.4	32	6.0	5.3	66	0.44	0.03	31	0.63	0.03	11
L87	16.5	M	2008	5.7	5.7	1	6.4	6.3	2	0.46	0.01	6	0.64	0.01	2
L87	21.5	M	2013	6.5	6.2	6	6.7	6.3	13	0.46	0.02	7	0.68	0.02	3
L88	15.5	M	2008	---	---	0	6.3	6.0	3	0.45	0.02	6	0.65	0.01	4
L89	20.5	M	2013	6.6	6.2	10	6.7	6.3	8	0.43	0.01	7	0.67	0.01	3
L91	13.5	F	2008	5.9	5.4	8	6.0	5.7	14	0.44	0.01	8	0.55	0.00	3
L92	13.5	M	2008	---	---	0	6.2	6.0	5	0.43	0.01	7	0.62	0.03	6
L92	18.5	M	2013	5.9	5.9	1	6.5	6.1	10	0.44	0.01	10	0.65	0.01	3
L94	13.5	F	2008	5.9	5.7	5	---	---	0	---	---	0	---	---	0
L94	18.5	F	2013	5.9	5.6	21	6.1	5.7	20	0.39	0.01	9	0.64	---	1

L95	12.5	M	2008	5.9	5.4	2	6.2	5.9	5	0.47	0.02	8	0.66	0.02	6
L95	17.5	M	2013	6.4	5.9	18	6.4	5.9	40	0.46	0.02	34	0.65	0.02	12
L103	5.5	F	2008	4.4	4.3	4	4.6	4.3	11	0.41	0.01	5	0.57	0.01	3
L103	10.5	F	2013	5.2	4.9	86	5.5	4.7	70	0.42	0.02	60	0.56	0.03	15
L105	3.5	M	2008	3.8	3.8	4	4.2	4.0	3	0.46	0.02	4	0.59	---	1
L105	8.5	M	2013	5.1	4.8	14	5.3	4.7	12	0.45	0.02	8	0.63	---	1
L106	3.5	M	2008	3.7	3.7	3	---	---	0	---	---	0	---	---	0
L106	8.5	M	2013	5.0	4.5	91	5.2	4.4	61	0.45	0.03	34	0.61	0.02	17
L109	1.5	M	2008	3.6	3.5	5	3.8	3.6	4	0.44	0.00	4	0.60	---	1
L109	6.5	M	2013	4.5	4.2	46	4.7	4.0	78	0.45	0.03	55	0.61	0.03	22
L110	1.5	M	2008	3.4	3.3	9	3.2	3.2	1	---	---	0	---	---	0
L110	6.5	M	2013	4.4	4.2	9	4.6	4.2	17	0.44	0.02	5	0.61	0.02	5
L113	3.5	F	2013	4.1	3.7	36	4.2	3.8	25	0.43	0.02	9	0.58	0.03	4
L116	2.5	M	2013	4.2	3.8	32	4.4	3.8	35	0.44	0.03	28	0.63	0.04	13
L118	2.5	F	2013	3.5	3.2	101	3.7	3.2	87	0.46	0.03	45	0.61	0.04	29
L119	1.5	F	2013	3.4	3.2	18	3.5	3.2	8	0.45	0.02	9	0.56	0.01	3