

# **Aerial Surveys: Effects of Aircraft Speed and Environmental Factors on Marine Megafauna**

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## Declaration

I declare that this thesis, as a whole or in parts, has not been submitted for a higher degree to any other university or institution.

I wish to acknowledge the following assistance in the research detailed in this report:

Lisa-Marie Harrison for her assistance in the statistical analysis and modelling of the data collected in this study.

Vic Peddemors for his contribution to the experimental design and logistic arrangements and organisation of the aerial surveys.

Robert Harcourt for his general help and guidance in all sections of this thesis.

All other research described in this report is my own original work.

A handwritten signature in black ink, appearing to read 'S. Dupont', with a stylized flourish at the end.

SALLY DUPONT

10 October 2016

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## **ABSTRACT**

Aerial surveys are commonly used to monitor animal population and behaviour in both terrestrial and marine settings. Using aerial surveys and a density surface model (DSM) I investigated the impact of environmental factors on marine megafauna. The underestimation associated with marine aerial surveys are caused by two factors: availability and perception biases. Both of these can potentially be resolved by reducing aircraft speed. In this thesis I investigated whether observers sighted a greater number of marine animals when the aerial platform (in this case helicopters) travelled at 80 knots compared to 100 knots. No significant difference in detection of dolphins, fish schools or sharks was found, suggesting that observer training and experience has a greater impact than speed on the number and type of animals seen. Given the significant increment in cost of both observer time and helicopter charter incurred from using a 20% slower speed, without an increase in data quality, retention of the 100 knot survey speed is recommended. No significant relationship was found between dolphin and fish school counts and either sea surface temperature (SST) or chlorophyll-a (Chl-a). This suggests the involvement of other factors in the distribution and habitat selection of marine animal population.

**Key words:** aerial surveys, aircraft speed, marine megafauna, environmental factors, density surface model (DSM), sea surface temperature (SST), chlorophyll-a (Chl-a)

## **INTRODUCTION**

Aerial surveys are a common ecological tool used extensively in both marine and terrestrial environments to monitor animal populations (Carretta et al. 1998, Newson et al. 2008, Herr et al. 2009, Poole et al. 2013). In some areas of the world, aerial surveys are used as a predator detection method. In Australia for example, it is now common to find helicopters surveying coastal areas as part of a shark detection program (Robbins et al. 2014). This allows swimmers and surfers to be warned of a shark presence, potentially reducing the risk of an attack. The sharks patrol surveys provide an opportunity for data collection that might not be possible otherwise taking into consideration the high financial cost associated with helicopter surveys. While helicopter surveys are capable of covering large coastal areas,

they often remain unvalidated for observer coverage and effectiveness, therefore it is important to refine aerial survey methods. The first chapter of this thesis investigates the effect of aircraft speed on the count of marine coastal animals, focusing on dolphins, sharks and fish schools. The aim is to provide recommendations for future aerial surveys, taking into account relevant factors such as financial cost and observer training.

Marine animal distribution varies both temporally and spatially, with many studies finding presence and/or abundance correlate with abiotic factors, particularly sea surface temperature (SST) (Selzer and Payne 1988, Bräger et al. 2003, Becker et al. 2010). Chlorophyll-a (Chl-a) has been used as a proxy for primary production and is often used to investigate associations of species of higher trophic levels such as dolphins and sharks (Grémillet et al. 2008). In the second chapter, I use the validated methodology of aerial surveys to gain a greater understanding of marine coastal species and their distribution. Seasonal and annual variations of bottlenose dolphins, sharks and fish schools are investigated as well as the impact of fine scale environmental factors such as SST and Chl-a. Combined, the two chapters of this thesis provide information that will help guide future researchers on the most important factors affecting marine coastal species habitat selection and identifies the best method of collecting valid survey data.

## **Chapter 1**

# **Aerial Surveys: The Effect of Aircraft Speed on Marine Megafauna Counts**

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## INTRODUCTION

Due to the vast expanse of the ocean, researching marine animals has always been logistically challenging. Aerial surveys are a widely used ecological tool that allows researchers to survey animals over relatively large areas quickly, and have been used extensively in both marine (see Carretta et al. 1998, Herr et al. 2009, Jean et al. 2010, Kessel et al. 2013) and terrestrial environments (see Newson et al. 2008, McRoberts et al. 2011, Poole et al. 2013). Abundance and density counts obtained from aerial surveys are used in population estimates where they play a critical role in the conservation and management of targeted animals (Semeyn et al. 2011, Martin et al. 2015).

There are many advantages to aerial surveys over other available platforms, including land-based observations commonly used in the long term monitoring of marine megafauna (Sease et al. 2001, Hastie et al. 2003). Aerial surveys are ten times faster than ship-based surveys (Winiarski et al. 2014b), and as a result, are able to cover a greater area in the same amount of time. Furthermore, flying at a higher altitude means that aerial surveys have a better visibility into the water column compared to both visual ship-based and land-based surveys for near surface animals (Hara 1990). However, there are some problems associated with the current implementation of aerial surveys.

The two main problems surrounding aerial survey are financial cost and underestimation of animal abundance. Firstly, although aerial surveys can sometimes be more cost-effective than other survey methods (Kingsford 1999), the associated financial cost often proves to be a limiting factor in their use (Camphuysen et al. 2004). Unfortunately, this problem is present to some degree in all aerial surveys and can rarely be avoided. It is therefore paramount to optimise aerial surveys in order to obtain the highest possible degree of accuracy in the information collected if using this method. Secondly, without correction, aerial surveys can severely underestimate population counts (Robbins et al. 2014, Fuentes et al. 2015). Counts obtained from aerial surveys can be partially corrected using distance sampling, a method that uses a metric of the distance between the observer and the animal to calculate the number of animals missed (Thomas et al. 2010). Taking into account the number of missed animals leads to more accurate abundance estimates (Royle et al. 2004).

Underestimates associated with aerial surveys are primarily caused by two main biases common to all survey methods: availability and perception biases (Pollock et al. 2006). Availability bias arises when an animal is present in the survey area but is submerged and hence not available for detection (Pollock et al. 2006). As a consequence, observers are limited by the number of animals available for sampling at the time the observers pass through the area. Perception bias occurs when an observer fails to sight an animal that is in fact available for detection (Certain and Bretagnolle 2008). Speed may exacerbate these biases, because hidden animals do not have as much time to become visible (availability bias) and observers have less time to detect available animals (perception bias) when travelling at higher speeds. There is evidence that detectability decreases as the speed of the aircraft increases (Caughley et al. 1976, Hone 1986), however this has yet to be formally tested. Theoretically, a minimum speed threshold exists, below which the possible increase in detectability becomes too low to be viable considering the impact of other factors such as observer fatigue, availability bias and overall financial cost. Conversely, a maximum speed threshold would also exist, above which availability bias becomes too great to justify any reduction in observer fatigue and financial cost. Speed at which a survey is conducted is therefore an important parameter to investigate when attempting to optimise aerial surveys.

Considering the prevalence and the high financial costs associated with aerial surveys, it is important to optimise their effectiveness. As outlined above, a trade-off exists between cost and detection rate when choosing the speed of an aerial survey. However, the measure of that trade-off remains unknown. This study investigates the effect of aircraft speed on marine megafauna sighting rates. We used twin helicopters, each with two independent observers, to concurrently survey at 80 and 100 knots. We hypothesise that there will be fewer sightings at the higher speed of 100 knots compared to 80 knots and use the results to make recommendations for refining aerial survey design.



## STUDY AREA

Sixteen transects (eight northbound and eight southbound) were flown along the New South Wales (NSW) coast between Stockton Beach in Newcastle ( $32^{\circ}54'53.8''$  S,  $151^{\circ}47'35.3''$  E) and Seal Rocks ( $32^{\circ}22'59.8''$  S,  $152^{\circ}31'53.6''$  E), a distance of 118 km, from 5 October 2015 to 9 October 2015 (Fig. 1). Four transects were conducted on the first day, starting at 11:30 Australian Eastern Standard Time (AEST) and finishing at 18:30. Six transects were conducted on the second day, starting at 7:30 and finishing at 17:50. No surveys were conducted on the third day due to bad weather. Due to deteriorating weather, only two transects were conducted on the fourth day, starting at 7:30 and finishing at 11:10. Four transects were conducted on the fifth day, starting at 7:00 and finishing at 14:00. Each survey took approximately one hour to complete. We used a tandem method similar to the one described by Carretta et al. (1998).



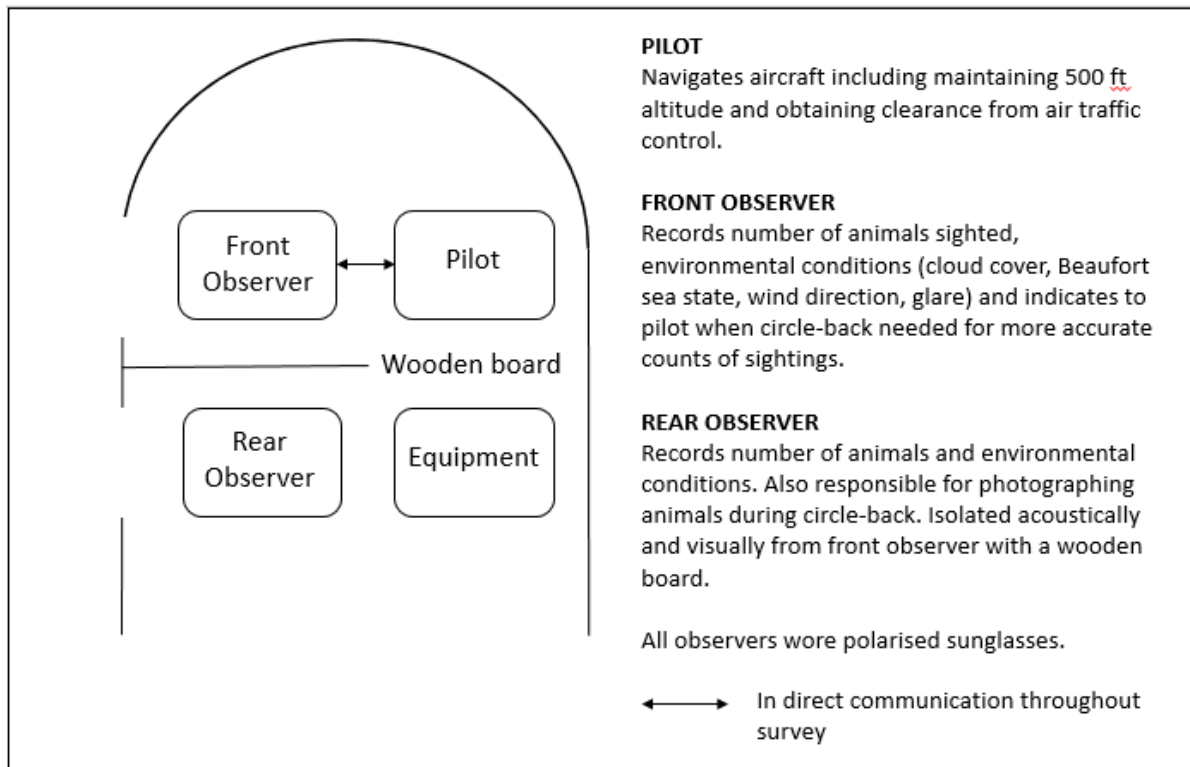
**Fig. 1.** Map showing geographical location of transects.

## METHODS

The transects were flown by two Robinson 44 helicopters travelling at an altitude of 500 ft (~150 m) and a distance of approximately 300 m out from the back surf line for the northbound transects and directly above the surf line when travelling south. The transect

width was therefore approximately 300 m. Two distinct flight speeds were used with one helicopter travelling at 80 knots while the other travelled at 100 knots, alternating for each of the transects. 100 knots was considered the control speed as the majority of marine aerial surveys have traditionally been conducted at that speed. 100 knots is the minimum safe flying speed for small aeroplanes traditionally used in surveys and thus widely adopted. The second helicopter flew at 80 knots on the assumption that a 20% difference in flight speed was large enough to detect a speed-induced sighting difference, and because any slower was unlikely to be practical in routine surveys given fuel usage and observer fatigue. The two helicopters remained in close proximity to ensure the same animals were available to all observers. However, due to the difference in speed, the faster helicopter would slowly pull ahead and so consequently was required to hover in wait for the slower aircraft every 15 minutes.

Each helicopter crew consisted of a pilot, one front observer and one rear observer. In both aircrafts, the front observer was experienced while the rear observer was novel, having little to no aerial survey experience. Observer pairs remained the same throughout the entire study; observers did not switch aircrafts. The two observers sat on the same side of the aircraft, with both doors removed (Fig. 2). To ensure observers were completely independent, the rear observer was separated visually from the front observer by a wooden board and acoustically via the helicopter's communications system operated by the pilot. Each observer recorded their observations into their own voice recorder, which was later transcribed.



**Fig. 2.** Interior schematic illustrating the seat configuration in each helicopter and how the two independent observers are separated visually by a wooden board. (Adapted from Pollock et al. 2006).

Observers scanned the water below for sharks, dolphins, fish schools, turtles, whales, rays and seals. Upon sighting an animal, observers recorded a waypoint of the location when perpendicular to the sighting using a handheld Garmin 760S Global Positioning System (GPS), as well as the angle to the animal using a Suunto inclinometer. Observers further recorded the species (if this was unknown, then the general animal type e.g. shark), number of individuals and swimming direction if applicable. For dolphin pods, circle-backs were performed in order to take photographs to improve the count of individuals. To ensure independence between each aircraft, photographs were only taken by the slower helicopter so as to not alert the other aircraft. Photographs were taken using a Nikon D7200 with a f3.5-5.6 18-200 mm lens. Changes in environmental conditions (e.g. sea state, glare, rain) were also recorded as they occurred and a waypoint taken. Sea state was measured on the Beaufort scale of 1 to 4, with 1 being flat surface conditions and 4 being waves with breaking crests and frequent whitecaps. Surveys were not conducted above a sea state of 4. Glare was given as a percentage of the total field of view affected (e.g. 10%) and cloud cover was measured on a scale of 0 to 8, with 0 being no visible clouds and 8 being completely

overcast. Water clarity was given on a scale of 1 to 3, with 1 being transparent and 3 being completely opaque. A waypoint was taken at the start and end of each survey or when leaving the transect to undertake circle-backs for photographs or to wait for the slower helicopter.

## **DATA ANALYSIS**

Due to logistical issues leading to a poor quality recording for one of the observers, we were unable to transcribe data for the last transect and thus had to exclude it from the analysis, leaving 15 transects in total. Sightings from each observer were matched using the associated GPS coordinates and sighting information and given a unique sighting number. This allowed us to determine which sightings were seen or missed by a particular observer and to further obtain a count for each of the two helicopters. For the purpose of this analysis, all shark species except for hammerheads were grouped into the one category because identification to species level was often not possible. Since all hammerheads were seen by only one helicopter, they were excluded from analysis so as to not skew the results. Furthermore, the number of other taxa observed (humpback whales, seals, turtles and rays) were too low for statistical analysis and were thus not included.

Distance sampling was used to account for decreasing observations with increasing distance from the transect. A detection function for each helicopter was calculated for dolphins, fish schools and sharks. The observing distance was left-truncated at 50 m since animals were not visible directly under the helicopter and right-truncated at 300 m so as to have comparable data for both north and south flight directions. Speed, flight direction and environmental factors were included as input variables in each detection function. Three models were fitted to the distance data for each species (hazard rate, half-normal and gamma) with Akaike Information Criteria (AIC) used to identify the best model. Hazard rate assumes constant detectability across the entire transect while half-normal assumes highest detection on the line before slowing dropping off in a curve. Gamma allows the apex (highest detection) to be anywhere along the transect, not necessarily on the line. The probability of detection was calculated as the average probability of detection from the detection function multiplied by the combined probability of the two observers in the

aircraft (inter-observer probability). Mark-Recapture distance sampling (MRDS), where sightings are ‘marked’ (Observer 1 only), ‘captured’ (Observer 2 only) or ‘recaptured’ (both observers), relaxes the  $g(0) = 1$  assumption of the traditional distance sampling framework (Burt et al. 2014). We used MRDS to provide a single count per helicopter, corrected for perception bias. A linear mixed-effects model was used to assess the relationship between aircraft speed and count of each species according to the following equation:

$$\text{Count} = \text{Speed} \mid \text{Transect} + \epsilon$$

where speed is fixed, transect is the random effect used to correctly pair observations and  $\epsilon$  is the error measured as the possible correlation (AR1) between a transect and the previous one. Furthermore, a paired two-sample t-test on both raw and adjusted counts was used to determine whether that relationship was significant. Lastly, by dividing the sightings of the novel observer by the sightings of the experience observer, a learning curve was able to be generated. All statistical analysis was performed using R (R Core Team 2015) and RStudio version 3.2.1 (RStudio Team 2015) and the MRDS package (Jeff Laake 2015).

## RESULTS

The number of unique sightings across all species by both helicopters at 80 and 100 knots is summarised in Table 1 below. From this table, the difference in counts between the two speeds appears minimal. The low number of sightings across the majority of groups (whales, turtles, rays and seals) justifies the exclusion of these species from the analysis.

**Table 1.** Summary of total unique sightings by both helicopters across all 15 transects.

	<b>SPEED (KNOTS)</b>	<b>TOTAL</b>	<b>MEAN PER TRANSECT</b>	<b>STD. DEV.</b>
<b>FISH SCHOOLS</b>	80	315	21.0	4.52
	100	295	19.7	4.89
<b>DOLPHINS</b>	80	148	9.9	10.25
	100	154	10.3	8.1
<b>HUMPBACKS</b>	80	10	0.7	0.58
	100	10	0.7	1.41
<b>HAMMERHEADS</b>	80	2	0.1	0
	100	1	0.1	NA
<b>SEALS</b>	80	1	0.1	NA
	100	1	0.1	NA
<b>RAYS</b>	80	38	2.5	2.99
	100	31	2.1	3.09
<b>TURTLES</b>	80	6	0.4	0.58
	100	16	1.1	2.36
<b>SHARK (UNIDENTIFIED)</b>	80	55	3.7	2.59
	100	47	3.1	1.65
<b>WHITE SHARKS</b>	80	8	0.5	0.89
	100	2	0.1	0

## Dolphins

The distance models applied found slightly different probability of detections ( $p$ ) between the two helicopters, as summarised in Table 2 below. Interestingly, Helicopter 1 was almost twice as likely to detect a dolphin when travelling north at 100 knots compared to 80 knots but less likely to sight a dolphin at 100 knots than 80 knots when southbound. In contrast, when northbound, Helicopter 2 was just as likely to detect a dolphin at 100 knots as 80 knots, and only slightly more likely to sight a dolphin at 80 knots than 100 knots when travelling south.

## **Sharks**

The probability of detection was very similar between the two helicopters. Both helicopters had a higher probability of detecting a shark when travelling south compared to when northbound. Furthermore, both helicopters had a slightly lower detection probability when travelling at 100 knots compared to 80 knots. Note the low sample size and high variation coefficient (Table 2).

## **Fish schools**

Overall, the detection probability for fish schools was similar between each helicopter. Notably, Helicopter 1 had a greater probability of detecting a fish school when travelling at 100 knots compared to 80 knots when northbound but the reverse was true when southbound. Helicopter 2 had a greater fish school probability of detection at 100 knots in both flight directions (Table 2).

**Table 2.** Summary of the probability of detection for each taxa at both 80 and 100 knots.

	HELICOPTER	SPEED	DIRECTION	N	PROBABILITY	CV
<b>DOLPHINS</b>	1	80	North	30	0.39	0.22
	1	100	North	26	0.80	0.26
	1	80	South	24	0.67	0.28
	1	100	South	35	0.49	0.16
	2	80	North	15	0.41	0.22
	2	100	North	23	0.42	0.64
	2	80	South	30	0.40	0.25
	2	100	South	21	0.36	0.17
<b>SHARKS</b>	1	80	North	3	3.32e-03	18.23
	1	100	North	9	0.18	0.88
	1	80	South	9	0.36	0.57
	1	100	South	17	0.30	0.32
	2	80	North	8	0.82	1.66
	2	100	North	6	0.21	0.59
	2	80	South	19	0.33	0.20
	2	100	South	8	0.27	0.53
<b>FISH</b>	1	80	North	35	0.39	0.15
<b>SCHOOLS</b>	1	100	North	23	0.60	0.30
	1	80	South	94	0.42	0.09
	1	100	South	74	0.36	0.14
	2	80	North	24	0.72	0.27
	2	100	North	31	0.77	0.04
	2	80	South	75	0.42	0.13
	2	100	South	70	0.75	0.20



## **Adjusted Counts**

Using the detection functions from the MRDS models, the raw number of sightings were adjusted to obtain a more accurate estimate of abundance of the survey area for each transect, helicopter and speed. This was done by dividing the count for each helicopter during each survey by the appropriate detection probability. A summary of the adjusted counts can be found in the Appendix.

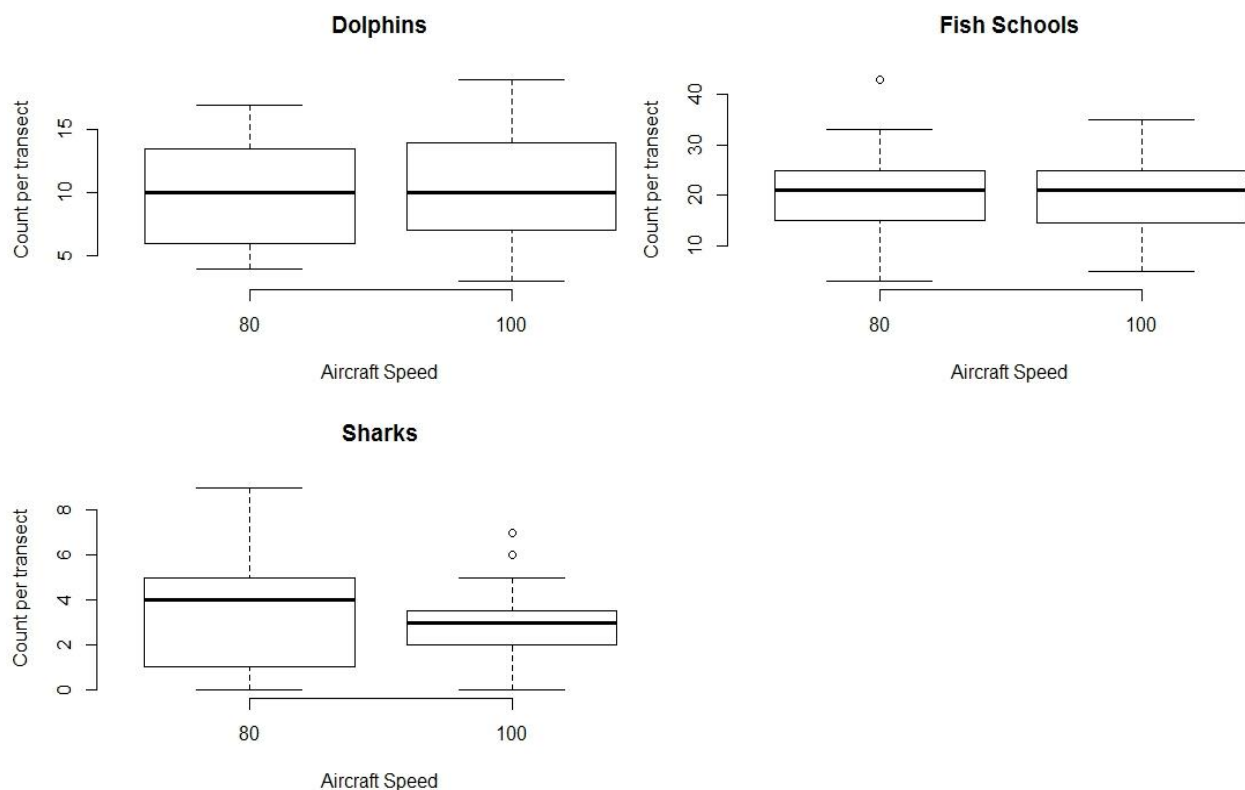
On average, the perception bias corrected counts were two to three times greater than the unadjusted number of sightings for dolphins. For sharks, the adjusted counts were on average between three to five times greater than the raw observations, however these numbers should be interpreted cautiously considering the low number of shark sightings. Unfortunately, some abundance estimates were unable to be calculated since the detection probability on which they are based failed to be generated due to insufficient numbers. Overall, the adjusted counts were two to three times greater than the raw counts for fish schools (see Appendix).

## **Effect of aircraft speed**

### **Raw Counts**

A two-sample paired t-test on the raw counts found no significant difference between 80 or 100 knots for sightings of dolphins ( $p$ -value = 0.395,  $t$  = -0.878), sharks ( $p$ -value = 0.423,  $t$  = 0.825) and fish schools ( $p$ -value = 0.332,  $t$  = 1.005). For dolphins, sighting at both 80 and 100 knots had very similar means (9.9 and 10.3 respectively) with an identical median. However, greater variation did appear in sightings at 100 knots compared to 80 knots (Fig. 3).

A similar relationship was observed for fish schools, with a mean of 21 schools sighted at 80 knots and 19.7 at 100 knots. Again, the median was the same in across both speeds. Furthermore, as seen in Fig. 3, the plots did not appear to show a difference in variation between the two speeds. For sharks, the mean was almost identical between 80 and 100 knots (3.7 and 3.1 respectively). However, the median was higher and greater variation was observed at 80 knots than at 100 knots.



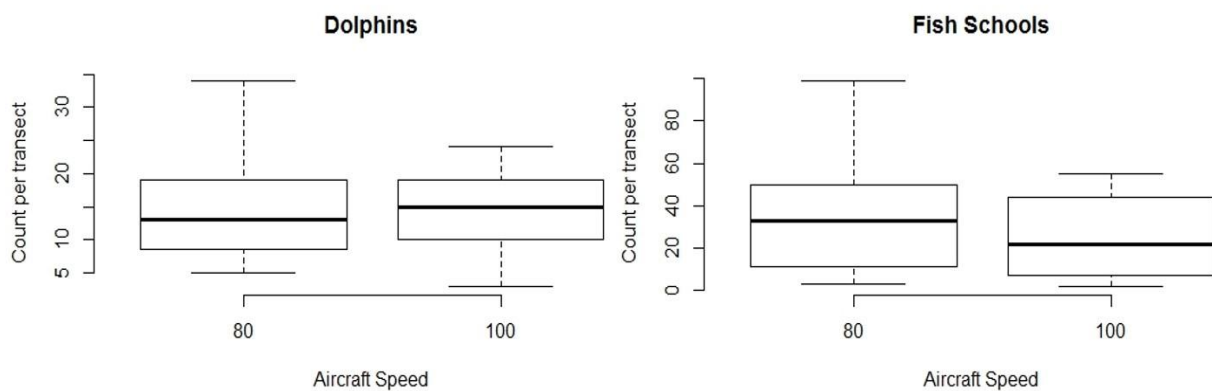
**Fig. 3.** Boxplots comparing raw bottlenose dolphin, fish schools and shark count per transect at 80 and 100 knots.

### Adjusted Counts

A paired two-sample t-test on adjusted counts revealed no significant difference between the two speeds tested with sightings of dolphins ( $p$ -value = 0.778,  $t$  = 0.287) and fish schools ( $p$ -value = 0.077,  $t$  = 1.911). Furthermore, a linear mixed-effect model found no correlation between consecutive transects for both dolphins ( $\Phi$  = -4.876e-06) and fish schools ( $\Phi$  = -1.023e-05). As can be seen in Fig. 4, the difference in count was not significant. For dolphins,

both 80 knots and 100 knots had almost identical means (14.9 and 14.5 respectively). However, the median was higher at 100 knots than 80 knots. Also, 80 knots did appear to show greater variation in the number of dolphins seen compared to 100 knots (Fig. 4).

For fish schools, there was a slightly larger difference between the mean of counts at 80 knots than 100 knots (35 and 25 respectively) although that difference still did not prove to be significant. Similar to dolphins, a greater variation in counts was recorded at 80 knots compared to 100 knots (Fig. 4). In addition, the median was lower at 100 knots than 80 knots.



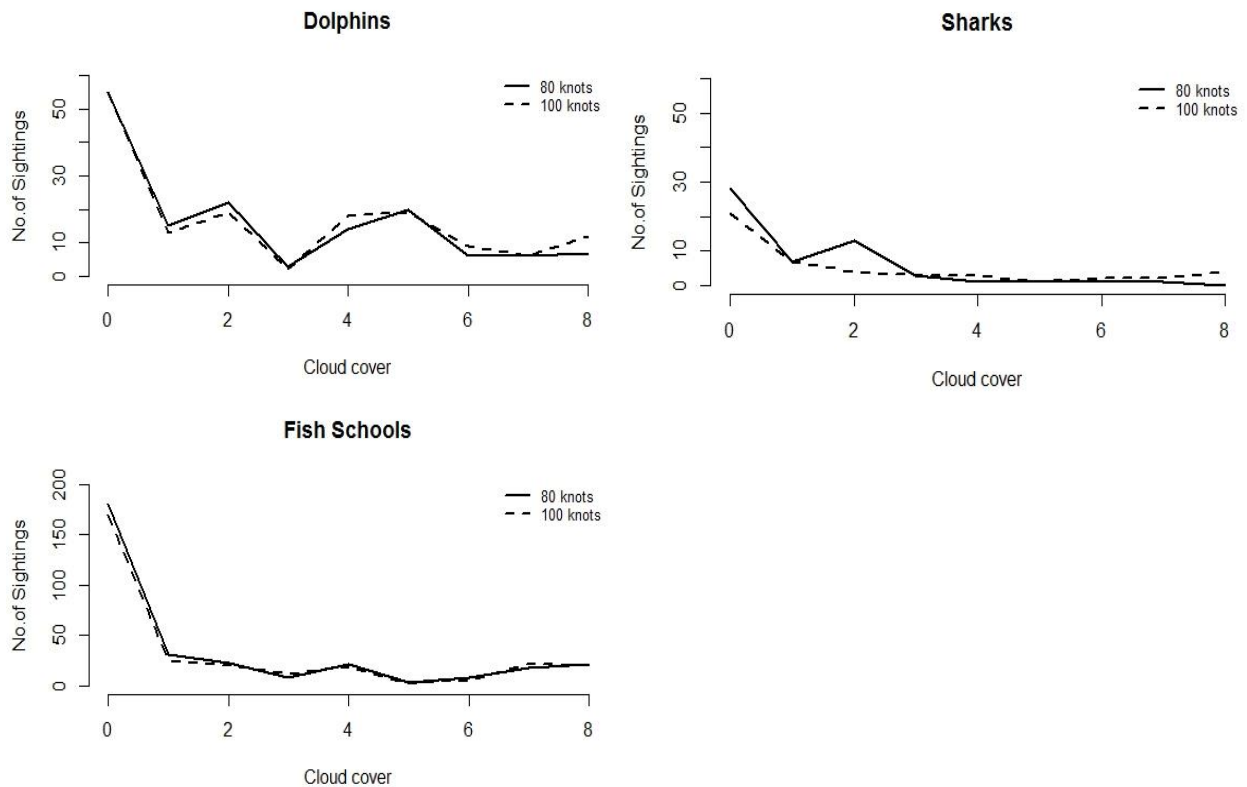
**Fig. 4.** Boxplots comparing corrected bottlenose dolphin and fish schools count per transect at 80 knots and 100 knots.

Unfortunately, not enough data was present to determine whether the relationship between speed and corrected counts was significant amongst sharks.

### Environmental factors

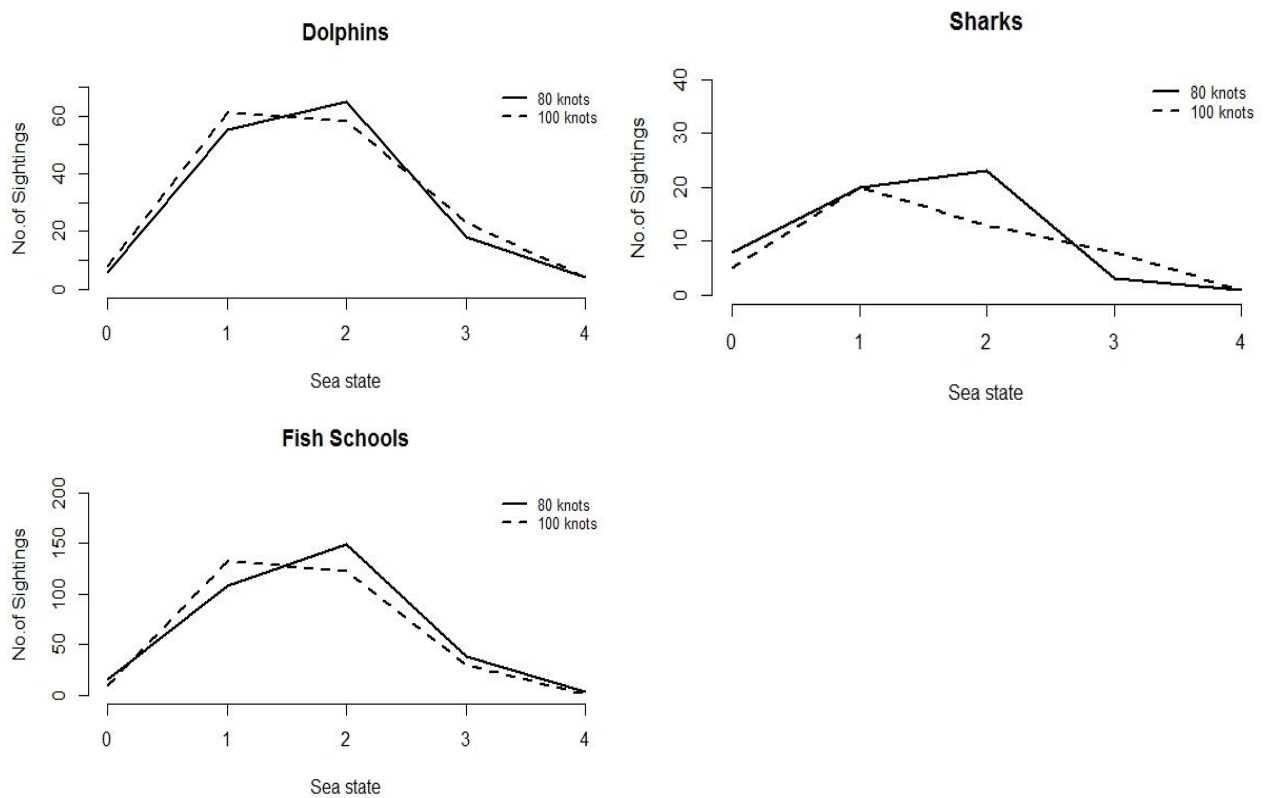
Although environmental factors (cloud cover, sea state and water clarity) were originally added to the detection functions, they were not found to be significant between the two speeds and were thus subsequently removed. The important finding is not the general trend between speed and environmental factors but rather the lack of significant difference between each speed at each environmental factor.

The number of sightings decreased with increasing cloud cover for dolphins, sharks and fish schools (Fig. 5). Not surprisingly, most animals were seen at zero cloud cover. Furthermore, there was almost no difference between 80 and 100 knots in relation to cloud cover.



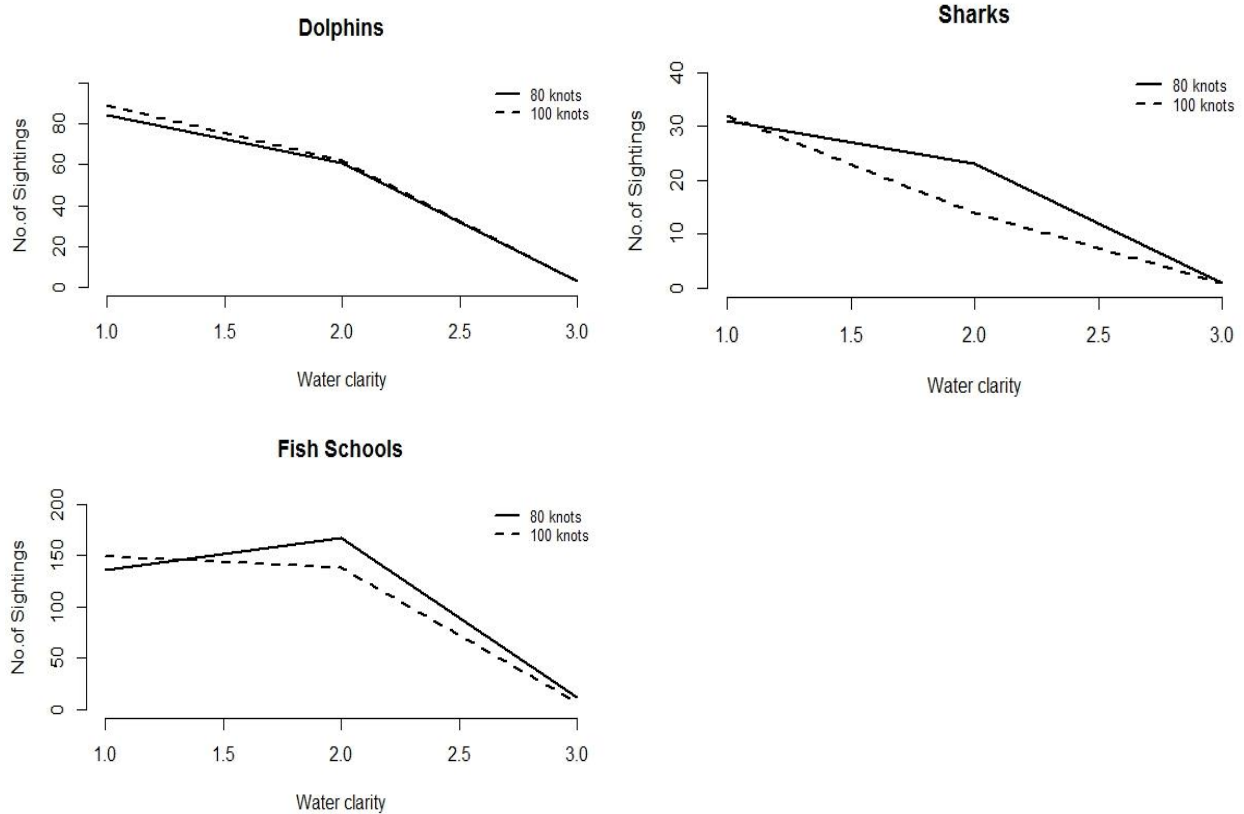
**Fig. 5.** The relationship between cloud cover and dolphin, shark and fish schools counts at 80 and 100 knots.

The effect of sea state on sightings followed a similar pattern for all three groups of interest. The number of dolphin sightings peaked at sea state 1 (100 knots) and 2 (80 knots) then trailed off (Fig. 6). The same trend was observed amongst sharks, with the greatest number of sightings at sea state 1 when travelling at 100 knots and sea state 2 when travelling at 80 knots. Similarly, most fish schools were seen at sea state 1 at 100 knots and sea state 2 at 80 knots.



**Fig. 6.** The relationship between sea state and dolphin, shark and fish schools counts at 80 and 100 knots.

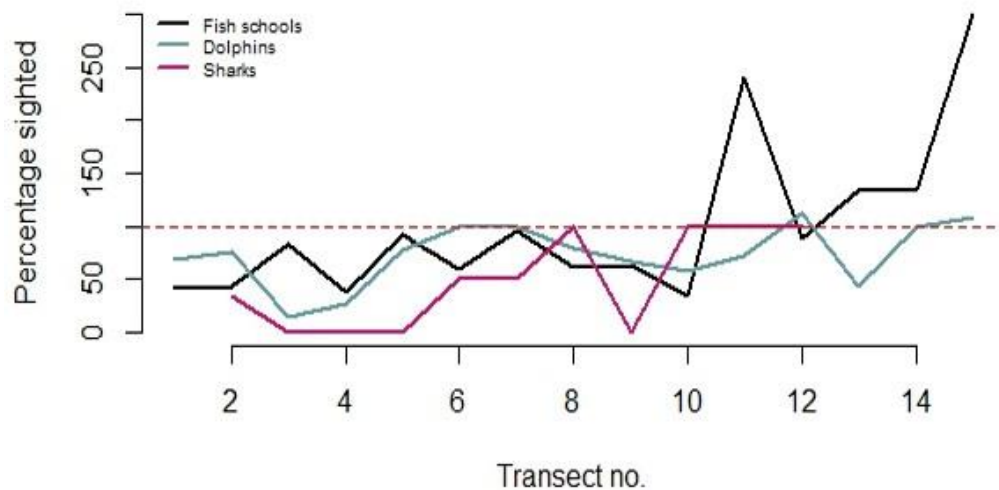
The relationship between water clarity and sightings were almost linear for dolphins and sharks. Not surprisingly, the number of dolphin sightings decreased with decreasing water clarity with almost no difference in detection between the two speeds (Fig. 7). A similar trend was observed with sharks, with the highest number of sightings occurring in clear water. Fish schools followed a slightly different trend with only a slow decrease in sightings until a water clarity of 2 and then a sharp decline into turbid water at a speed of 100 knots. At 80 knots however, the number of sightings increased until a water clarity of 2 again followed by a sharp decline (Fig. 7).



**Fig. 7.** The relationship between water clarity and dolphin, shark and fish schools counts at 80 and 100 knots.

### Learning curve

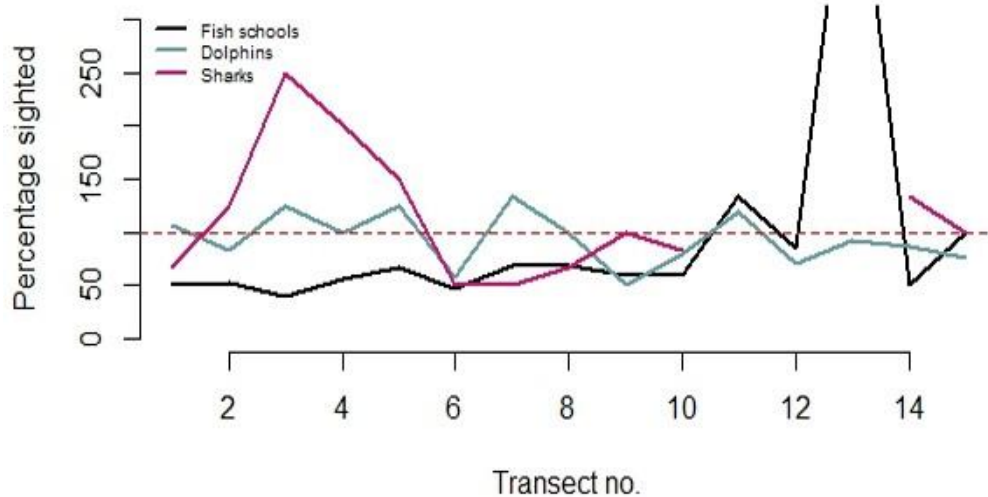
As a novel observer with no aerial survey experience, Observer 2 started with a dolphin sighting rate of approximately 60% that of Observer 1, the experienced observer, at the very first transect. This rate decreased before increasing again with Observer 2 reaching 100% sighting rate for dolphins by Transect 6 and surpassing Observer 1 at Transect 12 (Fig. 8). Although the graph is affected by the low number of shark sightings, Observer 2 reached 100% of Observer 1's shark sighting rate by Transect 8 but never surpassed it. With fish schools, Observer 2 reached 100% sighting rate by Transect 7 and surpassed Observer 1 by Transect 11.



**Fig. 8.** Learning curve as the percentage of Observer 1's sightings also seen by Observer 2 over all transects.

Observer 3 displayed a very different learning curve. Having some aerial survey experience, Observer 3 was on par with Observer 4 with dolphin sightings across all transects (taking into account natural variation between each transect) (Fig. 9).

With regards to sharks, Observer 3 surpassed Observer 4's sighting rate in the early transects before dropping off and maintaining a similar sighting rate to Observer 4. Unfortunately, since Observer 4 did not sight any sharks between Transect 10 and 14, the missing data did not allow a comparison over these transects, leaving the curve incomplete (Fig. 9). Observer 3's fish schools sighting rate remained 50 – 60% that of Observer 4's until Transect 11 where it surpassed the experienced observer.



**Fig. 9.** Learning curve as the percentage of Observer 4's sightings also seen by Observer 3 over all transects.

## DISCUSSION

Contrary to our initial hypothesis, we did not find any significant difference in bottlenose dolphin or fish school counts between aircraft speeds of 80 and 100 knots. This could be because the type of indicators used by observers to sight an animal (e.g. dolphin breaking the surface, contrast between fish school and sandy substrate) were not any more apparent at 80 knots compared to 100 knots. For events that could theoretically be advantaged by a slower speed, such as counting dolphins in large pods, we found that the slower aircraft was almost always required to perform circle-backs in order to allow both observers to accurately count the number of individuals. Consequently, flying slower did not allow adequate time for the observers to count individuals without slowing down or deviating from transect. Flight duration impacts observer fatigue and we were able to standardise this impact because the faster helicopter waited for the slower aircraft, so both teams of observers endured the same amount of flight time. Most aerial surveys are already flown at 100 knots (see Olson et al. 1998, Kessel et al. 2013, Fuentes et al. 2015), and we did not find evidence to indicate that this speed should be reduced.

Counts from aerial surveys are known to be underestimates of abundance. Marsh and Sinclair (1989) reported observers missing almost half of dugong groups surveyed while



Laake et al. (1997) calculated that 30% of available harbour porpoises were missed by observers. The results from our study are concordant with previous studies and highlights both the limitations of aerial surveys as a method and the need to correct raw counts for perception bias. The second reason aerial surveys produce such underestimates is that marine animals cease to be visible beyond a depth of only a few metres (Kessel et al. 2013, Martin et al. 2015), restricting the number of animals potentially available for detection, regardless of aircraft speed. This is especially true for non-air breathing animals such as sharks that are particularly susceptible to availability bias since they do not need to come to the surface. However, the shallow water and clear visibility are the reasons the counts were not corrected for water depth.

As mentioned in the results, the low numbers of shark sightings had an effect on the amount and type of data analysis able to be performed. The power of the results is limited and these results should therefore be interpreted cautiously. Sharks are notoriously difficult to sight, even by experienced observers, with Robbins et al. (2014) reporting a sighting rate of only 17% for helicopters. Although on the lower end, that is a similar shark sighting rate to that observed in this study. Following similar aerial survey parameters and conditions, Dicken and Booth (2013) reported a maximum sighting rate of seven sharks an hour. However, the mean sighting rate was closer to three, which is very similar to the sighting rate of this study.

Distance sampling assumes perfect detectability on the line, with the probability of detection decreasing as the distance from the line increases (Marques et al. 2007, Fewster et al. 2009). As seen in the detection model graphs (see appendix) in this study, this is not always the case. Furthermore, in some cases, the probability of detection actually increased with the distance from the line. This is most likely due to the fact that the truncated distance of 300 m used throughout the surveys is not great enough to reflect the decreasing trend, particularly with dolphins that can easily be sighted at even greater distances. When looking onshore, this may also be an artefact arising from bottom depth and seabed type, because animals further away above the shallow sand may be more visible than those closer to the helicopter but in deeper water.

In addition, in many instances Helicopter 2 appeared to have the greatest number of sightings within a narrow range in the centre of the survey area. This is most likely explained

by the two observers having previous experience in fixed-wing aerial surveys in which the observer is forced to focus on a narrow area between two lines on the glass of the aircraft window. This prior training appears to have discouraged Observer 3 and Observer 4 from perhaps utilising their entire field of view. The level of experience amongst observers varied greatly and may explain some of the variation observed in these results. Observer 2 was a novice observer prior to this study, having never performed any form of aerial surveying. This may explain their initially lower number of sightings compared to Observer 1, who by contrast had two years of aerial survey experience in conditions almost identical to the ones encountered in this experiment. Observer 2's data was therefore ideal for creating a learning curve for all species.

In contrast, Observer 3 had conducted aerial surveys in the past and therefore had some level of experience coming into this study. Although their experience was over a decade ago and did not involve sharks, it is likely that their familiarity with aerial surveys of dolphins and whales played a role in his higher initial sighting rate and different learning curve compared to Observer 2. This is especially true since Observer 2's learning curve revealed a timeframe of 6-8 hours of aerial surveys needed for a novice observer to reach a level similar to that of an experienced observer. Having previously spent more than 10 hours conducting aerial surveys, Observer 3's similar sighting rate to Observer 4 is not surprising. Unfortunately, due to the nature of this study and the different speeds at which the helicopters were travelling, it was not possible to compare observers between aircrafts.

It is important to note that the learning curves observed in this study represent only two observers and should be interpreted accordingly. The amount of time needed for a novel observer to reach a level similar to an experienced observer will vary between individuals. Furthermore, back observers had a smaller field of view. This unavoidably gave the front observers (which was the experienced observer in both helicopters) a slight advantage and thus a higher detection rate since they were able to see further ahead and therefore had more time to sight an animal (Martin et al. 2015).

The results of this study are concordant with previous literature, with Fuentes et al. (2015) concluding that less experienced observers had a lower sighting rate than experienced observers. Observer 2's learning curve is very similar to the one reported by Beard (1999), who also concluded that completely novel observers initially sighted approximately half of

the animals seen by experienced observers. Observer 2's initial dolphin sighting rate was well above the one reported in Laake et al. (1997), who found that inexperienced observers recorded less than one quarter of harbour porpoises sighted by experienced observers. However, the difference in species and conditions, as well as personal differences, may explain the disparity between these two studies.

Although not found to have a significant impact on sighting rate, the environmental trends observed in this study are most likely due to the amount of time spent at each factor rather than any true influence. For example, the higher number of dolphin sightings observed at sea states 1 and 2 are likely due to the fact that the majority of flights were conducted at these sea states, and is not necessarily an indication that more dolphins would be seen at sea state 2 compared to sea state 0 if allocated the same amount of flight time. However, Barlow et al. (2001) found the number of sightings to decrease with each Beaufort sea state. Pollock et al. (2006) also found sea state, turbidity and depth to affect the availability of dugongs which suggests that environmental factors may have an impact on sighting rate. These should therefore be taken into consideration in any experimental design involving aerial surveys.

For management purposes, we recommend that marine aerial surveys be flown at 100 knots. This takes into account the high financial cost associated with aircraft operation and observer fatigue, in addition to the results of this study finding no significant difference between the two speeds tested. Furthermore, in order to maximise the number of sightings, we recommend that all surveys include two observers (not including the pilot) whenever possible. Having a second observer will significantly increase the chances of an animal being seen, thereby greatly improving the validity of any subsequent analysis. Finally, based on the learning curves generated by this study, we recommend training inexperienced observers around six to eight hours in order to reach a sighting rate equivalent to that of an experienced observer. This time frame starts from the time a particular species is sighted (e.g. if no sharks are sighted during the first two hours of training, then two hours will need to be added on to the training time).

This study is just one example of how aircraft speed affects the performance of aerial surveys, however further research is needed to replicate these results in order to increase validity. Due to the dynamic nature of the marine environment and its coastline, it is

important that aerial surveys be assessed over a wide variety of conditions of varying depth and (Robbins et al. 2014). The use of analogues could vastly improve our method because depth, substrate type and total animals available for sampling can be strictly controlled. This would also allow for animals with low density to be included, such as shark species, without requiring untenable survey hours to obtain enough data. Although this study found no difference between 80 and 100 knots, studies have used speeds greater than 100 knots (Graham and Bell 1989, Hara 1990, Certain and Bretagnolle 2008), and the maximum speed at which aerial surveys can be flown without compromising sighting rate remains to be investigated. In addition, speed is just one aspect of aerial surveys. Other parameters such as altitude also may also prove to be important factors involved in optimising aerial surveys as a method.

## **CONCLUSION**

In conclusion, we found no improvement in adjusted sighting rates of bottlenose dolphins or fish schools when flying at 80 knots compared to 100 knots, indicating that aerial surveys of marine megafauna can continue to be flown at the traditional speed of 100 knots. Ultimately, the optimal parameters for each survey may depend on a number of factors including the environment and type of animals (Pollock and Kendall 1987). High inter-observer discrepancy was found, indicating the importance of accounting for observer effects in the experimental design. The novel observer required 6-8 hours of survey time to reach a similar sighting rate to an experienced observer. These results will aid in the more effective use of future aerial surveys.

## **ACKNOWLEDGEMENTS**

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## **Chapter 2**

# **Factors Influencing the Nearshore Distribution of Sharks, Fish and Dolphins in NSW Waters**

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## INTRODUCTION

Comprising of mostly higher level predators, marine megafauna have the capacity to cause major ecological changes to all levels of the food web. In this context, megafauna refers to any marine animal big enough to be seen from a helicopter (eg. dolphins, big fish, sharks etc). Small variations in the abundance or distributions of marine megafauna appear to affect community structure (Steneck and Sala 2005). Furthermore, even the movements of migratory predators have been found to have massive effects directly, and indirectly through trophic cascade on the ecosystem, without predation actually taking place (Steneck and Sala 2005, Terborgh and Estes 2013). As a result, recognising the habitat use and distribution of marine megafauna is essential for understanding marine ecosystems.

Many environmental factors have been shown to impact the distribution of marine megafauna. Biotic factors such as prey distribution and predator avoidance, and abiotic factors such as sea surface temperature (SST), salinity, water depth, chlorophyll-a (Chl-a) concentration, currents and upwelling can affect the distribution of a broad range of marine megafauna (Davis et al. 1998, Davis et al. 2002, Block et al. 2011, Mendez et al. 2011, Schlaff et al. 2014). Consequently, these environmental factors can be used to estimate species distribution and habitat selection (Selzer and Payne 1988, Bräger et al. 2003). Many of these factors can be monitored remotely, effectively replacing *in situ* data collection (Gremillet, 2008).

SST and Chl-a are thought to be two of the most important environmental factors. SST is thought to affect marine megafauna directly by impacting thermoregulation (Bräger et al. 2003), and indirectly by affecting predator and prey distributions (Watts and Gaskin 1985, Neumann 2001, Heithaus and Dill 2002, Bräger et al. 2003). SST displays high annual variation in shallow inshore waters (Bräger et al. 2003), making it an ideal factor to investigate. Chl-a is a proxy for phytoplankton which is a critical component at the base of the food web and an indication of biomass (Il and Yentsch 1957), and therefore prey distribution. Consequently, it may play an important role in marine animal habitat selection and distribution. Due to their complexity, modelling is often used to investigate the

relationship between environmental factors and marine megafauna distribution and abundance (Forney 2000).

Density surface models have many advantages for understanding marine megafauna distribution. Generalised additive models (GAMs) have been widely used to analyse species distribution (Guisan et al. 2002, Thuiller 2003, Block et al. 2011). There are two main reasons: 1) being 'generalised' allows them to model counts and presence/absence data, 2) 'additive' smoothers are non-parametric and therefore allow data-driven, non-linear relationships to be modelled without assuming a certain distribution. Density surface models (DSMs) further expand on GAMs by incorporating the detection function, survey design (e.g. multiple transects) and X (Eastings), Y (Northings) surface to capture spatial patterns. In this study, we used DSMs to investigate how coastal marine megafauna counts and environmental factors, specifically SST and Chl-a, varied on an annual and seasonal scale in NSW waters.

## **SURVEY AREA**

Seventy surveys were flown along the New South Wales (NSW) coast between Stockton Beach in Newcastle ( $32^{\circ}54'53.8''$  S,  $151^{\circ}47'35.3''$  E) and South Wollongong Beach ( $34^{\circ}26'46.65''$  S,  $150^{\circ}54'59.94''$  E), a distance of approximately 250 km, over a three-year period from 21 December 2013 to 27 April 2016 (Fig. 1). Surveys were consistently conducted in a southbound direction starting around 10:45 Australian Eastern Standard Time and finish around 12:30.



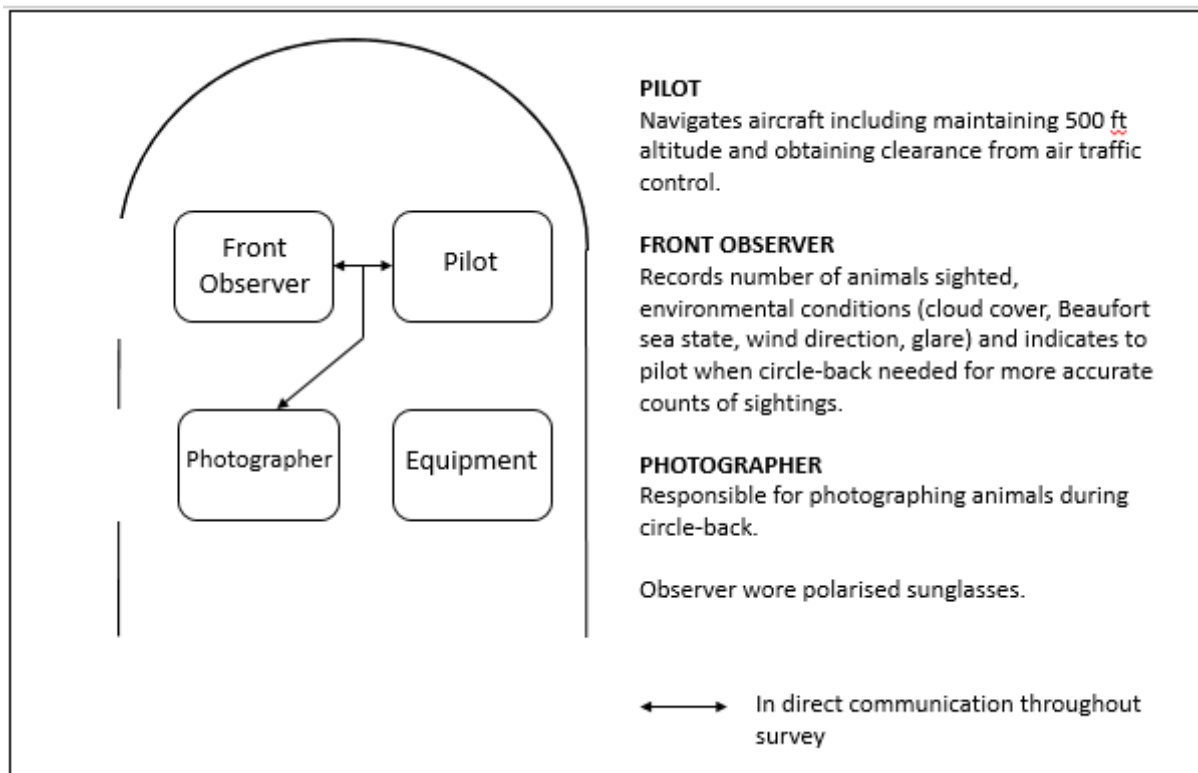


**Fig. 1.** Map showing location of surveys

## **METHODS**

### **Aerial Surveys**

The surveys were flown by a Robinson 44 helicopter travelling at an altitude of 500 ft (~150 m), a speed of 100 knots directly above the surf line (~10 m from shore). The helicopter crew consisted of a pilot, a front observer and a rear photographer. The observer and photographer sat on the same side of the aircraft, with both doors removed (Fig. 2). Observer, photographer and pilot were in constant communication throughout the flights. The observer recorded their observations into a voice recorder which was later transcribed. Although the primary purpose of the photographer was to provide a visual record of sightings, they also alerted the front observer of any animals that may have been missed.



**Fig. 2.** Interior schematic illustrating the seat configuration in the cockpit. (Adapted from Pollock et al. 2006).

Observers scanned the water below for sharks, dolphins, fish schools, turtles, whales, rays and seals. Upon sighting an animal, the observer recorded a waypoint of the location using a handheld Garmin 760S Global Positioning System (GPS), as well as the angle to the animal using a Suunto inclinometer. The observer further recorded the species (if this was unknown, then the general animal type e.g. shark), number of individuals and swimming direction if applicable. For dolphin pods, circle-backs were performed to allow for photographs in order to obtain a more accurate count of individuals. Photographs were taken using a Nikon D7200 with a Nikon f3.5-5.6 18-200 mm lens. Changes in environmental conditions (e.g. sea state, glare, rain) were also recorded as they occurred and a waypoint taken. Sea state was measured on the Beaufort scale of 1 to 4, with 1 being flat surface conditions and 4 being waves with breaking crests and frequent whitecaps. Surveys were not conducted above a sea state of 4. Glare was given as a percentage of the total field of view affected (e.g. 10%) and cloud cover was measured on a scale of 0 to 8, with 0 being no visible clouds and 8 being completely overcast. Water clarity was given on a scale of 1 to 3,

with one being transparent and 3 being completely opaque. A waypoint was also taken at the start and end of each survey or when leaving the transect to take photographs.

### **Environmental factors**

Sea surface temperature (SST) data was obtained from the National Oceanic and Atmospheric Administration (NOAA) (<http://coastwatch.pfeg.noaa.gov/erddap/griddap/jplG1SST.html>). Satellite SST data was collected for each date the survey flights were conducted for every 0.01 degree change in latitude and longitude along the survey. Chlorophyll-a (Chl-a) data was obtained from NOAA (<http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMBchla1day.html>) for each date the survey flights were conducted. Southern hemisphere seasonal climatologies were used throughout this study, where summer is December through to February, autumn is March through May, winter is June through August and spring is September through November.

## **DATA ANALYSIS**

### **Aerial surveys**

All shark species except for hammerheads were grouped into one category. Since too few hammerheads were sighted, they were excluded from the analysis. We further excluded other species including whales, turtles, rays and seals since their numbers were too low. The observing distance was left truncated at 50 m (since the observer could not see directly below the helicopter) and right truncated at 1000 m (greater than which we were not able to feasibly sight animals). A detection function was calculated for dolphins and fish schools. Unfortunately, the number of sharks was too low for the generation of a detection function. Three models were fitted to the distance data for each species (hazard rate, half-normal and gamma) with Akaike Information Criteria (AIC) used to identify the best model. Environmental factors collected during the surveys was included as input variable in the detection function. However, there were not found to add anything to the models and were subsequently removed. The detection function was analysed using R (R Core Team 2015) and R Studio version 3.2.1 (RStudio Team 2015) and the 'MRDS' package (Jeff Laake 2015).

## Environmental Factors

SST data was available for all but one flight day (31 Dec 2015), and this date was consequently excluded from the analysis, leaving 69 flights in total. Our environmental factors analysis followed closely that of Miller (2015b). SST and Chl-a data within 4 km of the shore were extracted in order to allow for comparison with sightings from our flight data and a raster of environmental conditions were created for each day. Each sighting was matched to the closest raster cell. Unfortunately, environmental data was missing from certain areas along the coast, forcing us to exclude some of our sightings since they could not be matched to an appropriate SST or Chl-a. Chl-a was analysed in the same fashion as SST. Chl-a data was interpolated onto the same 4 km grid as SST, allowing each of our sightings to be matched to a corresponding Chl-a and SST data point. A density surface model (DSM) was then used to fit the SST data, Chl-a and detection function obtained from our survey flights for both dolphins and fish schools species according to the following equation:

$$\text{Count} \sim s(\text{Northing}) + s(\text{SST}) + s(\text{Chl-a})$$

Where ‘Northing’ is the change in latitude, ‘s’ is the smoother term and the restricted maximum likelihood (REML) was used at the ‘method’. The data was assumed to have a quasi-Poisson distribution. Since the Chl-a data was a lot more sparse than SST, we followed the method outlined by Wood (2006), using random effects and indicator factors to prevent the model from also excluding SST where there was no Chl-a. The R packages ‘Distance’ (Miller 2015a) and ‘DSM’ (David L. Miller 2015) were used for this analysis.

## RESULTS

Table 1 below provides a summary of all species and the number of sightings per season across the three-year timespan of this study. Becker et al. (2010) suggest a sample size of at least 80 for satellite SST models. As seen in Table 1, the overall low total number of sightings justifies our exclusion of most species and our focus on fish schools and bottlenose dolphins for our analysis.

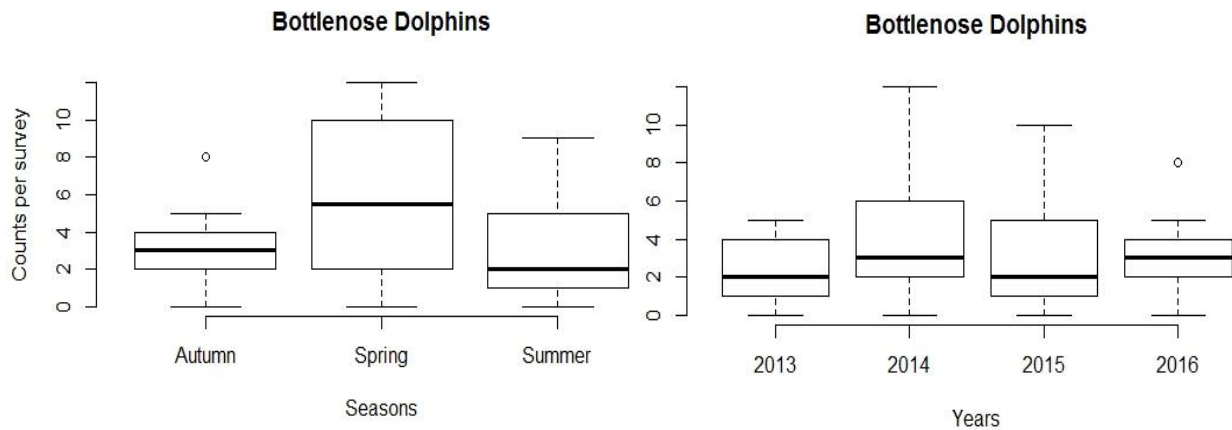
**Table 1.** Summary of all sightings by taxa and seasons.

	AUTUMN	SPRING	SUMMER	TOTAL
<b>FISH SCHOOLS</b>	427	502	378	1307
<b>BOTTLENOSE DOLPHINS</b>	61	88	98	247
<b>HUMPBACK WHALES</b>	1	8	0	10
<b>SEALS</b>	9	5	5	19
<b>SHARKS (UNIDENTIFIED)</b>	4	1	5	10
<b>HAMMERHEAD SHARKS</b>	11	3	41	55
<b>WHITE SHARKS</b>	0	1	20	21
<b>TURTLES</b>	23	8	1	32
<b>RAYs</b>	47	39	31	117

### **Annual and seasonal variations**

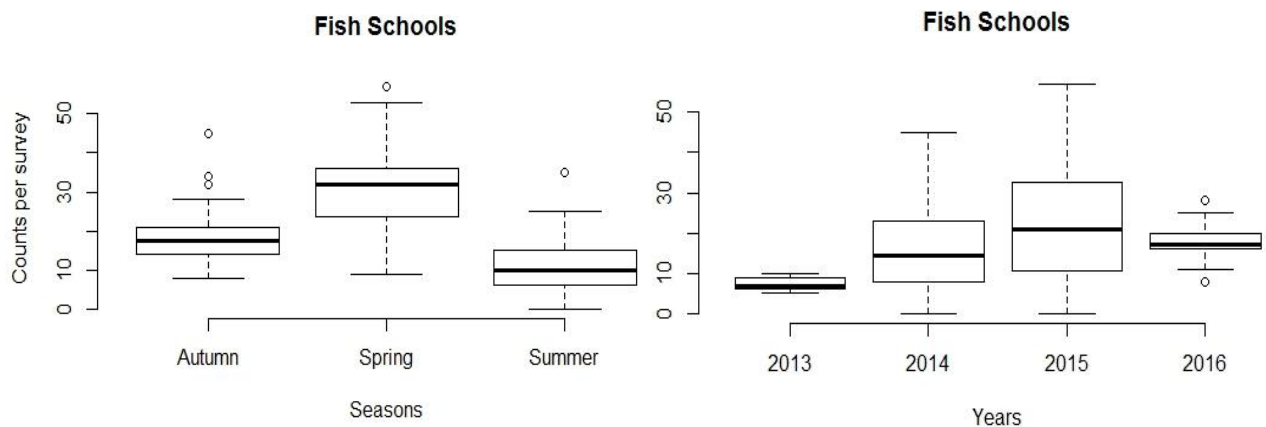
Flights were flown over four summers, three autumns and two springs. Unfortunately, no flights were conducted in winter. Note there were no surveys in spring 2016 in the boxplots below since that season fell outside the temporal extent of our data collection.

Overall, dolphin counts per survey were highest in the spring and lowest in summer (Fig. 3). However, variation can be observed between the sampling years. The highest number of dolphins per survey were sighted in 2016, while the least number of dolphins were observed in 2013 (Fig. 3). The highest number of dolphins per survey was recorded in spring 2014 with summer 2013 showing the lowest number of observed dolphins (Fig. 3).



**Fig. 3.** Boxplot showing relationship between bottlenose dolphin sightings per survey and seasons/years.

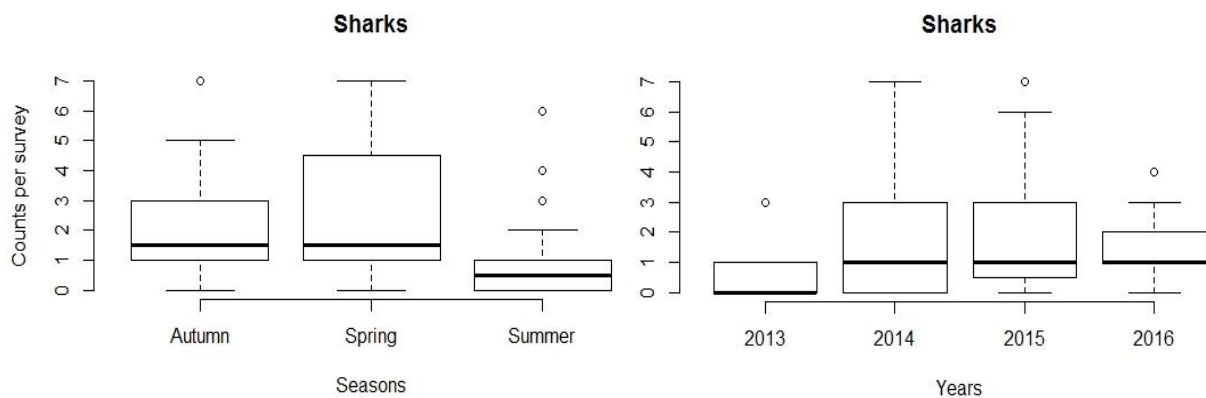
Similar to dolphins, fish schools appeared more prominent in spring and least in summer (Fig. 4). The greatest number of fish schools per survey were observed in 2015, with the least number of fish schools recorded in 2013 (Fig. 4). Overall, the highest number of fish schools per survey were sighted in spring 2015, with the lowest number of fish schools seen in summer 2013 (Fig. 4).



**Fig. 4.** Boxplot showing relationship between fish schools counts per survey and seasons/years.

Although the number was low overall, less sharks were sighted in summer. The median number of sharks per survey was identical for both autumn and spring (Fig. 5). Interestingly,

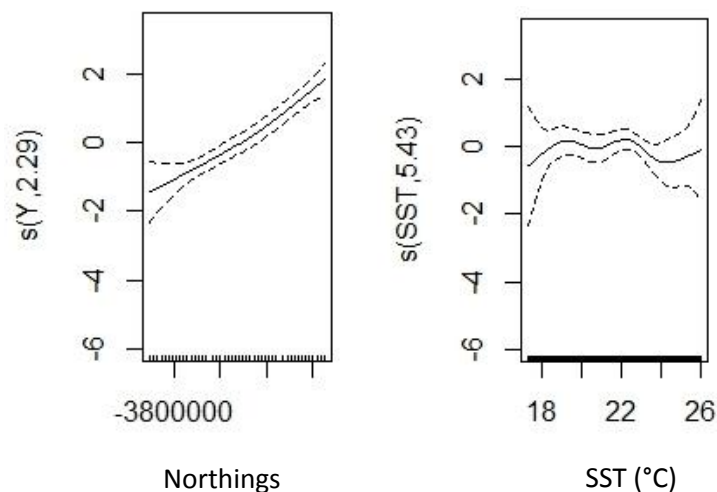
although greatest variation was observed in 2014, the median number of sharks per survey was the same across 2014-2016. The lowest number of sharks per survey was observed in 2013 (Fig. 5). Overall, the greatest number of sharks per survey was recorded in spring 2014, with the lowest number sighted in summer 2013.



**Fig. 5.** Boxplot showing relationship between shark counts and seasons.

## Density Surface Models (DSM)

### Dolphins



**Fig. 6.** Model showing relationship of northings, SST and Chl with dolphin counts. Dashed lines represent twice the standard error.

**Table 2.** Model summary for bottlenose dolphins with SST and Chl-a.

	<i>P</i> -value
<b>Family:</b>	Quasi-poisson
<b>Parametric coefficients:</b>	
Intercept	<2e-16
Sqrt(Chl)	0.442
<b>Approx significance of smooth terms:</b>	
s(Northings)	3.64e-16
s(SST)	0.71
N = 4140	Deviance explained = 12.1%

The model revealed a statistically significant ( $p=3.64e-16$ ) linear relationship between dolphins and geographical coordinates, with the number of dolphins increasing with increasing northing (Fig. 6). More dolphins were seen in the northern parts of our survey area (Newcastle area) than in the southern parts (Wollongong area).

### SST

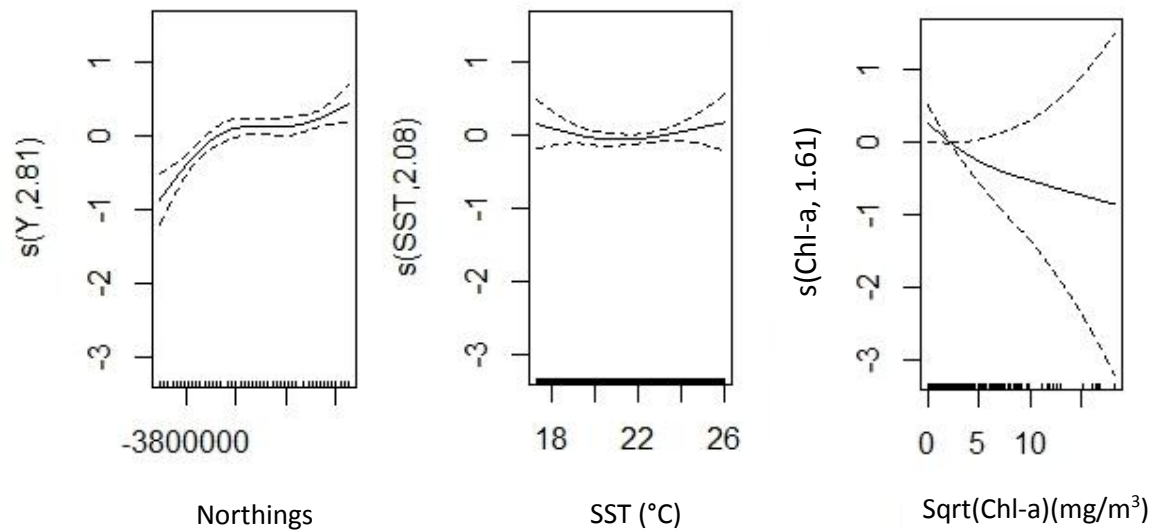
Temperatures ranged from 18 - 26°C however the relationship between SST and dolphin counts was not significant ( $p$ -value = 0.708) (Table 2). The model revealed a relatively flat line around 0 with a slight fluctuation at either end of our temperature scale (Fig. 6).

### Chl-a

Chl-a concentration ranged from 0 – 335 mg/m<sup>3</sup>. Since the data was heavily skewed towards lower Chl-a concentrations, a square root of Chl-a concentration was required for model convergence. The relationship between Chl-a and dolphin counts was found to be linear, so it was subsequently removed from being a smooth term in the model. The linear relationship was not significant ( $p$ -value = 0.442) (Table 2). In relation to dolphins, neither SST or Chl-a improved the model.



## Fish Schools



**Fig. 7.** Model showing relationship of northings, SST and Chl with fish school count. Dashed lines represent twice the standard error.

**Table 3.** Model summary for fish schools with SST and Chl-a.

	<i>P</i> -value
<b>Family:</b>	Quasi-poisson
<b>Parametric coefficients:</b>	
Intercept	<2e-16
<b>Approx significance of smooth terms:</b>	
s(Northings)	7.18e-16
s(SST)	0.403
s(sqrt(Chl))	0.102
N = 4140	Deviance explained = 2.35%

A different family (tweedie) was also applied to assess its effect on the model. However, since it did not improve the model, the quasi-poisson family was chosen as the most appropriate. A similar pattern to dolphins between count and northing was seen, with

increasing fish school counts as northing increased ( $p = 7.18e-08$ ) (Fig. 7). More fish schools were seen in the northern part of our surveys area (Newcastle area) than in the southern part (Wollongong area). However, considering the very low deviance explained (2.35%), this trend likely explains only a very small proportion of the variation in fish school distribution.

### **SST**

Fish schools were seen at SST ranging from 18-26°C, however that relationship was not significant ( $p$ -value = 0.403) (Table 3). The model revealed an almost flat line around 0 with a small fluctuation at either end (Fig. 7).

### **Chl-a**

Again, the square root of Chl-a concentration was needed for the model since the data was skewed towards lower Chl-a concentrations. Since the relationship between Chl-a concentration and fish school counts was not linear, Chl-a was used as a smooth term in the model. That relationship was, however, not significant ( $p$ -value = 0.102) (Table 3). Similar to dolphins, neither SST or Chl-a improved our model of fish school counts.

## **DISCUSSION**

This study shows broad annual and seasonal variation of dolphin, shark and fish distributions along the coastal waters of NSW. However, no fine-scale relationship between distributions and environmental factors was found.

### **Annual Variation**

Annual variation was observed between the three-year span of this study for bottlenose dolphins, sharks and fish. The increase in sightings visible across all three species from 2013 to 2014 could reflect a change in observer experience as well as true variation in animal abundance. Although 2013 as a whole consistently recorded the lowest number of sightings, flights only began in December of that year. 2013 therefore only incorporated one month of data, rather than the 6 months found in 2014 and 2015. Interestingly, although flights were only conducted in the first half of 2016, some of the highest number of sightings of dolphins, fish schools and sharks were recorded.

## **Seasonal variation**

The seasonal variation among bottlenose dolphins found in this study corroborates the findings of Heithaus and Dill (2002), who reported a lower bottlenose dolphin density in summer and a greater density in winter in Western Australia. Likewise, Lusseau (2005) found a similar trend in New Zealand bottlenose dolphins. However, our findings differ from Forney and Barlow (1998), who found no seasonal difference in the abundance of bottlenose dolphins along the Californian coastline, suggesting intra-species variation. The relationship between distribution and seasons also appears to vary between cetacean species. For example, research has found Risso's and common dolphins to be more abundant in winter (Forney and Barlow 1998), but Dall's porpoises and Pacific white-sided dolphins to be more abundant in spring (Dahlheim et al. 2009). This intra and inter-species variation suggests either that factors differ between environments of cetacean populations, or that the same factors may influence populations differently.

## **Environmental Factors**

Despite strong seasonal and SST and Chl-a variations, we were unable to link bottlenose dolphins and fish distribution to fine-scale environmental factors. The lack of significance in the relationship between SST and Chl-a with both fish schools and dolphin counts found in this study is difficult to explain.

Numerous studies have found a relationship between cetacean species and environmental factors (e.g. Selzer and Payne 1988, Fullard et al. 2000, Georges et al. 2000, Bräger et al. 2003, Becker et al. 2010). Furthermore, these studies encompass many different types of analyses (e.g. kernel (Grémillet et al. 2008), classification and regression tree (CART) (MacLeod et al. 2007), and GAM (Forney 2000)). Due to the theoretical and practical support for the use of DSMs for this application (Guisan et al. 2002, Thuiller 2003, Herr et al. 2009, Winiarski et al. 2014a), it is unlikely that the choice of model explains the lack of relationship found in our study. Our sample size was well above the 80 minimum sightings recommended by Becker et al. (2010) when using satellite-derived SST with cetacean habitat-selection models. Furthermore, the temporal and spatial extent of our study should have been sufficient to have allowed us to detect a correlation, especially considering the annual and seasonal trends highlighted in our raw data. One possibility is that a mismatch in

scale between our sightings and the environmental satellite data prevented the detection of a significant relationship. The 4 km resolution grid used in the models may be too low to allow the detection of a significant relationship between sightings and environmental covariates, particularly in coastal areas. Additionally, due to its similar optical properties to churning sand (Gohin et al. 2008, Chen et al. 2013), obtaining accurate satellite data of Chl-a close to shore can be difficult. This may provide a potential reason for the lack of significant relationship between dolphins and fish and Chl-a found in our study.

Bottlenose dolphins (genus *Tursiops*) represent all the cetaceans observed in this study. Both the *Tursiops* genus, and the three species comprising it, display wide habitat ranges (Scott and Chivers 1990, Connor et al. 2000, Hale et al. 2000). Therefore, it may be that the bottlenose populations in this area are not strongly affected by the small local changes in SST and Chl-a found in this study. This may be supported by the low deviance explained in our models, indicating only a very small difference between our distribution model and the null.

The distribution of bottlenose dolphins is likely to be influenced by both prey availability and predator presence rather than a direct effect of SST (Watts and Gaskin 1985, Neumann 2001, Heithaus and Dill 2002, Block et al. 2011). One possible hypothesis for the lower summer distribution of bottlenose dolphins is their avoidance response to sharks, which were found to be more abundant in summer and less so in cooler temperatures (Heithaus and Dill 2002). Although we found that shark and dolphin abundance were both highest in spring and lowest in summer, we could not effectively test this relationship due to low number of sharks.

Prey distribution may have a greater impact on dolphin distribution. Porpoise distribution has been found to correlate with herring (prey) abundance (Watts and Gaskin 1985). Furthermore, spinner dolphins have been reported to follow the migratory pattern of their prey in Hawaii (Benoit-Bird and Au 2003). Hastie et al. (2004) directly linked areas of high bottlenose dolphin abundance to foraging opportunity provided by a high presence of prey species. Fish counts were highest in summer and lowest in winter, showing the same trend as dolphins. Chl-a is an important environmental factor because it is used as a proxy for phytoplankton, which has been found to support biomass – and therefore the prey species

of dolphins - of an ecosystem (Il and Yentsch 1957). However, we did not find a direct relationship between fish schools and either SST or Chl-a. Consequently, we would not expect to find a direct relationship between dolphins and Chl-a. It is possible that these biotic factors are having a greater influence over dolphin and fish school distribution, thereby overriding the weaker relationship between these animals and the abiotic environmental factors studied.

Since we did not find a significant relationship between bottlenose dolphin or fish school counts and environmental factors, investigating that relationship with SST and Chl-a anomalies might provide greater insight. The sudden variation to the normal range associated with anomalies may drive a sudden, significant change in the distribution of marine animals that could potentially be detected. Furthermore, the relationship between the proximity of dolphins to fish schools remains to be investigated. This would provide an assessment of a predator-prey relationship, with a more direct link than environmental factors by investigating two consecutive levels of the food web. In addition, SST and Chl-a represent only two environmental factors. Other environmental factors such as depth (Baumgartner 1997, Cañadas et al. 2002) and salinity (Baumgartner 1997) could provide further information on the distribution and habitat selection of the bottlenose dolphin and fish school populations found in the geographical location of our study.

## **CONCLUSION**

Although we detected strong annual and seasonal changes, we were unable to link coastal marine animal distribution to fine scale environmental factors. The relationship between bottlenose dolphin and fish school distribution, and SST and Chl-a was not found to be significant. It is possible that the resolution of our models was insufficient in detecting the correlation between dolphin counts and environmental factors found in the literature. However, these results may suggest that interactions between marine coastal animals and environmental factors may not always be apparent or able to be detected.

## **ACKNOWLEDGMENTS**

We would like to thank the pilots, Brett Kiteley and Joshua Wales, as well as Rochelle Tonkin from Touchdown Helicopters without whom this project would not have been possible. Sally Dupont is funded by a Macquarie RTP Scholarship. Lisa-Marie Harrison is funded by a Macquarie Research Excellence Scholarship. The aerial surveys are run as part of the NSW Shark Meshing (Bather protection) Program administered by the NSW DPI. Particular thanks to Tony Andrews, Christine Rae and Tony Chen of NSW DPI for their assistance in managing aerial survey contracts.

## CONCLUSION

The results of this thesis addresses some of the issues affecting aerial surveys and their use. The first chapter refined aerial surveys as a method with regards to speed and found no justification, taking into account time and financial cost, to reduce the current aircraft speed of 100 knots to 80 knots. It is therefore recommended that this speed, 100 knots, is retained for future surveys of marine coastal species. The results also highlight the impact of inter-observer differences, in particular the role of experience in both the number and type of animals seen. It is therefore recommended that novel observers are trained for a period of 6-8 hours in order to reach a similar sighting rate to that of an experienced observer. Sighting rate is also dependent on the distribution of marine animals within the survey area.

In the second chapter, the relationship between environmental factors and the distribution of dolphins, fish and sharks in NSW waters was investigated. The results showed distinct seasonal variations, with the greatest number of animals sighted in spring and the least in summer. However, we were unable to link this seasonal variation to fine-scale environmental factors such as SST and Chl-a. This suggests that the survey design from this study may not be the most effective method in detecting the correlation between coastal marine species and inshore environmental factors.

The two chapters included in this thesis provide an indication on the direction of future research. Although we did not find reducing aircraft speed by 20% to be beneficial, the minimum viable speed considering financial cost and observer fatigue is yet to be examined. The maximum speed threshold, where aerial surveys can be conducted without compromising sighting ability, also warrants further exploration. In addition, repeating the same method of varying speed but over a coastal environment of varying substrate type and depth would increase the validity of our findings and our recommendation of aircraft speed. The contrast of a dark animal against a sandy substrate was one of the main indicators used to identifying an animal. A darker rocky substrate or greater depth is likely to affect sighting rate, potentially magnifying the effect of speed.

A change in survey design, for example having transects perpendicular to the shore rather than parallel, might be a solution to linking shark, fish and dolphin distribution to environmental factors such as SST and Chl-a by increasing the offshore spatial extent of the sighting and satellite data. Many studies investigating marine animal distribution and environmental factors are conducted on populations that are further offshore (see Baumgartner 1997, Corkeron et al. 1997). Increasing the survey area to include a greater portion of the coast may also improve the accuracy surrounding dolphins which are capable of moving great distances quickly (Wood 1998). SST anomalies could be a significant factor by acting as a stressor through an unexpected sudden variation to the normal range of the species habitat (Leaper et al. 2006). This may force a change in the behaviour and distribution of marine animals that could be measured. Furthermore, since we were unable to link animal distribution to environmental factors, it is worth investigating a more direct predator-prey relationship between dolphins and fish. The relationship between two consecutive trophic levels may prove to play a greater role in the distribution of coastal marine animals such as dolphins than environmental factors.

Ideally, based on the findings in this thesis, future studies will incorporate a helicopter speed of 100 knots to assess the distribution of coastal marine animals along a greater spatial area, including further offshore. These will also include a number of environmental factors (SST, SST anomalies, Chl-a, salinity, depth) as well as incorporate predator-prey relationships into the analysis. These future studies will provide a significant contribution to our understanding of marine megafauna distribution which will greatly aid in the conservation and management of these animals.



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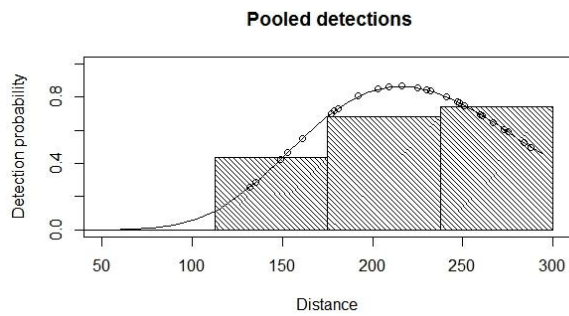
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## Appendix

### Distance Models

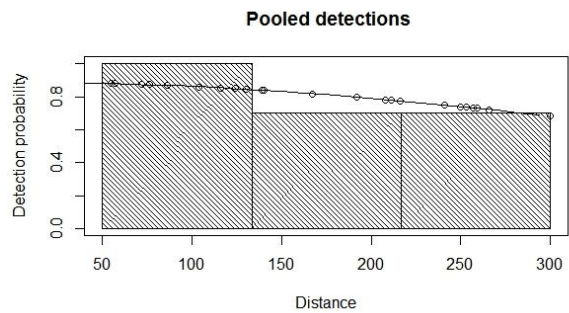
#### Dolphins – 80 knots

##### Helicopter 1, 80 knots – Northbound



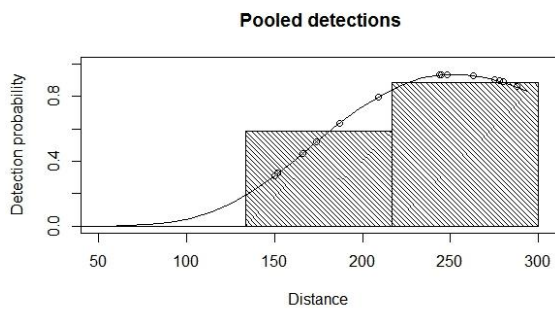
N = 30,  $p = 0.3873116$ , CV = 0.2172195

##### Helicopter 1, 80 knots – Southbound



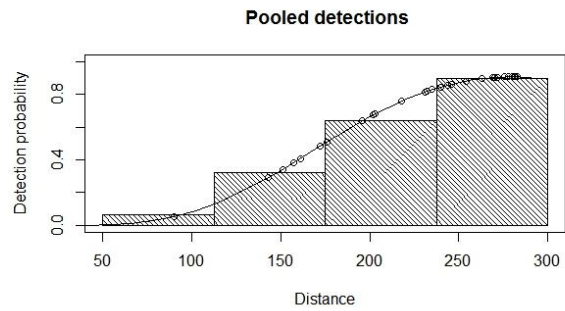
N = 24,  $p = 0.6690644$ , CV = 0.2780224

##### Helicopter 2, 80 knots – Northbound



N = 15,  $p = 0.4087224$ , CV = 0.2158986

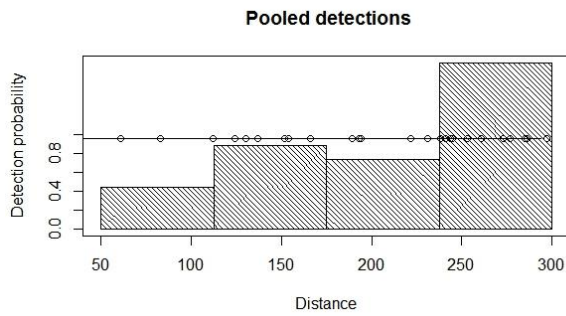
##### Helicopter 2, 80 knots - Southbound



N = 30,  $p = 0.4017756$ , CV = 0.2518779

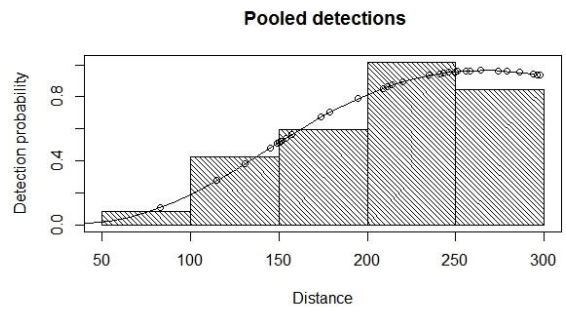
## Dolphins - 100 knots

**Helicopter 1 - northbound:**



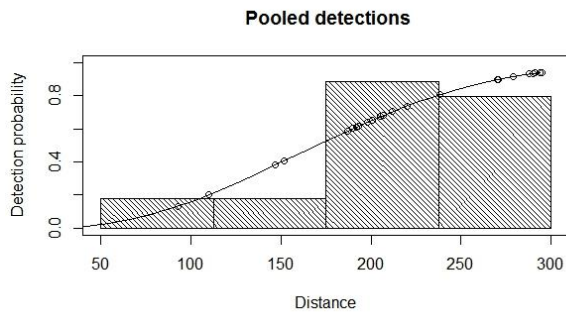
$N = 26$ ,  $p = 0.7968265$ ,  $CV = 0.2623114$

**Helicopter 1 - southbound:**



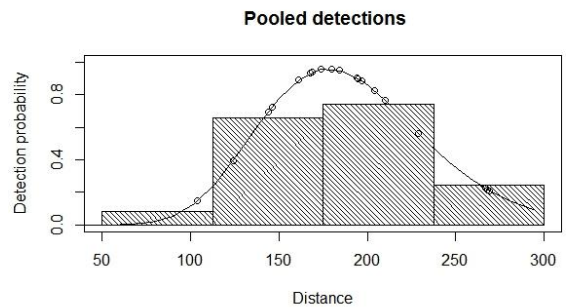
$N = 35$ ,  $p = 0.4940033$ ,  $CV = 0.1602111$

**Helicopter 2 - northbound:**



$N = 23$ ,  $p = 0.4234025$ ,  $CV = 0.6399239$

**Helicopter 2 - southbound:**



$N = 21$ ,  $p = 0.3594106$ ,  $CV = 0.1696719$

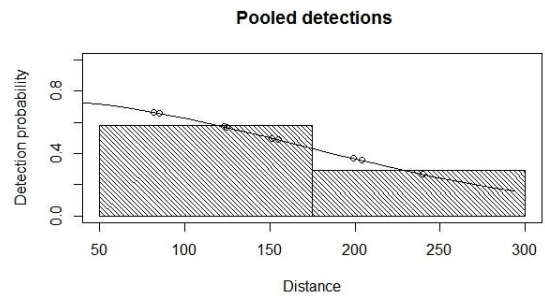
## Sharks – 80 knots

### Helicopter 1 - northbound:

Distance model could not be generated due to insufficient sample size

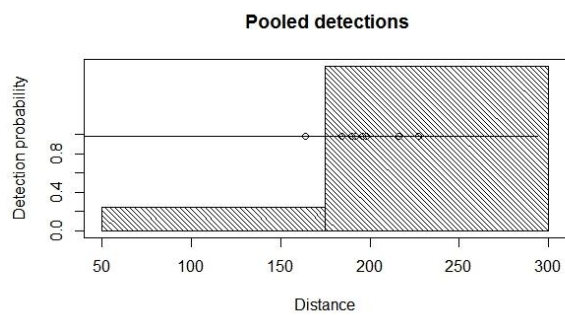
$N = 3$ ,  $p = 3.323351e-03$ ,  $CV = 18.23088$

### Helicopter 1 - southbound:



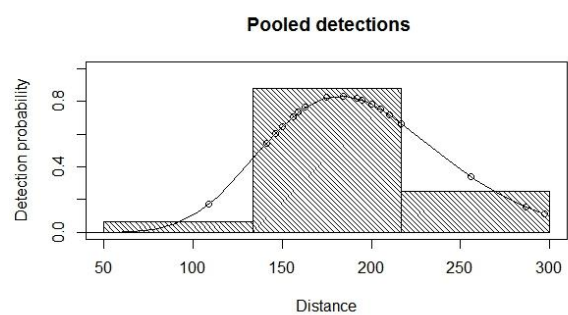
$N = 9$ ,  $p = 0.3622927$ ,  $CV = 0.5741545$

### Helicopter 2 - northbound:



$N = 8$ ,  $p = 0.8163261$ ,  $CV = 1.659658$

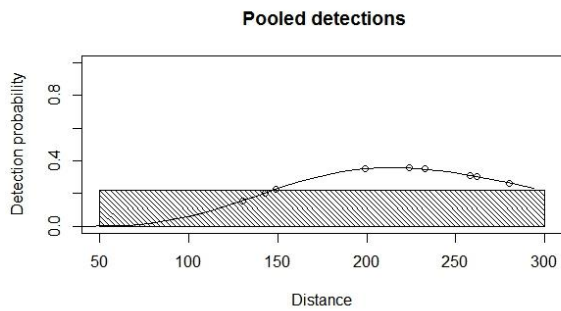
### Helicopter 2 - southbound:



$N = 19$ ,  $p = 0.3311056$ ,  $CV = 0.1979704$

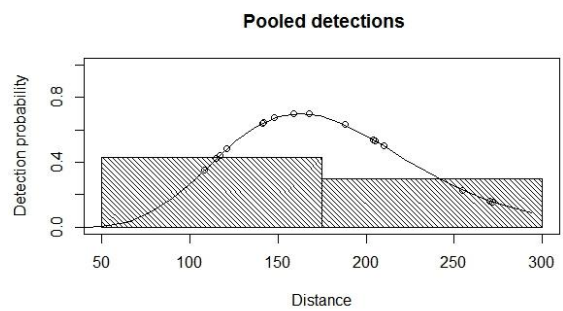
## Sharks – 100 knots

### Helicopter 1 - northbound:



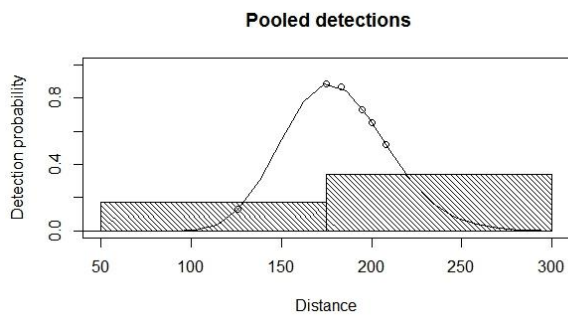
$N = 9$ ,  $p = 0.1822007$ ,  $CV = 0.8830183$

### Helicopter 1 - southbound:



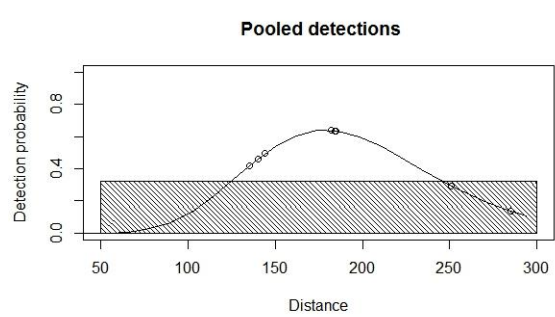
$N = 17$ ,  $p = 0.3038321$ ,  $CV = 0.3178294$

### Helicopter 2 - northbound



$N = 6$ ,  $p = 0.2132405$ ,  $CV = 0.5941587$

### Helicopter 2 - southbound

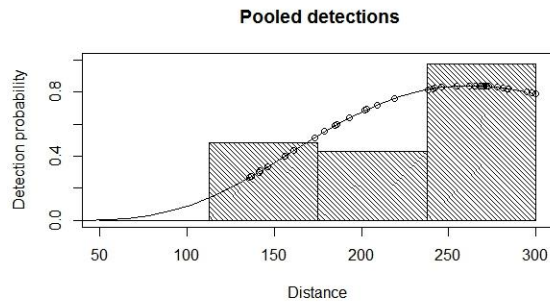


$N = 8$ ,  $p = 0.2678197$ ,  $CV = 0.5284953$



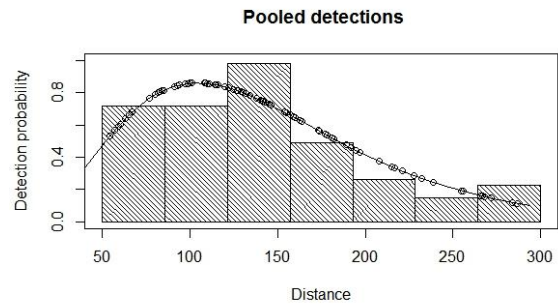
## Fish Schools – 80 knots

**Helicopter 1 - northbound:**



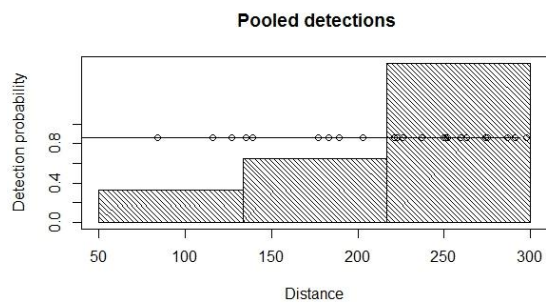
$N = 35$ ,  $p = 0.3946887$ ,  $CV = 0.1547355$

**Helicopter 1 - southbound:**



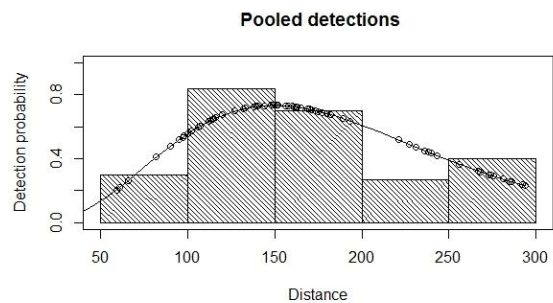
$N = 94$ ,  $p = 0.4226455$ ,  $CV = 0.08903772$

**Helicopter 2 - northbound:**



$N = 24$ ,  $p = 0.7183679$ ,  $CV = 0.2679257$

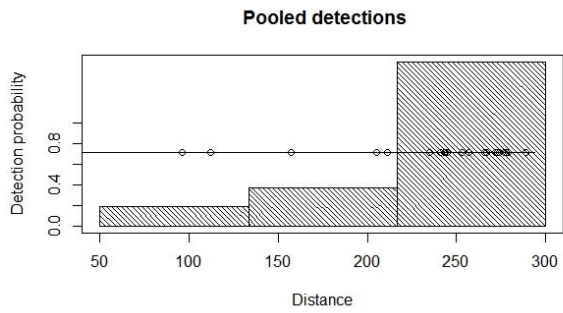
**Helicopter 2 – southbound:**



$N = 75$ ,  $p = 0.4180895$ ,  $CV = 0.1295849$

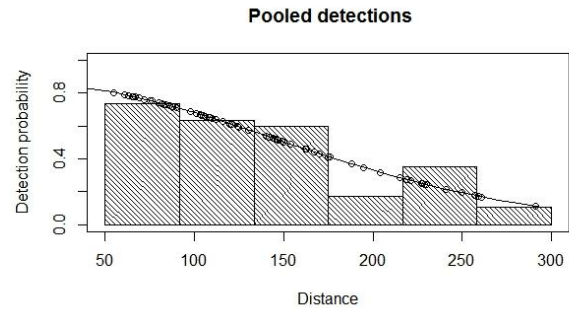
## Fish Schools – 100 knots

**Helicopter 1 – northbound:**



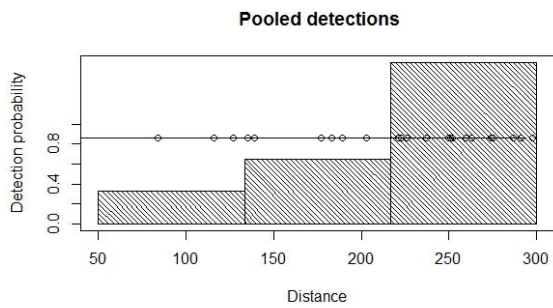
$N = 23$ ,  $p = 0.5962987$ ,  $CV = 0.2966942$

**Helicopter 1 – southbound:**



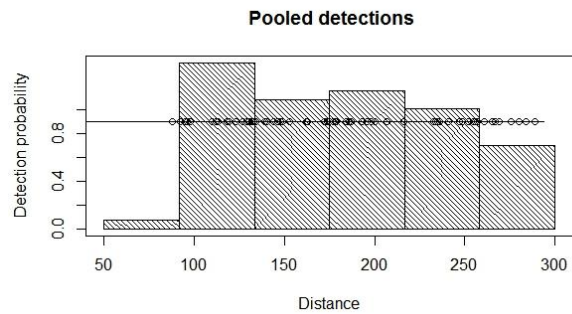
$N = 74$ ,  $p = 0.3608314$ ,  $CV = 0.1430879$

**Helicopter 2 – northbound:**



$N = 31$ ,  $p = 0.7731273$ ,  $CV = 0.04049474$

**Helicopter 2 – southbound:**



$N = 70$ ,  $p = 0.7540685$ ,  $CV = 0.1973625$

## Raw vs adjusted counts

### Dolphins

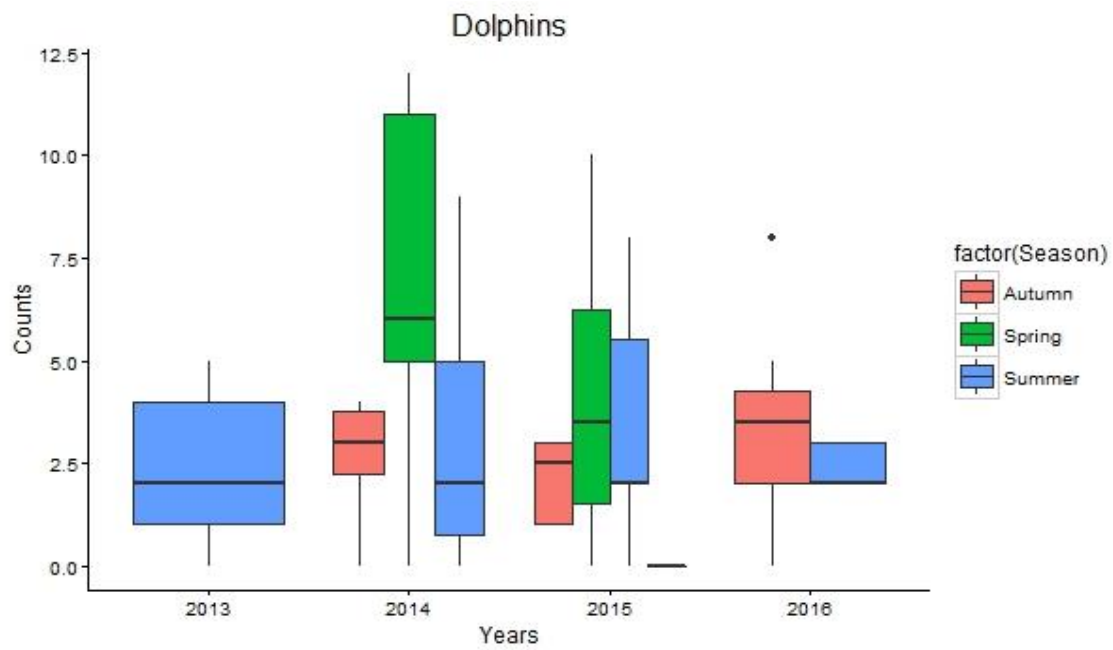
TRANSECT NO.	HELICOPTER	SPEED	UNADJUSTED	ADJUSTED	CV
1	1	80	13	34	0.277
	2	100	8	19	0.680
2	1	100	8	16	0.296
	2	80	4	10	0.405
3	1	100	6	8	0.449
	2	80	3	7	0.428
4	1	80	10	15	0.380
	2	100	8	22	0.272
5	1	80	5	13	0.353
	2	100	5	12	0.703
6	1	100	9	18	0.284
	2	80	11	27	0.316
7	1	100	2	3	0.684
	2	80	2	5	0.501
8	1	80	4	6	0.495
	2	100	5	14	0.317
9	1	80	4	10	0.379
	2	100	2	5	0.788
10	1	100	6	12	0.329
	2	80	4	10	0.405
11	1	100	6	8	0.449
	2	80	3	7	0.428
12	1	80	10	15	0.380
	2	100	8	22	0.272
13	1	80	8	21	0.309
	2	100	8	19	0.680
14	1	100	12	24	0.259
	2	80	11	27	0.316
15	1	100	12	15	0.368
	2	80	7	17	0.324

## Sharks

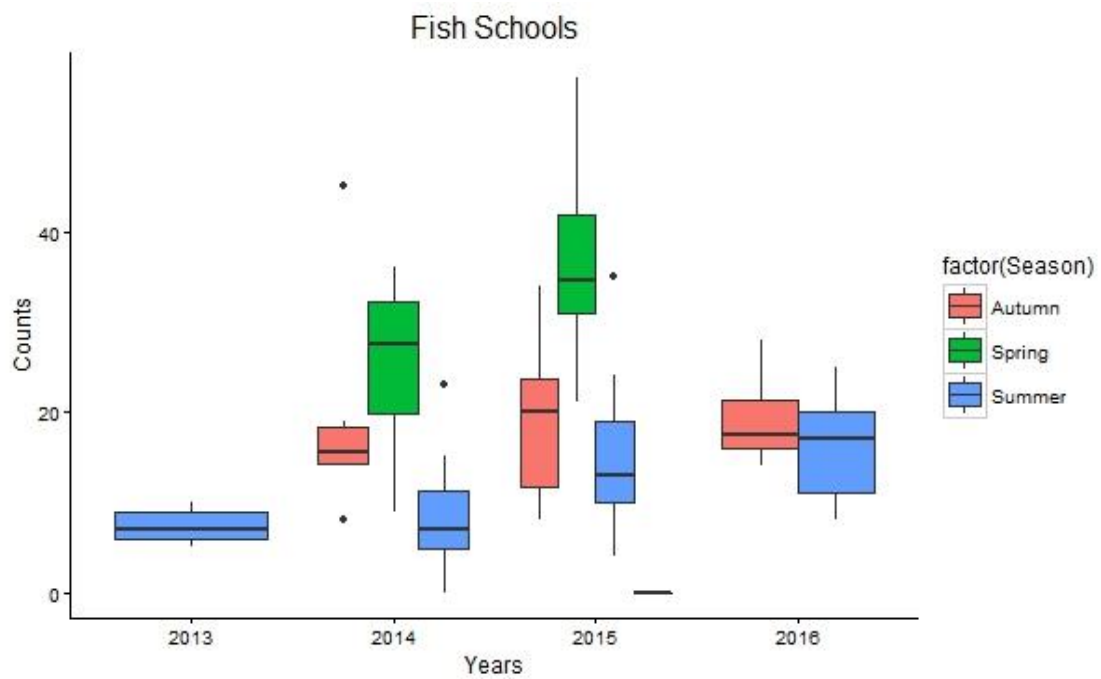
TRANSECT NO.	HELICOPTER	SPEED	UNADJUSTED	ADJUSTED	CV
<b>1</b>	1	80	0	0	0.000
	2	100	1	19	0.637
<b>2</b>	1	100	3	10	0.450
	2	80	4	12	0.349
<b>3</b>	1	100	3	16	0.917
	2	80	2	2	1.778
<b>4</b>	1	80	4	11	0.648
	2	100	3	11	0.607
<b>5</b>	1	80	1	N/A	N/A
	2	100	1	5	0.753
<b>6</b>	1	100	2	7	0.503
	2	80	3	9	0.387
<b>7</b>	1	100	3	16	0.917
	2	80	4	5	1.720
<b>8</b>	1	80	4	11	0.648
	2	100	2	7	0.643
<b>9</b>	1	80	2	N/A	N/A
	2	100	1	5	0.753
<b>10</b>	1	100	7	23	23.039
	2	80	8	24	0.284
<b>11</b>	1	100	1	5	0.981
	2	80	0	0	0.000
<b>12</b>	1	80	1	3	0.832
	2	100	3	11	0.607
<b>13</b>	1	80	0	0	0.000
	2	100	0	0	0.000
<b>14</b>	1	100	5	16	0.402
	2	80	4	12	0.349
<b>15</b>	1	100	2	11	0.933
	2	80	2	2	1.778

## Fish Schools

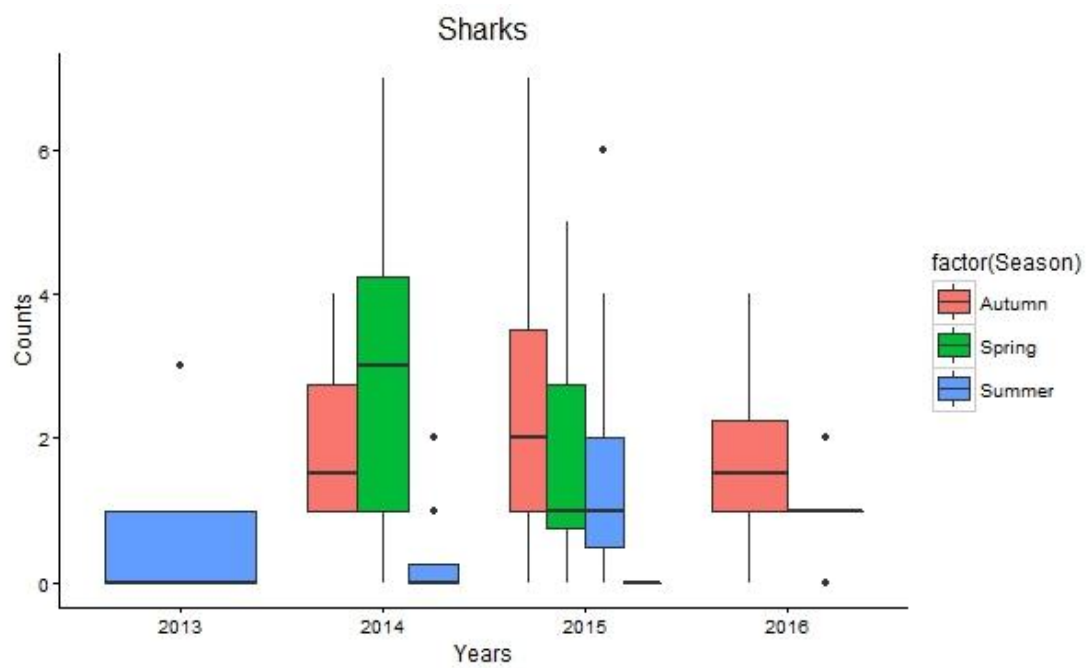
TRANSECT NO.	HELICOPTER	SPEED	UNADJUSTED	ADJUSTED	CV
1	1	80	9	23	0.260
	2	100	4	5	0.441
2	1	100	17	47	0.204
	2	80	15	36	0.211
3	1	100	1	2	0.827
	2	80	7	10	0.418
4	1	80	22	52	0.165
	2	100	17	23	0.289
5	1	80	12	30	0.238
	2	100	9	12	0.296
6	1	100	20	55	0.196
	2	80	20	48	0.194
7	1	100	13	22	0.366
	2	80	9	13	0.389
8	1	80	42	99	0.134
	2	100	31	41	0.252
9	1	80	13	33	0.233
	2	100	15	19	0.231
10	1	100	20	55	0.196
	2	80	22	53	0.189
11	1	100	6	10	0.433
	2	80	6	8	0.438
12	1	80	30	71	0.148
	2	100	22	29	0.271
13	1	80	1	3	0.647
	2	100	3	4	0.509
14	1	100	17	47	0.204
	2	80	18	43	0.200
15	1	100	3	5	0.536
	2	80	2	3	0.656



**Fig. 8.** Boxplot showing the relationship between bottlenose dolphin sightings per survey per season and year.



**Fig. 9.** Boxplot showing the relationship between fish school counts per survey per season and year.



**Fig. 10.** Boxplot showing the relationship between shark counts per season and year.