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Mortality rate trends of Australian fur seal pups, Arctocephalus pusillus doriferus, and possible factors affecting pup mortality in the Bass Strait of Australia

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SIT Study Abroad

Mortality rate trends of Australian fur seal pups, *Arctocephalus pusillus doriferus*, and possible factors affecting pup mortality in the Bass Strait of Australia

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SIT Study Abroad
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ISP Ethics Review

(Note: Each AD must complete, sign, and submit this form for every student's ISP.)

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ABSTRACT

Australian fur seals (AFS), *Arctocephalus pusillus doriferus*, are upper trophic predators endemic to the Bass Strait of south-eastern Australia. Their populations have been monitored since the mid-1900s to assess ecosystem health and the continual recovery of the species from extensive hunting in the early 19th century. The best way to track the environmental conditions and recovery of AFS populations is by monitoring the pups that are confined to the breeding colonies. This study looked particularly at the mortality rates of AFS pups because mortality of the young is a good indicator of population dynamics.

The aim of this study was to determine unusual versus usual mortality rates and the factors affecting them for AFS pups. Mortality and total pup population data was obtained from the pup database which contains all the AFS pup data collected since the 1980s up to the 2017-2018 breeding season. Two pup estimates, Capture-Mark-Resight (CMR) and Direct count total, were used in conjunction with the dead pup count for Deen Maar Island, Seal Rocks, The Skerries, and Cape Bridgewater breeding colonies. Data were analyzed in RStudio. A Generalized Linear Model (GLM) was developed to determine differences between breeding site and season on pup mortality rates. Body condition of live pups was also studied to examine whether health of the AFS pups provide insight into mortality rates. This was investigated by calculating a Body Condition Index (BCI) and developing a GLM to determine whether breeding season, site, and pup sex affect this variable. Pup mortality rates generally fell under 15%. Although Cape Bridgewater and the 2013-2014 season at Seal Rocks showed unusually high mortality rates than other locations and seasons, there were no significant differences between breeding locations nor seasons. However, due to the limited data on dead pup numbers, these results were not entirely conclusive. Furthermore, the calculated BCI did not align well with veterinarian observed body conditions of pups and the GLM results were highly variable. For this reason, the BCI results could not provide insight on mortality rate trends. Given the results of this study, it will be necessary in the future to use more accurate

and frequent methods for acquiring dead and live AFS pup numbers to better understand ecosystem health and population recovery.

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Thank you to Jess Pulvirenti for allowing me to carpool with her to work during most of my ISP. She was so helpful in teaching me the proper fieldwork techniques for the penguins. Thank you also to Marjolein van Polanen Petel for allowing Jess, Emma, and I to partake in holding and weighing the day old penguin chicks.

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LIST OF FIGURES

1. INTRODUCTION

1.1. *Background on AFS Population*

The hunting of Australian fur seals (AFS), *Arctocephalus pusillus doriferus,* began at least 8,000 years ago by Aboriginal people (Kirkwood et al., 2005). In the late 18^{th} century, AFS were severely depleted due to large scale commercial hunting (Warneke, 1982). Between 1800 and 1810, it is estimated that the number of seals caught in the Bass Strait Archipelago was 240,000 (Lewis, 1929). In particular, the Seal Rocks colony alone yielded 1000 AFS skins a year during this time (Warneke, 1966). Prior to this period, the annual total AFS pup production is estimated to have been between 20,000 and 50,000 at 26 colonies in Bass Strait (Warneke, 1982). By 1860 only 100 individuals survived at Seal Rocks (Warneke, 1966) and 16 of the Bass Strait colonies had been completely wiped out (Warneke, 1966; McIntosh et al., 2018).

It was not until 1890 that legal protections were set in place for fur seals in Victorian waters (Warneke, 1966). Due to the increase in numbers, as a result of these protections, professional fisherman began to complain about AFS interfering with their operations (*e.g.,* damaging nets, following fishing boats, taking barracouta from the line, and dispersing shoals of fish) (Lewis, 1929). However, in 1929 a report by Chief Inspector of Fisheries and Game concluded that AFS were not a threat to the fishing industry, so population control measures were not necessary. In order to appease fisherman, the policy at the time was continued that allowed the shooting of seals interfering with fishing operations (Lewis, 1929). In 1941, complaints culminated in the approval for killing 1000 seals at Seal Rocks and in 1948 authorization was given for killing of seals in Victorian waters based on a permit system (total limit of 2000 per annum) (Warneke, 1966). In 1948 691 seals were killed and utilized for oil, meat, and leather (Warneke, 1966). Illegal shootings from boats and destruction of individual seals by fishing operations continued until 1975 when all

Australian seals became protected under the *National Parks and Wildlife Conservation Act* (Shaughnessy and Warneke, 1987).

From 1986 to 2007, monitoring was opportunistic, then from 2007 a coordinated range-wide census was performed every five years (McIntosh et al., 2018). From 1986 to 2002, the growth rate of seal pups was 5% per annum (Kirkwood et al., 2010). However, as of 2007, the number of identified breeding sites was determined to be 20, indicating that although the number of sites had increased; the overall population was still in recovery back up to the 26 colonies from pre-sealing years (McIntosh et al., 2018). The population recovery of AFS since over-harvesting has been slow (Kirkwood et al., 2010). Researchers argue that this relatively slow rate of recovery may be due to human activity, such as lethal interactions with fisherman and fisheries (*e.g.,* high rates of entanglement in marine debris) (Kirkwood et al., 2005). It may also be influenced by the relatively poor feeding environment adjacent to the colonies and competition for breeding sites and prey with other otariids (*e.g., A. forsteri* and *N. cinerea*) in Bass Strait (Kirkwood et al., 2005) and their low fecundity rate (Gibbens et al. 2009). In 2013, the census found the first reduction (-4.2% per annum) in AFS pup numbers (McIntosh et al., 2018). This trend has continued with numbers remaining depressed in the 2017 census (McIntosh, 2018). These drops are concerning to researchers since AFS populations were thought to be doing well prior to 2013.

1.2. *Australian Fur Seal Species*

AFS are the largest of all eight fur seal species in the world with females that weigh up to 120 kg and males over 360 kg (Arnould and Warneke, 2002). They are conspicuous, large-bodied predators (Kirkwood et al., 2010) endemic to south-eastern Australian waters (Kirkwood et al., 2005). They breed and haul-out on the shores of small rocky islands mostly within the Bass Strait, which lies between mainland Australia and Tasmania (Kirkwood et al., 2005). They forage exclusively over the shelf waters of south-eastern Australia, making them a geographically restricted fur seal species (Kirkwood et al., 2005).

AFS exhibit a synchronized annual breeding cycle (McIntosh et al., 2014): pups are born between November and mid-December and remain at the colony until they are 8 months old (Gibbens and Arnould, 2008). Females birth their first pup around 3-4 years of age, while males do not attain sufficient size and experience to hold their own breading territories until they are at least 9 years old (Warneke and Shaughnessy, 1985). Females regularly alternate between foraging at sea and suckling their pups onshore (Bradshaw et al., 2000).

Pups weigh between 10 and 15 pounds at birth (Warneke, 1966). They have distinguishably sleek black oily-looking coats that are molted soon after the end of the breeding season (Warneke, 1966). While their mothers are off foraging at sea, unattended pups derive comfort from mutual contact by congregating in groups of 50 or more called pods, since conditions are generally harsh for the young pups (Warneke, 1966).

AFS are predominantly benthic foragers that prey on demersal and pelagic schooling species along with benthic species (Hume et al., 2004; Hardy et al., 2017). Due to their feeding habits and the rapid exploitation of marine resources by humans, there has been an increase in the interactions between fur seals and commercial fisheries (Arnould et al., 2003). This has led to concerns about the impact of commercial fishing on prey availability and the accidental entanglement in fishing nets on AFS (Arnould et al., 2003).

1.3. *Significance of Monitoring AFS Populations*

The populations of AFS in Bass Strait have been monitored since the mid-1900s to assess the potential extent of current human-based interactions (Arnould et al., 2003). Monitoring the abundance and population trends of upper trophic level predator species provides measures of ecosystem health and successful management (McIntosh et al., 2018). AFS pose management challenges such as interactions with fisheries, economic value through tourism, impacts on other important marine species (*e.g.,* seabirds), and emergency situations (*e.g.,* oil spills) (McIntosh et al., 2018). Knowledge of population trends help managers to maintain updated protected areas, mitigate natural resource extraction, and other utilization of wildlife resources (McIntosh et al., 2018). Finally, due to their position towards the top of the marine food web, AFS are affected by variation in the intensity and location of food resources in the marine environment (Bradshaw et al., 2000). For this reason, variation in the biological parameters of AFS may offer insight into changes in the marine environment occurring lower down in the food web (Bradshaw et al., 2000).

1.4. *Mortality Rates*

The mortality of pups and juveniles is an indicator of population dynamics for large mammals like AFS (Eberhardt, 1981). In a previous study it was found that a major driving variable of another fur seal species population, the Pribilof Islands North Pacific fur seal (*Callorhinus ursinus*), was the survival of young fur seals (Eberhardt, 1981). Despite the importance of mortality rates on population dynamics of other fur seal species, there is still little quantitative data on mortality rates and the factors affecting mortality of AFS (Arnould et al., 2003). Most studies use a suggested 15% by Warneke (1982) as a minimum mortality rate in the first two months of AFS pup life, when they are sedentary and do not readily enter the sea. However, this 15% value has not been closely researched.

Despite the limited research on AFS, the mortality of pups of other seal species have been investigated. One study on the closely related South African fur seal, *Arctocephalus pusillus pusillus*, found that most pups die shortly after birth in November and December every breeding season (De Villiers and Roux, 1992). The mortality rate during the first month was 20% (De Villiers and Roux, 1992) - 5% higher than the estimate used in AFS studies. They also found a differential rate of mortality between male and female fur seals, with significantly more females dying (De Villiers and Roux, 1992).

In another study, on Long-nosed fur seals, *Arctocephalus forsteri*, it was found that the mortality rate of seal pups in the first two months of life was also 20% and 40% in the first year of life (Mattlin, 1978). According to this study, starvation accounted for 70% of the deaths in the first two months of life, however, stillbirths, suffocation, drowning, and trampling were also significant factors to the pup mortality rate (Mattlin, 1978). However, another study on the Long-nosed fur seals found the pup mortality at six major breeding colonies in South Australia to be 4.4% (Shaughnessy et al., 2015). This is much less than the Mattlin (1978) study which examined colonies in New Zealand.

This study aims to closely investigate the mortality rates of AFS pups across breeding colonies and breeding seasons within the Bass Strait in order to determine trends and normal versus unusual rates. Pup mortality trends will then be analyzed in order to understand possible factors affecting mortality rates. The factors analyzed in this study include location of the breeding colony, breeding season, and pup body condition.

2. METHODS

2.1. *Study Breeding Colonies*

Overall distribution: AFS are found from Montague Island, New South Wales, to southern Tasmania, and throughout Bass Strait and South Australia to a western limit of Williams Island (McIntosh et al. 2018). More than 2/3 of the present population is concentrated at three sites in Bass Strait – Judgement rocks, Seal Rocks, and Deen Maar Island (Warneke, 1982). This study looked particularly at the breeding AFS colonies at Deen Maar Island, Seal Rocks, The Skerries, and Cape Bridgewater, since these were the sites with the most available data of live and dead AFS pup counts.

Deen Maar Island (38.25S, 142.00E) is a triangular-shaped island, 2 km long and 1 km wide, lying 22 km off of western Victoria, Australia. Its top is a featureless plateau, 35-45m high. Seals are distributed continuously along the west side of the island, on shore platforms, narrow beaches, scree (product of rock fall) slope, and in sea-worn caves. (Warneke, 1988). At the south-western end of the island is the Seal Bay breeding area which is comprised of a boulder beach, cliffs, and a steep scree slope that enable access to the plateau (Shaughnessy et al., 2002).

Seal Rocks (38.31.45S, 145.06.00E) is a major breeding colony that comprises two small basal islands lying 1 km off the southwest corner of Phillip Island, Victoria, Australia. The larger island consists of two small areas of plateau ranging from 8 to 10m high. The highest concentrations of breeding seals are found on the east side beach (Main Beach) of this island. They also congregate on the inner portion of the reef platform and on a boulder beach behind (Warneke, 1988). Fur seals also breed on the smaller island, Black Rock (Shaughnessy et al., 2000).

The Skerries (37.45.15S, 149.30.45E) are three low graphite islets that extend in a 350-800m line. They are separated by narrow shallow channels. Seals breed on the all three islets, on course sand and granite boulders (McIntosh et al., 2018).

Cape Bridgewater (38.22.0S, 141.24.0E) is a relatively small breeding colony to the west of Deen Maar where the seals are breeding in a large sea cave. However, its population between 2007 and 2013 grew by 60% per annum indicating that it is a rapidly growing colony (Fig. 1).

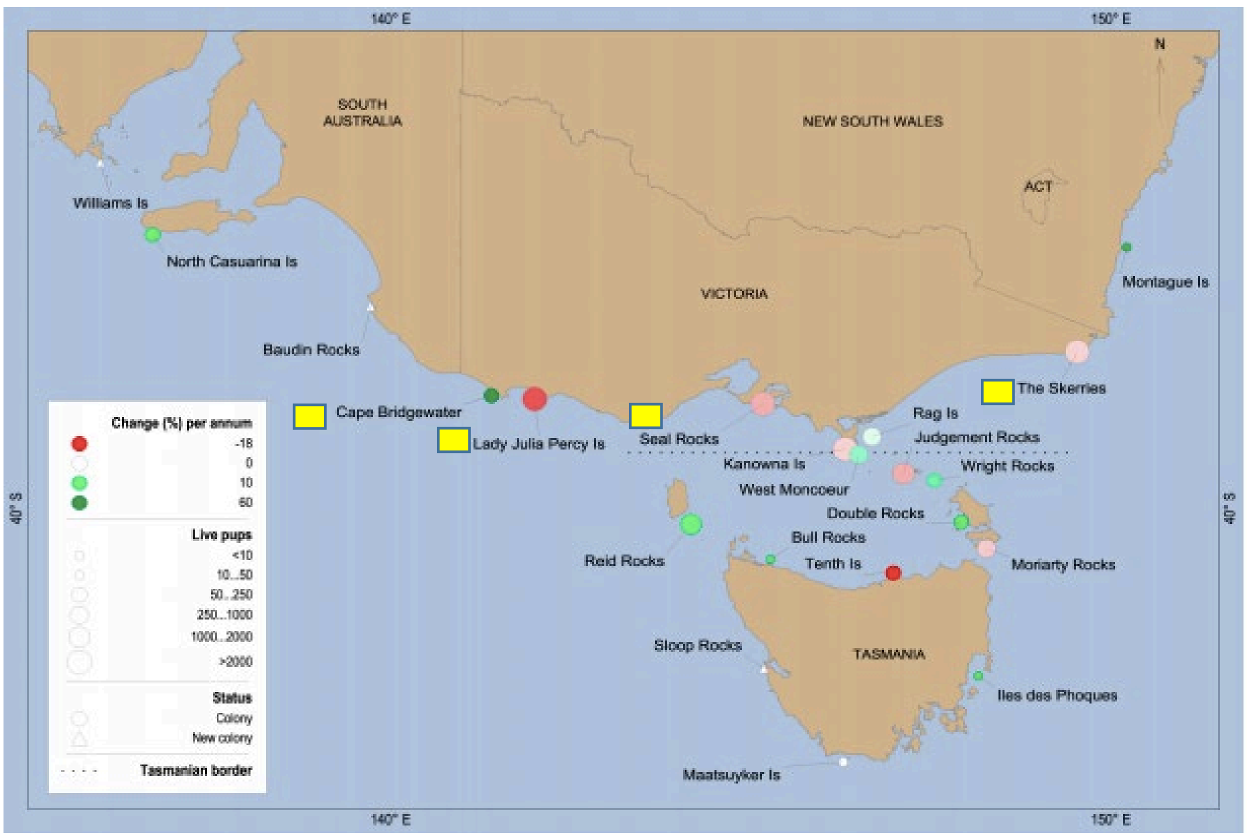

Fig. 1. Map showing the range of AFS with change (%) per annum between 2007 and 2013 censuses (McIntosh et al., 2018). In this paper, Lady Julia Percy Island is referred to as its Aboriginal title, Deen Maar Island. Deen Maar Island, Seal Rocks, The Skerries, and Cape Bridgewater – the focus sites of this study – are indicated by yellow squares.

2.2. *Pup Population*

The best way to track the recovery and conditions of AFS populations is by monitoring the pups that are confined to the breeding colony (McIntosh et al., 2018). AFS pup numbers can provide an indication of population size – a key population statistic – and their growth rate is a reflection of food availability, foraging efficiency of lactating females, and prey availability (Kirkwood et al., 2005; Bradshaw et al., 2000). Monitoring pup populations is also an easier method for tracking AFS population. Pups are small and readily identifiable because they retain their dark natal pelage until their first molt and they do not swim well or flee to sea when disturbed during surveys (Littan and Mitchell, 2002).

2.3. *Capture-Mark-Resight (CMR) Estimates*

CMR has been commonly used as a method for tracking pup abundance in the censuses. AFS pups were marked by clipping black guard hair on the head to reveal the lighter underfur. Capture across different studies was spread evenly across the breading area to ensure all parts of the AFS population had been marked. In the Littan and Mitchell (2002) study, for example, pups were resighted over a 2-3 day period after allowing between 1-2 days for the mixing of marked and unmarked fur seals. The numbers of both marked and unmarked seal pups were counted during resighting and overall abundance of the entire colony was estimated using the calculated arithmetic mean.

CMR provides more accurate estimates of AFS pup numbers than direct counts or aerial photographs. However, it does cause a high amount of disruption to the pups. CMR is particularly useful when large numbers of pups are present and for accounting the obscured portion of pups not quantified in direct and aerial counts. (Kirkwood et al., 2005).

2.4. *Direct Ground Counts*

Direct ground counts have also been commonly used for tracking pup abundance in the censuses. This method provides a census of the visible portion of pups present, which is affected by factors such as tide, sea conditions, time of day, temperature, and observer experience (Kirkwood et al., 2005).

The direct ground count method is not very accurate but it is useful when there is insufficient time for CMR or when CMR will be too disruptive to the pups. Direct counts can lead to underestimates when an unknown proportion is obscured or overestimates due to recounting pups. (Kirkwood et al., 2005).

2.5. *Mortality Rates*

The rates of pup mortality were determined by using the data from the AFS pup database compiled by Karina Sorrell and myself at Phillip Island Nature Parks. This database contains all AFS pup data collected since the 1980s. Mortality rates were determined by adding direct counts of dead pups at a given study site to either the CMR derived or directly counted live pup populations for a particular breeding season. The directly counted dead pup numbers were then divided by the total pup (live and dead) population to determine the rate of mortality.

2.6. *Analysis of Mortality Rates*

All analysis of AFS pup mortality data, extracted from the overall pup database, was conducted in RStudio. The variables investigated in relation to the calculated mortality rates were breeding site, breeding season, count method used, total live pups, and total dead pups.

The pup mortality rates acquired using the count methods CMR&Direct (total population estimated using CMR and Direct count used to determine dead pup numbers) and Direct were compared using a Welch Two Sample t-test. This test was used to determine whether there is a significant difference in the AFS pup mortality rates depending on the method used to determine the live population numbers.

Boxplots were used to look at the average pup mortality rates within a given site (Deen Maar, Seal Rocks, The Skerries, and Cape Bridgewater) and count method used (CMR&Direct and Direct). Variation in the data within the sites could also be visualized in these plots.

The Direct count derived AFS pup mortality rates were compared between Seal Rocks and Cape Bridgewater, because they had five breeding seasons of data that could be compared. Significance between the mortality rates of Seal Rocks and Cape Bridgewater was determined using an ANOVA test. A scatterplot and boxplot were used to visualize the relationship between mortality rates and trends across the same seasons at the two different sites.

Plots of the trends across breeding seasons within a site were only created for sites that had at least three data points available for a given count type, since trends could only be determined with three or more points. For this reason, visualizations of trends could only be developed for Deen Maar (CMR&Direct count), Seal Rocks (Direct count), and Cape Bridgewater (Direct count). The trends across sites within a single season could only be made for the 2017-2018 breeding season, because this was the only season with data available from the CMR&Direct counts for Cape Bridgewater, Deen Maar, Seal Rocks, and The Skerries. Other seasons did not have enough data of the same method across all the sites.

The relationship of AFS pup mortality rates to breeding colony site and breeding season was determined using a Generalized Linear Model (GLM) for the regression analysis of the Direct count data. The CMR&Direct data was significantly sparser than the Direct count data so it was excluded from this analysis. Regression analysis is useful for understanding which of the independent variables (*e.g.,* breeding season and site) are related to the dependent variable (*e.g.,* proportion of dead pups). GLM was used for analysis instead of ANOVA or t-tests, because of the heterogeneity of the pup data. GLM has three properties that make it useful when creating a model for data with non-constant variance: 1) Error structure – GLM can take into account a variety of different errors (*e.g.,* binomial errors, which are useful for proportional data like that of dead pups to total pups), 2) Linear predictor – the GLM structure relates each observed value (*e.g.,* proportion of dead pups) to the linear predictor which is the linear effect of the explanatory variables (*e.g.,* breeding site and season), and 3) Link function – this relates the mean value of proportion of dead pups to its linear predictor (Crawley, 2013). Overall, the GLM of the pup mortality data consisted of a distribution of the proportion of dead pups, a predictor function specifying breeding site and season as covariates, and a link between the predictor function and the mean of the dead pup proportion distribution (Zuur et al., 2013).

To determine whether the GLM model for the dead pup proportion data was a good fit for the regression analysis, multiple tests were performed. The first test was a plot of Cooks Distance for the model. This was useful for identifying outliers in the observations for breeding site and season. If any significant points were observed, the model was invalidated. Then a visual regression was made to determine how far off the expected and observed values were under the assumed model. This model identified which values were driving the lack of fit to the model, if this was overdispersed then the model was invalidated. In this study, the best GLM of the dead pup proportion data in relation to breeding site and season was a negative binomial distribution, which is commonly used when analyzing proportional data.

2.7. *Body Condition*

Monitoring the body condition of wild animals such as AFS can provide information about survival, reproductive success, and "well-being" of the population (Arnould, 1995). Furthermore, body condition can provide insight into factors influencing an animal's interactions with its environment (Arnould, 1995). One common and simple way of generating indices of body condition for seals has been the use of body mass and morphometrics (Arnould, 1995).

This study looked at the length, mass, and observed body condition of AFS pups at The Skerries (2017-2018), Seal Rocks (2017-2018, 2016-2017), and Cape Bridgewater (2017-2018) (Table 1). This information was provided from the raw Excel datasheets from when Bec McIntosh and her team went out with collaborator Dr. Rachael Gray (University of Sydney, Senior Lecturer

Veterinary Pathology) to monitor the health of the pups. A physical assessment of the observed body condition was obtained by feeling the spine and hips and associated body fat along a scale from poor to excellent. Body condition was also estimated with an index calculated from the length and weight measurements. In one study on New Zealand fur seals, a morphometric index of pup condition was estimated by comparing all pups measured across years using a linear regression of length versus mass (Bradshaw et al., 2000). The length measurements were taken by placing the pup in a light bag and weighing them with a hook scale (Roberts and Neale, 2016). Mass measurements were taken by using a tape measure and recording the linear distance from nose-tip to tail-tip of pups held in an outstretched position (Roberts and Neale, 2016).

Table 1. Total number of male and female AFS pups per site and season sampled for body condition measurements.

The Skerries		Seal Rocks				Cape Bridgewater	
2017-2018		2017-2018		2016-2017		2017-2018	
M	F	M	F	M	F	M	F
16	7	25	15	32	18	22	13

To begin with, a scatterplot was created comparing AFS pup weight to length in order to determine if there was a correlation between body mass and length. A Welch Two Sample t-test was then conducted to determine if the ratio of weight to length differed between male and female pups. If the results were that males and females differed, then the body condition index would have to be calculated using different regression lines for the two sexes.

This study used the same calculation as Bradshaw et al. (2000) for the body condition index (BCI) of the AFS pups. Applying the regression equation to *log_e length* (L) gave loge_e predicted Mass (M_p):

$$\log_e M_\mathrm{p} = a + b*\log_e L$$

where *a* and *b* are the least-squares regression coefficients. The relative condition index (CI) could then be determined by solving the ratio of observed mass (M_o) to M_p:

$$CI = M_o/M_p$$

The BCI was compared to the observed body conditions in order to determine whether the two methods for determining condition provided similar results. A GLM was then designed to determine whether breeding site, season, and sex affect the BCI of AFS pups. The model was validated similarly to proportion of dead pups by evaluating the Cooks Distance plot and by looking at the dispersion of data from the expected values of the model. The best GLM for the BCI data was the one fitted with Gaussian errors to account for non-normality. The residuals of BCI were plotted based on location, season, and sex in order to determine which of these variables affect the BCI of AFS pups. A full comparative test was not able to be conducted between BCI and pup mortality proportions, due to the limited BCI averages available for only two seasons at three sites.

3. RESULTS

3.1. *Mortality Rates*

Pup mortality rates significantly differed between CMR&Direct and Direct count methods ($p < 0.05$) (Fig. 2). For this reason, CMR&Direct and Direct count data were kept separate from each other during analysis of mortality rates across sites and seasons.

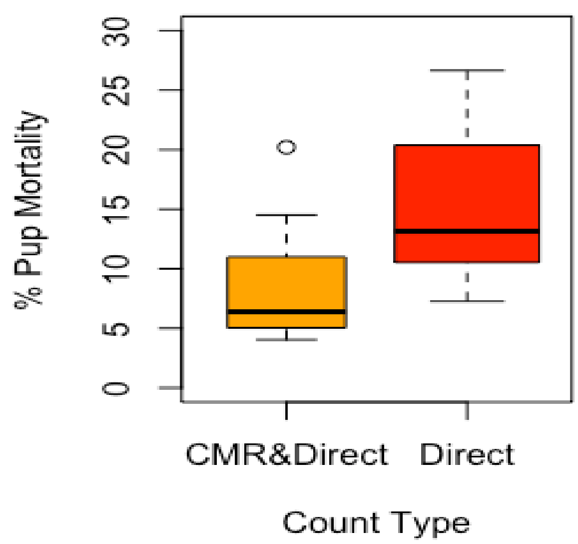

Fig. 2. Boxplot of AFS pup mortality rates gathered from all available CMR&Direct and Direct dead pup count data ($t = 2.556$, $df = 16.617$, $p = 0.021$) for Deen Maar Island, Seal Rocks, The Skerries, and Cape Bridgewater.

The average mortality rates of The Skerries and Dean Maar Island from the CMR&Direct method were both around 5% (Fig. 3; Fig. 4). Whereas, the Direct count average mortality rate for The Skerries was nearly double that of the CMR&Direct count average rate (Fig. 3). The data for The Skerries was similar over the two breeding seasons, per count method (Fig. 3).

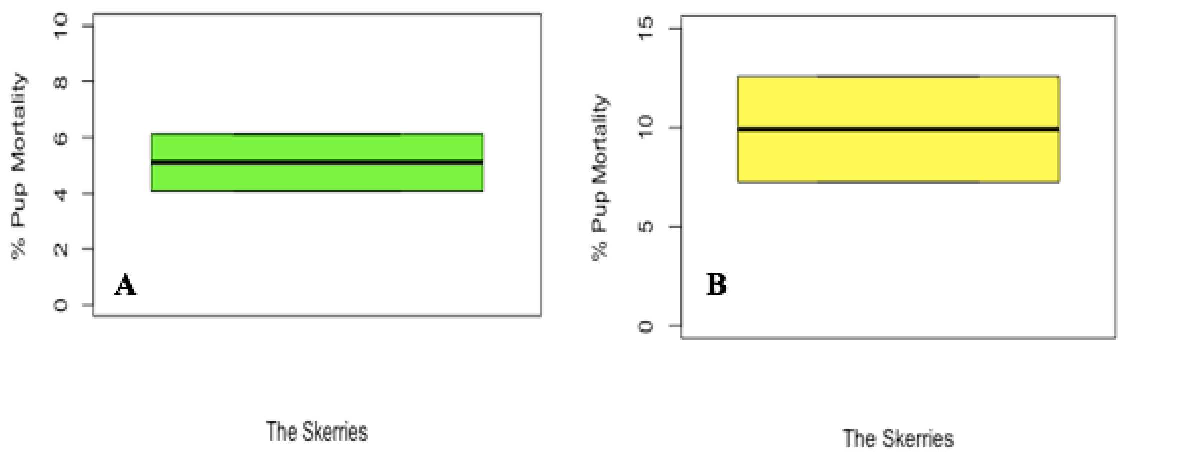

Fig. 3. Boxplots of AFS pup mortality rates at The Skerries acquired using CMR&Direct (A) and Direct (B) count methods across multiple breeding seasons. (A) January – 2017-2018, 2014-2015 (mean = 5.10%, median = 5.10%), (B) January – 2017-2018, February – 2013-2014 (mean = 9.91%, median = 9.91%).

The CMR&Direct count method mortality rates for Deen Maar Island were more variable than The Skerries (Fig. 4). Between the 1999-2000 and 2017-2018, the morality rates seemed to be declining at Deen Maar Island (Fig. 5).

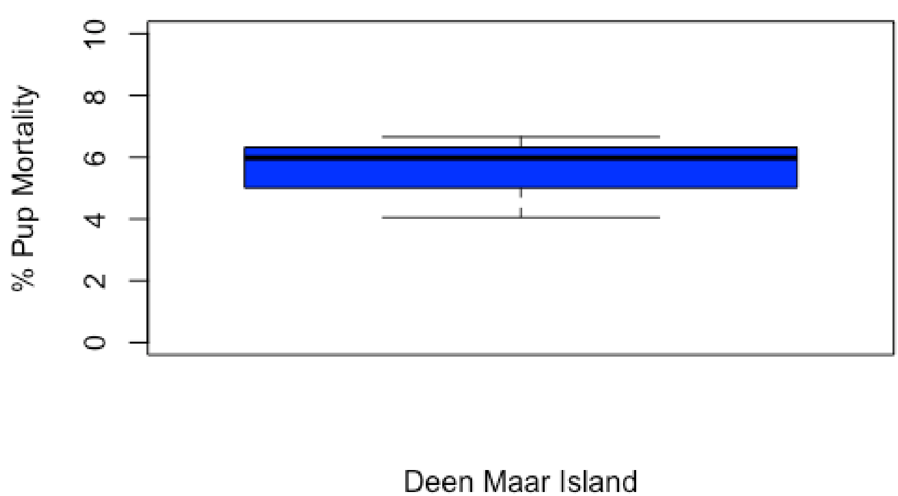

Fig. 4. Boxplot of AFS pup mortality rates at Deen Maar Island acquired using CMR&Direct count methods across three breeding seasons in January – 2017-2018, 2013-2014**, 1999-2000 (mean = 5.56%, median = 5.98%).
**2013-2014 data was acquired between November and December.

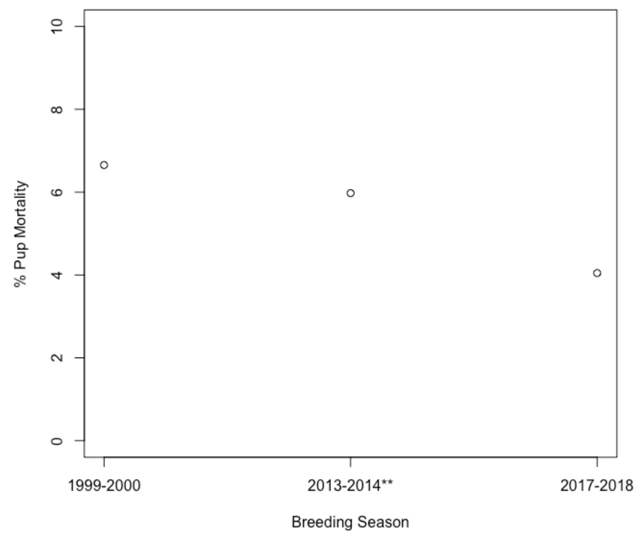

Fig. 5. **Deen Maar Island** scatterplot plot of AFS pup mortality rates of three breeding seasons acquired using the CMR&Direct count method.
**2013-2014 data was acquired between November and December, while the other seasons were collected in January.

Unlike Deen Maar Island, the pup mortality rates at Cape Bridgewater were higher. The average mortality rate at Cape Bridgewater across five breeding seasons worth of data was about 21% (Fig. 6). The rates across five breeding seasons seemed to be on the rise from 2013-2014 to 2015-2016, with rates around 25% seasons, which then dropped down near 10% in the 2016-2017 breeding season (Fig. 7). The rate increased closer to 20% again in the 2017-2018 season (Fig. 7).

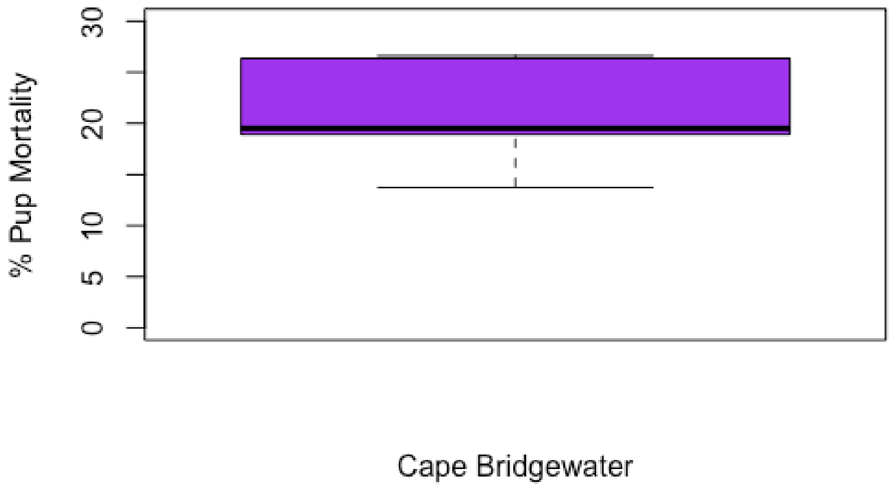

Fig. 6. Boxplot of AFS pup mortality rates at Cape Bridgewater acquired using the Direct count method across five consecutive breeding seasons in January – 2013-14 to 2017-2018 (mean = 21.03%, median = 19.52%).

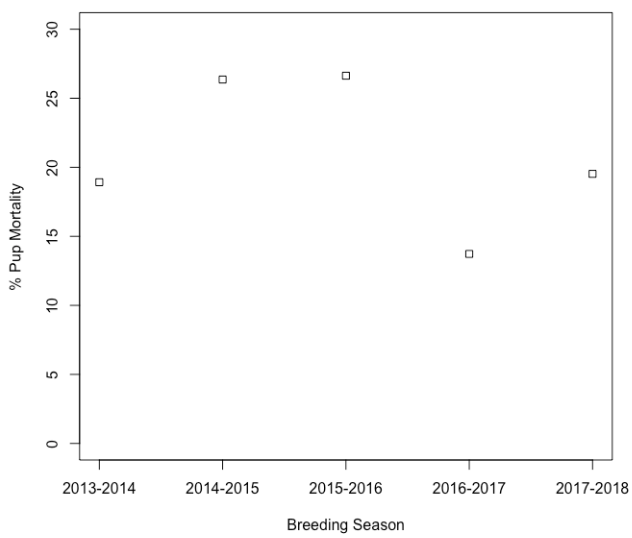

Fig. 7. **Cape Bridgewater** scatter plot of AFS mortality rates across five breeding seasons acquired using the Direct count method in January.

Both the CMR&Direct and Direct count methods produced similar mortality rates at Seal Rocks, with rates between about 10%-12% (Fig. 8). The Direct count data for Seal Rocks had one data point that stood out much higher than the rest of the mortality rates across the five seasons (Fig. 8). This point came from the 2013-2014 breeding season when the mortality rate was just over 20%, and then dropped back down to 10% the next season and stayed stably around 10% since then (Fig. 9).

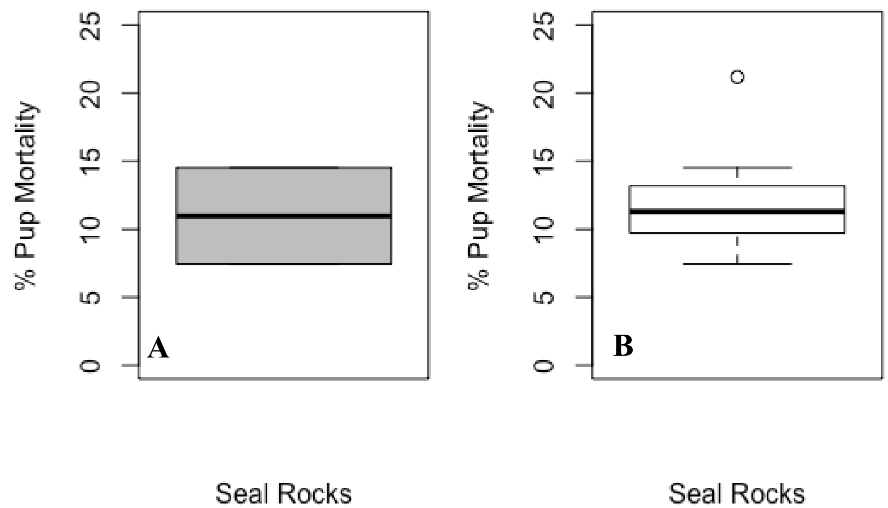

Fig. 8. Boxplots of AFS pup mortality rates at Seal Rocks acquired using CMR&Direct (A) and Direct (B) count methods across multiple breeding seasons in December. (A) 2017-2018, 2013-2014, (B) five consecutive seasons from 2017-2018 to 2013-2014. (A) Mean = 10.98%, median = 10.98%, (B) mean = 12.25%, median = 11.30%.

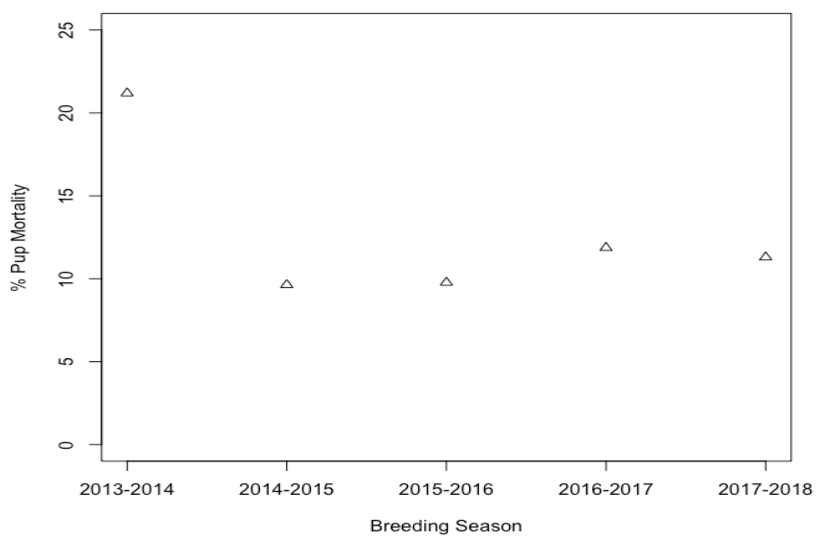

Fig. 9. **Seal Rocks** scatter plot of AFS pup mortality rates across five breeding seasons acquired using the Direct count method in December.

Since Seal Rocks and Cape Bridgewater had the most overlapping data within the same five consecutive breeding seasons using the Direct count method, the mortality rates of these two sites were compared. An ANOVA test was conducted and it was found that there was not a significant difference between the pup mortality rates at Seal Rocks and Cape Bridgewater ($p > 0.05$) (Fig. 10). Despite not being significantly different, other than the 2013-2014 outlier data point at Seal Rocks, the mortality rates of the other four seasons fell fairly close to the downward sloping trend line (Fig. 11). Whereas, for Cape Bridgewater, the mortality rates per season were much more scattered above and below the slightly downward sloping trend line.

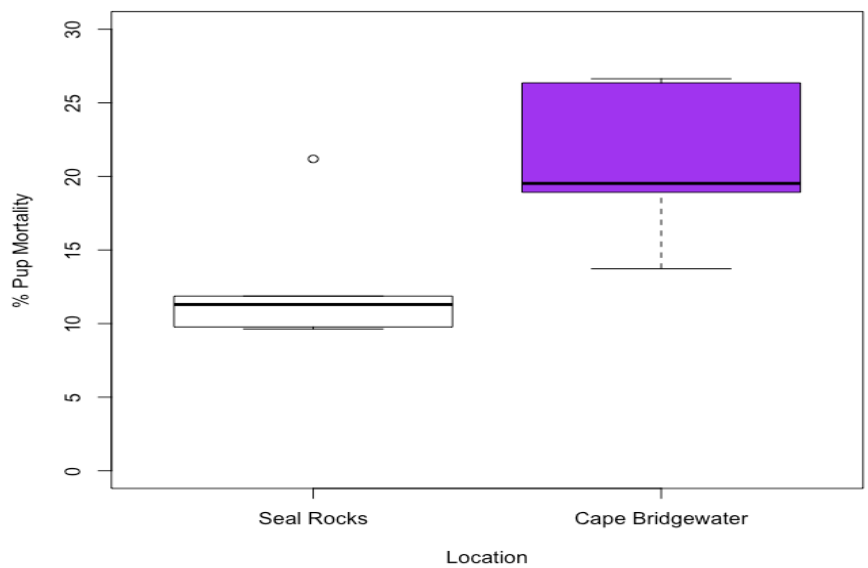

Fig. 10. Boxplots of AFS pup mortality rates across five breeding seasons at Seal Rocks and Cape Bridgewater collected using the Direct count method. Seal Rocks data was collected in December; Cape Bridgewater was collected in January over consecutive breeding seasons from 2017-2018 to 2013-2014. (F-value = 0.582, *df* = 1, p = 0.501).

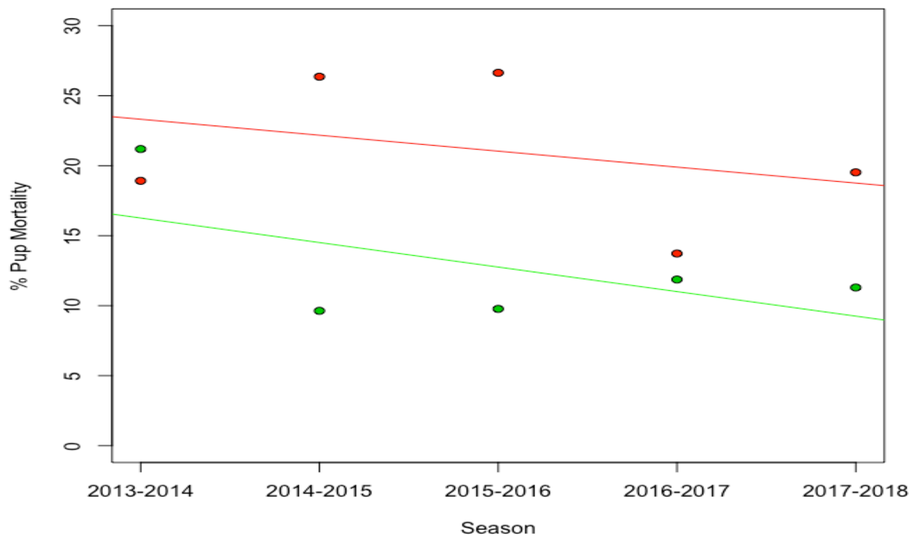

Fig. 11. Scatterplot with trend lines of AFS pup mortality rates between the Direct counts for Seal Rocks (green) and Cape Bridgewater (red).

The only breeding season and count method that had mortality rates from all breeding sites was the 2017-2018 season data acquired using the CMR&Direct count method. The mortality rate at Cape Bridgewater was more than double that of the three other breeding sites. Deen Maar, Seal Rocks, and The Skerries all had rates under 10% (Fig. 12).

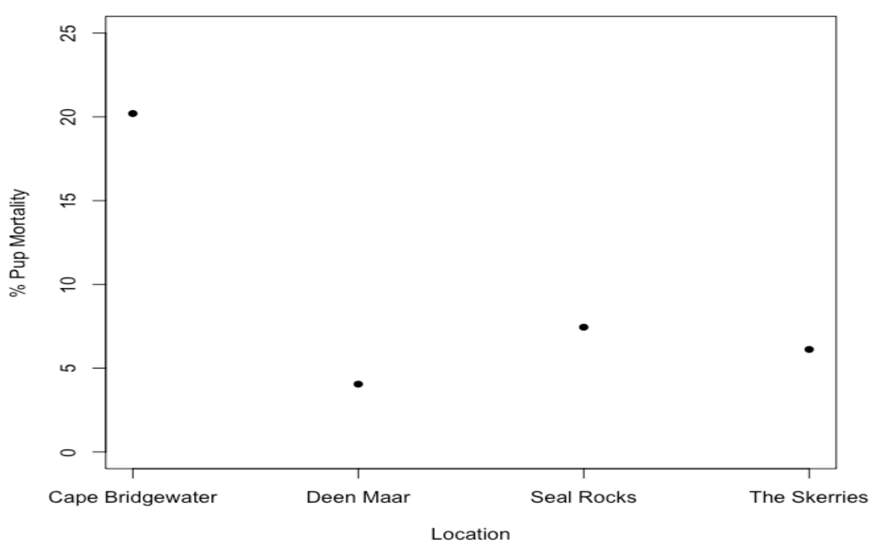

Fig. 12. **2017-2018** breeding season trend plot of AFS mortality rates across four breeding colonies acquired using the CMR&Direct count method. Cape Bridgewater data was collected in January; Deen Maar in January; Seal Rocks in December; The Skerries in January.

3.2. *Negative Binomial GLM for Proportion of Dead Pups*

The GLM was only developed for the Direct count data derived proportion of dead AFS pups due to the sparse CMR&Direct data that was found to not be able to fit any of the possible GLMs. Unfortunately, this also meant having to exclude Deen Maar Island from data analysis, because it only had CMR&Direct dead pup counts. The model was overdispersed (dispersion parameter > 5) when using the Poisson distribution, therefore the negative binomial distribution was the final model used for the GLM (Fig. 13; Fig. 14). There were no significant outliers in the Cooks Distance plot which validated the final model (Fig. 13). The Pearson residuals data fell fairly close to the fitted values, further indicating that the negative binomial was the best fitting model (Fig. 14).

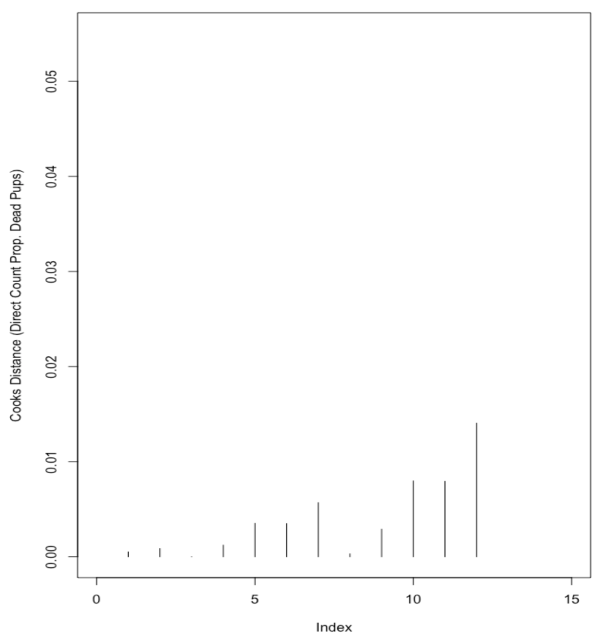

Fig. 13. The Cooks Distance values for the Direct count negative binomial GLM for proportion of dead pups.

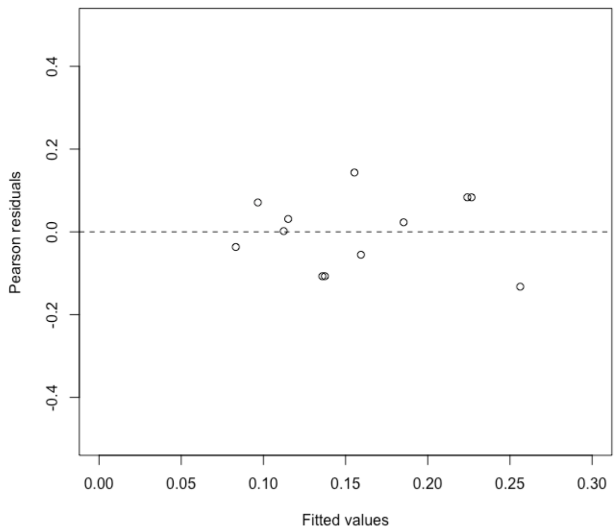

Fig. 14. Scatterplot of the Pearson residuals of the Direct count negative binomial GLM for proportion of dead pups versus fitted values in relation to breeding site and season.

The visual regression plot of the negative binomial GLM indicated that there was very little variation in the effects of different breeding sites on proportion of dead pups (Fig. 15). The same was true for breeding season (Fig. 16). The summary of the negative binomial GLM confirmed the data presented in the plots, since none of the breeding sites or seasons had a significant effect on the proportion of dead pups (no p-values < 0.05) (Table 2).

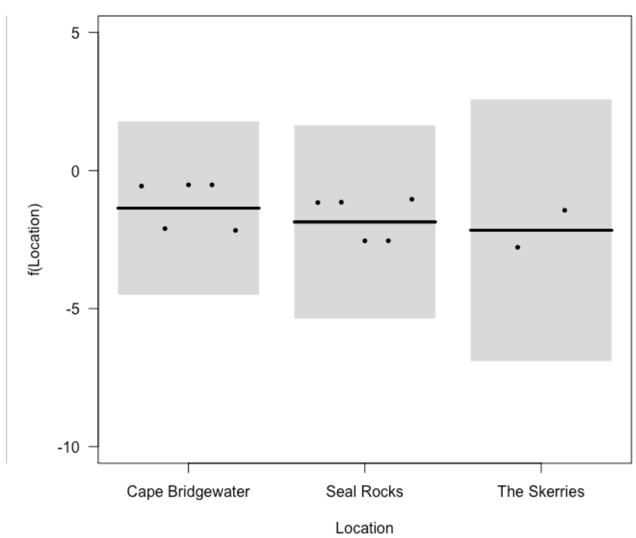

Fig. 15. Visual regression plot of the negative binomial GLM of the proportion of dead AFS pups in relation to breeding site.

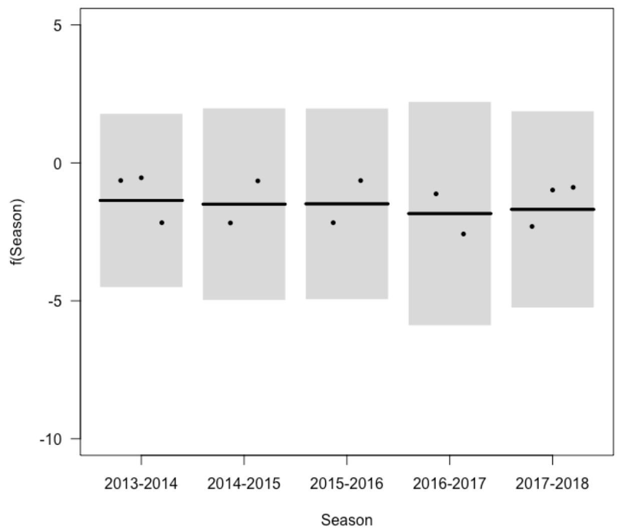

Fig. 16. Visual regression plot of the negative binomial GLM of the proportion of dead AFS pups in relation to breeding season.

Table 2. P-values for the coefficients from the summary of the negative binomial GLM for proportion of dead AFS pups in relation to breeding site and season. Any coefficients not presented in this table had higher p-values than the ones shown.

Independent Variable	P-Value
Seal Rocks	0.753
The Skerries	0.759
2014-2015	0.952
2015-2016	0.956
2016-2017	0.848
2017-2018	0.879

3.3. *Body Condition Index*

In order to confirm the validity of using weight and length of pups in body condition calculations, the two measurements were plotted against one another. A positive correlation was found between weight and length measurements for pups (Fig. 17). A significant difference was also found between the weight to length values for male and female AFS pups (Fig. 17). As a result, the body condition index (BCI) values had to be calculated separately for males and females.

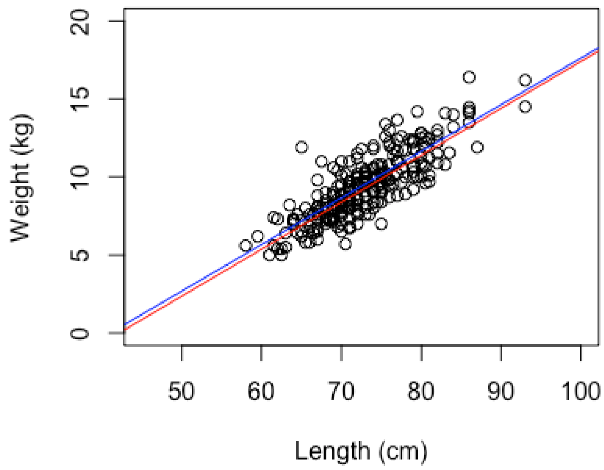

Fig. 17. Scatterplot of body weight (kg) versus length (cm) of live AFS pups (correlation coefficient = 0.825). Red trend line indicates female pup data; blue line indicates male pup data (t = -4.553, *df* = 230.96, p = 8.536×10^{-6}). AFS pup body measurement data gathered at Cape Bridgewater (2017-2018), Seal Rocks (2017-2018, 2016-2017, 2015-2016), and The Skerries (2017-2018).

The calculated BCI was then compared to the body condition observations made by the veterinarian. For the female AFS pups the BCI values were highly variable in their correspondence to the observed body condition (Fig. 18). The pups in good observed condition had higher BCI values than excellent condition pups which had high variability in BCI values (Fig. 18). The BCI values for males were less variable, but similar across the different observed body conditions (Fig. 19).

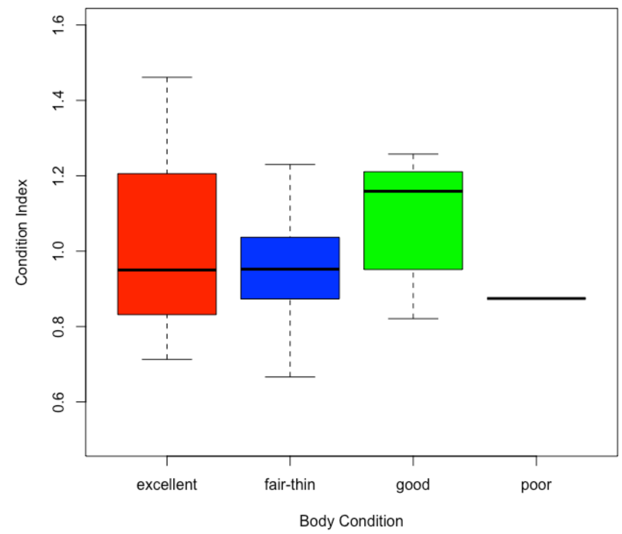

Fig. 18. BCI (condition index) versus veterinarian observed body condition for live female AFS pups.

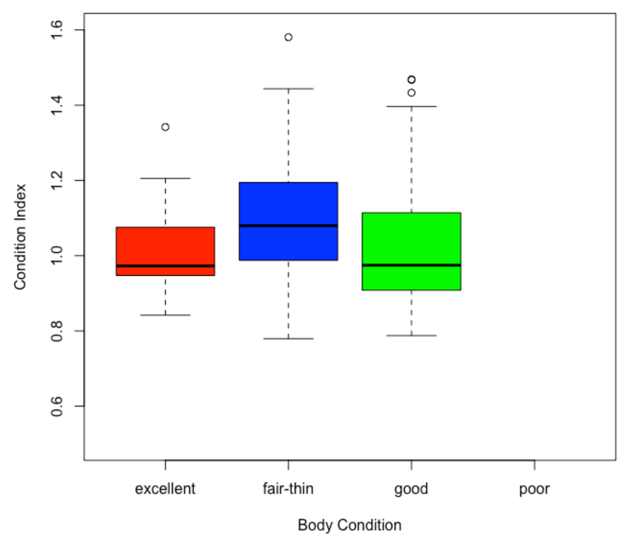

Fig. 19. BCI versus veterinarian observed body condition for live male AFS pups.

3.4. *Gaussian GLM for the BCI of live pups*

A GLM was developed to determine whether breeding location, season, and pup sex had an effect on the BCI of AFS pups. The GLM that best fit this data was a Gaussian distribution (Fig. 20; Fig. 21). There were no significant outliers in the Cooks Distance plot which validated the model (Fig. 20). The Pearson residuals data was a bit variable around the fitted values, however, this was the least varied of all the tested models (Fig. 21).

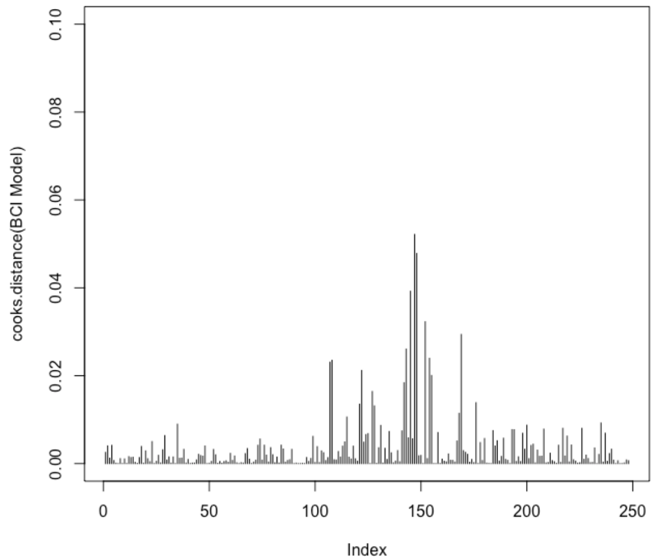

Fig. 20. The Cooks Distance values for the Gaussian GLM for the BCI of AFS pups.

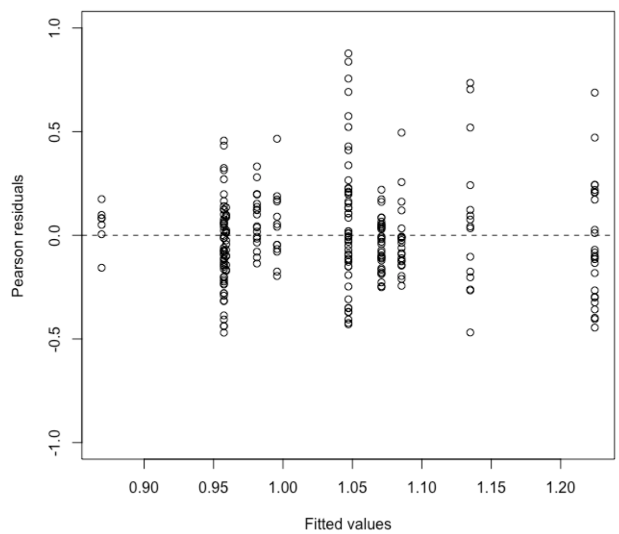

Fig. 21. Scatterplot of the Pearson residuals of the Gaussian GLM for the BCI of AFS pups versus fitted values in relation to breeding site, season, and sex.

The visual regression of the Gaussian GLM for BCI in relation to breeding site, indicated that breeding site, season, and sex may have had a significant impact on the body condition of AFS pups (Fig. 22; Fig. 23; Fig. 24; Table 2). In the visual model for the effect of breeding site, Seal Rocks was highly variable showing that something significant may have been occurring at this particular site (Fig. 22). From the GLM summary, Seal Rocks had a significant p-value (<0.05) indicating that this site differed in AFS pup body conditions compared to other breeding locations. The regression for the model based on breeding season also showed high variability in the data (Fig. 23). In the summary, the GLM showed that the 2017-2018 season in particular had significantly different body conditions than the other seasons (p-value < 0.05) (Table 2). Finally, the data for sex of the pups was also variable in the presented model (Fig. 24). The summary of the model presented that there was a significant difference in body condition between male and female pups (Table 3).

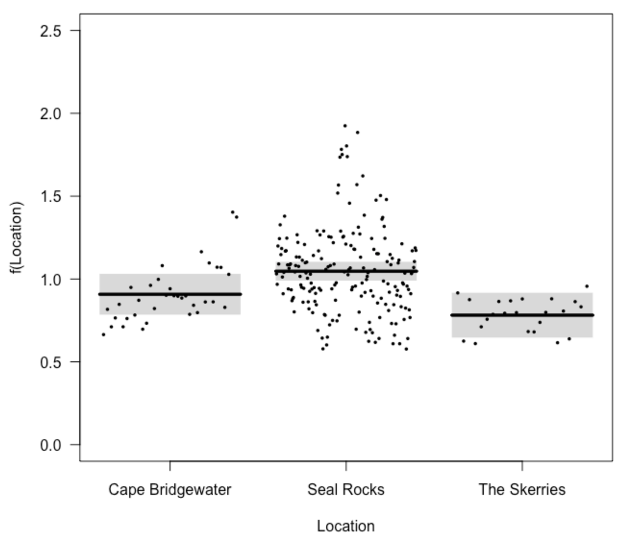

Fig. 22. Visual regression plot of the Gaussian GLM for the BCI of AFS pups in relation to breeding site.

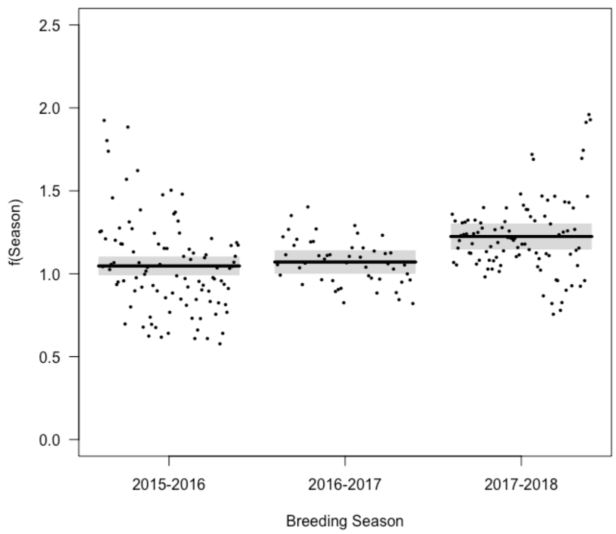

Fig. 23. Visual regression plot of the Gaussian GLM for the BCI of AFS pups in relation to season.

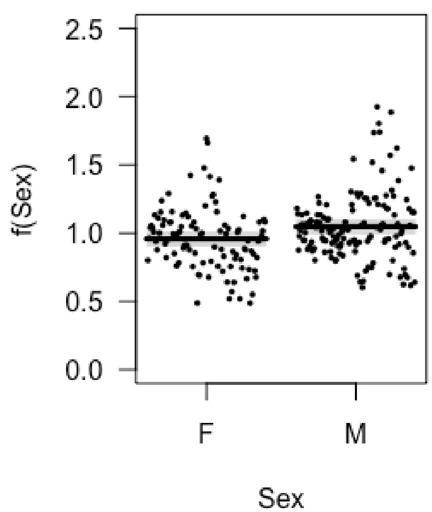

Fig. 24. Visual regression plot of the Gaussian GLM for the BCI of AFS pups in relation to sex.

Table 3. P-values for the coefficients from the summary of the Gaussian GLM for the BCI of AFS pups in relation to breeding site, season, and sex. Any coefficients not presented in this table had higher p-values than the ones shown.

Independent Variable	P-Value
Seal Rocks	0.0134**
The Skerries	0.0524
2016-2017	0.572
2017-2018	1.18×10^{-4}**
Male pups	0.0047**

**Indicates a significant p-value.

4. DISCUSSION

The AFS pup data that was gathered to determine pup mortality was done using either CMR to determine total live pup numbers and a direct count to determine dead pup numbers or a Direct count of both live and dead pups. The CMR&Direct collected data was significantly lower than those from Direct counts (Fig. 2). This is most likely due to CMR being a more accurate method for determining total population numbers (Kirkwood et al., 2005). Direct counts are more prone to underestimates since they do not take into account pups obscured from sight. Since the CMR live pup populations were generally higher than Direct counts, but the dead pup counts were underestimated due to the errors of direct counting, the proportion of dead pups to total pups was a lower ratio than that for Direct counts. For this reason, the pup mortality rate analysis for CMR&Direct and Direct count methods were kept separate. The difference between the methods is basically a data transformation, being of a different scale, and either may be used for the purpose of monitoring trends and effects.

Out of the four breeding colonies studied, Deen Maar Island had the lowest mortality rates gathered from the CMR&Direct count method (~6%) (Fig. 4). It was expected that Deen Maar would have a higher rate of pup mortality, at least in comparison with the other sites, due to the presence of persistent organic pollutants (POPs) bioaccumulated in this region, which has led to the fatal alopecia syndrome in the AFS population (Taylor et al., 2015). Alopecia has been seen in up to 50% of juvenile females at Deen Maar Island, which affects thermoregulation increasing the risk of mortality (Taylor et al., 2015). It would be expected that with such high prevalence of disease causing toxins in the environment around Deen Maar, that this would have an effect on pup mortality if mothers with alopecia cannot fully provide for their young, or if there are negative impacts on reproductive success linked to pup health. However, using the CMR&Direct method may not have been able to capture the full effects of this disease on pup mortality. Deen Maar Island is characterized by rocky terrain at the base of high cliffs and frequent wave wash. Dead pups may have slipped through the gaps between the large boulders or been washed away, so they were missed in counts. For these reasons, the ratio between dead and total pups may have been underestimated due to the geography of this site and the limitation of using direct count for identifying dead pups.

Unlike Deen Maar, Cape Bridgewater had the highest average mortality rate across five breeding seasons using the Direct count method (mean ~ 21%) (Fig. 6). Cape Bridgewater is located relatively close to Deen Maar Island (Fig. 1), and has similarly been found to have alopecia present in its AFS population, possibly due to the same toxins found around Deen Maar (McIntosh, 2016). However, it may have presented higher rates of mortality from the Direct count method because the large breeding cave could have protected AFS pup carcasses from being washed away or eaten by birds (Fig. 25). It is possible that more accurate dead pup counts were acquired at this site, which indicated that AFS pup mortality at Cape Bridgewater were typically above the commonly used 15% mortality rate (Warneke, 1982), and closer to the 20% mortality pup rates in the first two months of life found for other fur seal species (De Villiers and Roux, 1992; Mattlin, 1978).

The average pup mortality rates at Seal Rocks for both the CMR&Direct and Direct count methods fell under 15% (Fig. 8). There has been more data collected using the Direct count method at this location, allowing for trends to be depicted across five breeding seasons. In comparison with Cape Bridgewater, the mortality rates at Seal Rocks have been much more stable over the course of the five seasons (Fig. 11). However, in the 2013-2014 season the pup mortality rate at Seal Rocks spiked up to over 20%, which may have been the cause as to why the rates between Seal Rocks and Cape Bridgewater did not show a significant difference (Fig. 9; Fig. 10). Other than this season, the Seal Rocks rates were more similar to The Skerries and Deen Maar, which all fell under 15% (Fig. 3; Fig. 4), similar to the lower mortality rate in Long-nosed fur seals found by Shaughnessy et al. (2015). It remains possible that sites other than the Cape Bridgewater cave are subject to loss of dead pups (waves and carrion eaters) and vulnerable to being underestimated when reliant on a single visit at the end of the breeding season.

The 2013-2014 breeding season fell after the hottest recorded Australian summer in observational record (IMOS). Hot summers such as this increase seawater temperatures, which impact marine ecosystems. One study on Australian sea lions in South Australia found that their populations were declining at 1.14% during the breeding season each year (McIntosh et al. 2012). They determined that the yearly survival rates of pup cohorts were negatively correlated with the sea surface temperatures in the areas where the sea lions foraged (McIntosh et al. 2012). Fur seals are closely related to sea lions, which means that environmental changes that affect Australian sea lions may have similar impacts on AFS. This means that after a summer period of unusually warm oceanographic conditions in areas such as Seal Rocks, primary production may be limited. As a result, female AFS may not have been able to provide sufficient food to their pups (McIntosh et al. 2012), resulting in an increase in pup mortality rates for this season.

The negative binomial GLM for proportion of dead AFS pups signified that neither breeding site (Cape Bridgewater, Seal Rocks, and The Skerries) nor breeding season (2013-2018) had an effect on pup mortality rates (Fig. 15; Fig. 16). Although Cape Bridgewater had high mortality rates in comparison to the other sites (Fig. 7; Fig. 12) and Seal Rocks had a high mortality rate in the 2013-2014 season (Fig. 9; Fig. 11), these locations and this season were not found to be significant in an overall comparison across sites and seasons (Table 1). However, these results were based off of very limited data on pup mortality. It is possible that with more data to compare and more power in the model, the trends at Cape Bridgewater and Seal Rocks may actually have been significant. In a study on live AFS pup population trends, it has been found that large colonies like Seal Rocks and Deen Maar, have had reductions in pup numbers, while newer colonies like Cape Bridgewater have shown increases since 2007 (McIntosh et al., 2018). Evidently populations vary, so it may be possible that with more data, pup mortality rates may also show significant variation at different breeding sites across different seasons.

The strong positive correlation between weight and length of AFS pups (Fig. 17) confirms the idea that it is necessary to account for body size when analyzing changes in body mass since mass is proportional to length (Bradshaw et al., 2000). Unlike in other studies that have looked at fur seal pup body condition, this study found a significant difference in the ratio of weight to length for males and female pups (Fig. 17). It was expected that for pups of different sexes in the first two months of life, body condition would not have been considerably different from one another. This result indicates that body condition may be affected by the sex of the pup. This was found to be true in the Gaussian GLM for BCI in relation to sex (Fig. 24; Table 2). Furthermore, breeding location and season also had a significant impact on the BCI of AFS pups (Fig. 22; Fig. 23; Table 2). In particular, Seal Rocks and the 2017-2018 seasons were significantly different, with higher BCI indices than the other sites and seasons (Table 2, Figs 22-23). It was interesting that the calculated BCI values did not align well with the observed body conditions by a certified veterinarian, leading to doubts as to whether the calculation used on body mass and length was the best method for determining body condition for pups (Fig. 18; Fig. 19). Pups may have recently finished a meal of milk that could affect mass measurements. With further health information via histology of blood, fur and rectal samples (Gray, R., unpublished data), we may be able to test the value of the two body condition methods as indices of pup health. Other methods that could be used to more reliably identify body condition include sampling total body water and total body lipid data (Arnould, 1995).

Pup body condition is a good indicator of food availability in the environment and foraging efficiency of females (Bradshaw et al., 2000). For this reason, it was expected that body condition trends would align with the mortality rate trends, because poor body condition at a location or within a specific season should lead to higher mortality in pups. Due to sparse and missing data for both body condition and mortality rates, we were unable to test this with precision. In the future, with a longer time series of more accurate data, pup condition could supply insight for mortality rates within given sites and seasons.

5. CONCLUSION

Based on the results of this study, it seems that the typical mortality rates in the first two months of life at major breeding colonies in the Bass Strait region of Australia are under 15%. This finding is different from previous studies on other closely related fur seals which have higher mortality rates of 20% (Mattlin, 1978). In fact, the unusual mortality rates for AFS were those at Cape Bridgewater and the 2013-2014 breeding season at Seal Rocks were 20% or slightly higher. It could be that the Cape Bridgewater site captures dead pup carcasses, being a cave, resulting in more accurate counts.

Although Cape Bridgewater had the highest observed mortality rates across multiple seasons of all the sites, its overall live pup population has been dramatically increasing since 2007 (McIntosh et al., 2018). Yet, major breeding colonies such as Deen Maar and Seal Rocks, which had generally lower mortality rates (under 15%), have shown significant decreases in live pup populations (McIntosh et al., 2018). It is hard to determine the impacts of breeding location on mortality rates with such limited data, which may be the cause for insignificant results across the entire negative binomial GLM for the proportion of dead pups.

The same holds true for the body condition data. With a BCI index that did not align with the veterinarian observations and that had a high amount of variability, it is difficult to determine whether breeding location, season, and sex impact the health of AFS pups, and therefore, how their health affects their mortality rates.

Since mortality rates and the factors affecting them provide knowledge about population dynamics, insight into changes in the marine environment, and success of management practices (Eberhardt, 1981; Bradshaw et al., 2000; McIntosh et al., 2018), it will be necessary in the future to collect more frequent and accurate data for AFS pups. Both CMR and Direct count methods are logistically demanding, expensive, and cause significant disturbance to wildlife (McIntosh et al., 2018). As a result, population monitoring is low in frequency and trends are low in precision which has led to reduced confidence in analyses. This makes it difficult to accurately monitor the recovery process of AFS from commercial harvesting in the early 1800s. For this reason, alternative methods need to be developed in order for researchers to obtain quality information on AFS population trends with minimal disturbance in order to gain accurate information on ecosystem health.

One such method currently being tested is the use of Remote Piloted Aircraft (RPA) (McIntosh et al., 2018). RPAs have begun to be used by McIntosh et al. (2018) to survey AFS abundance at Seal Rocks. An RPA at 40 m altitude can produce pup counts 20-32% higher than ground counts with better resolution and minimal disturbance. With this method, higher quality data can be obtained at more frequent levels. In the future, the images produced from RPA surveys can be used to determine total and dead AFS pups with a higher accuracy in order to get better results for pup mortality rates across more days within breeding seasons and sites.

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