Humpback whale use of the Kimberley: understanding and monitoring spatial distribution

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WAMSI Kimberley Marine Research Program

KMRP Report

Project 1.2.1

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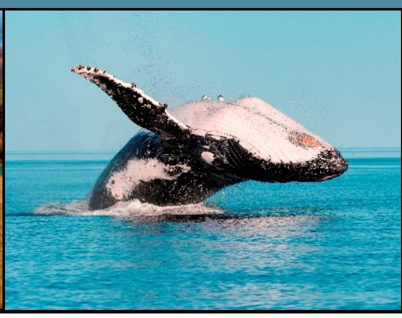
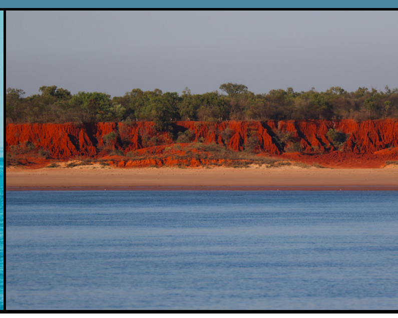

WAMSI Kimberley Marine Research Program

Initiated with the support of the State Government as part of the Kimberley Science and Conservation Strategy, the Kimberley Marine Research Program is co-invested by the WAMSI partners to provide regional understanding and baseline knowledge about the Kimberley marine environment. The program has been created in response to the extraordinary, unspoilt wilderness value of the Kimberley and increasing pressure for development in this region. The purpose is to provide science based information to support decision making in relation to the Kimberley marine park network, other conservation activities and future development proposals.

Front cover images (L-R)

Image 1: Satellite image of the Kimberley coastline (Source: Landgate)

Image 2: Kimberley reefs and islands (Source: Department of Biodiversity, Conservation and Attractions)

Image 3: Humpback whale breaching (Source: Pam Osborn)

Image 4: Pender Bay (Source: Chandra Salgado Kent, Curtin University)

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Contents

Executive Summary

Humpback whales traverse waters off the west coast of Australia as they migrate annually from summer feeding grounds in Antarctica to the nearshore waters of the Kimberley region where they breed and calve during winter. Despite extensive aerial and shipboard surveys by industry, tourism, community groups and researchers over the last three decades, there have been few attempts to synthesize these data to quantify spatial distributions and critical habitats for the species across the Kimberley. Such a holistic approach is urgently required to better inform management strategies for the species in an ecosystem that faces challenges of warming environments, industrial development and rapid growth of humpback whale populations. To address this need, all of the existing survey and tracking data of humpback whales was compiled and analysed to build a clear picture of the distribution, abundance, movements and habitat use (in particular calving areas) by the species through the Kimberley region and to identify the environmental factors that are associated with these patterns. Additionally, the project set out to identify information gaps and provide advice for future monitoring and management by assessing a range of methods including very high resolution satellite imagery for detecting and counting whales, aerial and boat based surveys and the use of a land based platform at Pender Bay.

Historical survey data of humpback whales collected across three decades (summing 13 years) were compiled from the Kimberley region of Western Australia, including from systematic and non-systematic surveys. These data were combined with environmental covariates obtained by remote sensing to develop spatial models using: density surface modelling, where distance sampling was coupled with generalised additive mixed modelling to produce density maps (individuals km^{-2}) predicted from environmental covariates; and species distribution modelling to produce habitat suitability maps predicted from the same environmental covariates developed from the presence-only sighting data from mostly non-systematic surveys.

The density surface models quantified the absolute abundance of humpback whales in a large area of the Kimberley region (from Gourdon Bay to the Maret Islands) at the two weekly intervals surveyed from mid-July to mid-October. The highest density occurred in mid-August, at 2182 individuals (one day snapshot at that time). When summing each of the two-week abundance estimates for the surveyed area and season, and assuming a two week length of stay in the region, it was possible to provide an estimate of the total number of whales using this area across this time period which was 9558 (lower CI=8190, upper CI=11169). Abundance and habitat suitability was highest in Pender Bay with Camden Sound also important but predominantly only in August. The consistent importance of Pender Bay throughout the season might be heightened by its location along the migratory path; i.e. it is an area where most whales have to pass through to enter and leave the region. However, results presented here suggest that all whales may not travel to more northerly sites and that calving and breeding may also occur at Pender Bay and possibly other areas further south. Only very low density of humpback whales was found north of Camden Sound (0-1 whale/km^2). Gourdon Bay, at the southern extent of the surveyed area was also found to have high density of whales, similar to or greater than densities at Camden Sound (3-4 whales/km^2). Satellite tracking data from 46 whales across three years also highlighted the importance of Pender Bay as a core area for humpback whales and that Eighty Mile beach was also an important area in the Kimberley. Considering all the evidence, we suggest that the distribution of humpback whales in the Kimberly extends from Eighty Mile Beach in the south to Camden Sound in the north. Surveys south of Gourdon bay would be needed to evaluate the importance of this area.

The top predictors of abundance were water depth and day of year, with the model predicting numbers to increase up to mid-August and to peak in waters around 35 m depth and decline in waters shallower than 25 m. Distance to coast was the most important predictor of habitat suitability for humpback whales, with habitat suitability highest within 20-40 km of the coast. These inshore areas may offer more protected conditions, such as from the strong tidal currents in the Kimberley, and might be especially important for an animal living on fixed energy, particularly for groups containing females and calves. Groups with calves present were found closer to shore and in areas with smaller spatial extent than areas used by all whale groups combined. Off the

Kimberley, SST was only important in August, with whales displaying a preference for temperatures around 24.5 and 26.5°C.

The second objective of this project was to evaluate potential cost effective methods for long term monitoring of the humpback whale population in the Kimberley. Given the remoteness and extent of the area, we opted to test the potential for using a remote sensing technique. We trialed very high resolution (VHR) (30 and 50 cm on ground resolution) satellite imagery from the WorldView satellites to detect and count whales at James Price point and in the Lalang-garram/Camden Sound Marine Park. Humpback whales could be identified in the satellite imagery and the calculated density obtained from images was comparable to that estimated using traditional survey methods. The results showed that the higher resolution imagery obtained from WorlView-3 (30 cm) was needed to detect and count humpback whales successfully. In addition, a semi-automated detection algorithm significantly reduced the time taken to count the whales in the images compared to visual searching by a person (~30 mins compared to 1 day). However use of VHR satellite imagery is only economically viable for small, discrete areas where high densities of whales occur such as Pender Bay or Camden Sound.

As another approach to long-term monitoring, Two Moons Whale and Marine Research Base at Pender Bay, WA have used a land based site manned by volunteers to gather data on humpback whale use of Pender Bay between 2009 and 2012 (Blake et al 2011). This project was evaluated, including assessing field methodology and trialing some changes to data collection in 2013 to determine whether this land based site could be used as part of a long term monitoring program of humpback whale population health and use of the Kimberley. Data collection included counts of all humpback whale groups (noting size and presence of calves) observed at 20 minute intervals from a cliff top viewing platform. These data were evaluated to assess the timing of the migration season, including peak in the number of individuals and the number of calves across the season and the distribution of whales within the Bay and adjacent waters. Whales were sighted between 400 m and up to 15 km from shore, however were most commonly sighted at 3-4 km from shore, potentially in association with particular water depths or benthic features, though more data would be needed to evaluate this. While the peak in number of groups with calves occurred from mid-August to September, there was a higher proportion of groups with calves early in the season, indicating that calves were being born near Pender Bay, and matching results from the distribution modelling here where groups containing calves were present along the southern section of the Dampier Peninsula early in the season (July).

Finally, we compared the strengths and weaknesses of different approaches to monitoring the Kimberley humpback whale population including recognising the different questions that could be answered by each method/protocol and some of the associated pros and cons. Where resources limit broader coverage of the region (either via satellite imagery or aerial surveys), tasking the WorlView-3 satellite to obtain images at Pender Bay or Camden Sound will provide an efficient, cost effective and independent system for monitoring Kimberley humpback whale population health into the future. As the Western Australian State Government owns assets in the form of vessels, vessel surveys of these areas could also be used to reduce costs and a basic protocol has been provided. Aerial surveys of the whole Kimberley region are key to monitoring trends in absolute abundance of Kimberley humpback whales over time, however they have high cost and need a high level of expertise. Although land-based surveys had the lowest cost, their ability to answer the key management questions was most limited.

Implications for management

Our study confirmed the importance of the Lalang-garram/Camden Sound Marine Park to breeding and calving humpback whales, but with the main use of this area by whales during August. The highest abundances and habitat suitability were detected at Pender Bay across the entire breeding season. Previously Pender Bay has been considered a staging area for whales travelling to and from more northerly areas in the Kimberley such as Camden Sound and Buccaneer Archipelago. Results presented here suggest that all whales may not travel to more northerly sites and that calving and breeding may also occur at Pender Bay and southwards along the Dampier Peninsula. While the Camden Sound site is encompassed within a marine protected area, Pender Bay currently has only limited protection by the multiple use zone, Kimberley Commonwealth Marine reserve. Thus additional sites in the Kimberley, like Pender Bay, should be considered important breeding habitat and suitable for additional protection.

Importantly, there have not been any systematic surveys of the Kimberley region, including Camden Sound since an aerial survey by the Centre for Whale Research (CWR) in 2007. While it is widely recognised that the population has been increasing each year as it recovers from the decimation of whaling, there is no current estimate of the absolute population size nor of how population growth may have affected spatial use in the important breeding grounds of the Kimberley. It is now crucial that a monitoring program be implemented to ensure this population is managed effectively into the future, given the growing pressures of climate change and other anthropogenic pressures in the marine environment. Differences in the spatial and temporal coverage of the datasets compiled and analysed here, prevented valid/robust analysis and detection of trends among years and highlights the importance of having, long-term, repeatable systematic survey data to effectively monitor trends. To this end, a basic protocol and design for ongoing vessel/satellite imagery surveys of humpback whale relative abundance at Pender bay and Camden Sound is provided. Annual aerial survey of the region (Eighty Mile Beach to Camden Sound) is necessary in order to be able to monitor trends in the Kimberley population abundance and should be considered where budget allows, but given that cost and expertise required is high, it should be undertaken every 5-10 years (at a minimum) to monitor distribution patterns and densities and identify emerging high density areas as the population continues to expand and potentially in response to changing sea temperatures.

Land based viewing platforms can provide a cost-effective means of acquiring data on whales that can be used for management and other purposes but have limitations (e.g. limited spatial extent and cannot be used to obtain an abundance estimate). Most important to the selection of a monitoring protocol is to have a clear question in mind and to ensure that the data collected can meet this purpose. The land-based site at Pender Bay can be used to collect data that will inform regional managers about the timing of the humpback whale migration season, as this can vary annually, including the timing and density of mother and calf groups. It can also be used as an indicator of the intensity of use of Pender Bay by humpback whales, including changes in timing and whale density throughout the migration season and between seasons.

Key residual knowledge gaps

Our abundance models have allowed us to understand the relative importance of the different areas in the Kimberley to whales generally, but not specifically for mothers and calves (we were only able to model habitat suitability for mothers and calves). Given that the distribution models clearly show that suitable calving habitat occurs beyond the Lalang Garram/Camden Sound Marine Park (between Camden Sound and Pender Bay and other areas along the coast of the Dampier Archipelago such as James Price Point) targeted surveys identifying neonates from post-neonates are needed to confirm if these areas are used for calving. There is generally a paucity of information on the presence of calves, particularly in their first few months of life. Neonate calves may be more cryptic and difficult to positively identify, depending on the survey methods used. Future surveys could focus on determining when calves are present and record details that indicate calf age such as colour and size (Chittleborough 1953, Kaufman & Forestell 2006, Irvine et al. 2017), or data on foetal folds and angle of dorsal fin (Cartwright & Sullivan 2009). This may provide more information to ascertain the relative importance of each site as a calving/nursing ground.

Our spatially explicit time-spent analysis of data from satellite tracking devices deployed on whales show that medium to high residency occurs at Eighty Mile Beach, with this area previously identified as a potential resting area for humpback whales. None of the survey data we compiled extended to Eighty Mile Beach, making patterns of humpback whale abundance and residency in this area a key residual knowledge gap. Deployment of satellite tracking devices of northbound whales south of Eighty Mile Beach would be useful to determine residency time in the different areas of the Kimberley and also assist with determining the area where calving takes place, i.e. the areas where northbound whales terminate their migration.

The land-based surveys at Pender Bay were useful for determining the seasonal trends in relative abundance and the migratory peak in the bay. The area covered, however, is restricted in distance from shore in which visual surveys can extend to. Consequently, counts of whales may not represent trends in abundance in the broader region. Running simultaneous land-based and vessel surveys in the Pender Bay and surrounding region hotspot would define the relationship in observed trends from land and patterns in the broader surrounding region. This knowledge would add significant value to what is already a useful and cost-effective method for long-term monitoring of humpback whales in Pender Bay. Tasking the satellite to obtain an image of this same area would also be extremely useful for comparing these three methods.

Another key knowledge gap is developing a better understanding of the overlap and degree of risk between humpback whale distribution / important areas (spatial and temporal) and industry activities (shipping, seismic, infrastructure, fishing, etc). This is particularly important given the rise in vessel activity associated with tourism as well as industry in the Kimberley. This could be achieved through a quantitative spatial risk assessment using both survey data and satellite tracking data mentioned above.

Chapter 1: Modelling the movement and spatial distribution of humpback whales in the nearshore waters of the Kimberley

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1 Introduction

One of the key steps to achieving visible, tangible and significant conservation benefits for the marine biodiversity of the Kimberley is to gain an understanding of how megafauna use the region. This information can enable managers to determine if and how patterns of use change over time in response to natural or anthropogenic pressures. The knowledge required for this process includes relative abundance, distribution, movement patterns (travelling, resting, etc.) and habitat use, along with the environmental context of these patterns. This information is fundamental to the delivery of appropriate management strategies at both single species and ecosystem scales.

Off the west coast of Australia, a population of 33,000 humpback whales (at minimum) migrate annually from summer feeding grounds in Antarctica to breed and calve during winter in the nearshore waters of the Kimberley (Salgado-Kent et al. 2012). This population was decimated during the whaling era, but is recovering strongly at an estimated rate of over 11% per annum (Salgado-Kent et al. 2012). Within the Kimberley region, Camden Sound has been identified as a key area for calving, with other important areas of aggregation including Pender Bay and the area surrounding Frost and Tasmanian shoals (Jenner et al. 2001).

Since the recognition of the nearshore waters of the Kimberley as a calving ground in the mid 1990's (Jenner et al. 2001), there have been many boat-based and aerial surveys of humpback whales in the region conducted by industry, researchers and others, along with complementary studies using satellite tagging to determine abundance, distribution and movement patterns of this population. However, much of the data remain unpublished and there has been no synthesis of this data in order to provide a broad understanding of how humpback whales use the Kimberley, particularly as a breeding area. Such information is vital for both the management of human activities, including the emerging tourism industry of whale watching in breeding grounds in Lalang garram/Camden Sound Marine Park, as well as the documentation of expansion or movement from this area as a result of population growth and increasing anthropogenic activities in the Kimberley region.

The purpose of our project was to compile and analyse existing survey and tracking data of humpback whales to build a clear picture of the distribution, absolute abundance, movements and habitat use (in particular calving areas) by the species through the Kimberley region and to identify the environmental factors that are associated with these patterns. Additionally, we set out to identify information gaps and provide advice for future monitoring and management (Chapter 4) by assessing a range of methods including high resolution satellite imagery for detecting and counting whales (Chapter 2), aerial and boat based surveys and the use of a land based platform at Pender Bay (Chapter 3).

2 Materials and Methods

Historical survey data of humpback whales were compiled from the Kimberley region of Western Australia (Table 1). These included dedicated (researchers and consultants on behalf of oil and gas companies) and non-dedicated (e.g. tourist operators and Customs surveillance) surveys from vessels and aircraft. These surveys usually took place between July and October and in addition to counting humpback whales, many surveys also recorded sightings of a range of other marine megafauna (e.g. dugongs, marine turtles, etc.). In some cases, the survey coverage was designed to address specific issues of an industry client that commissioned the research and was not necessarily related to the estimation of abundance and distribution of humpback whales throughout their range in the Kimberley region (e.g. RPS Group/Woodside surveys focussed at James Price Point, Table 1). Each dataset was assessed to determine the appropriate modelling method to be used for analysis. Where a dataset was collected with distance sampling methods (Buckland et al. 2011) and survey paths were available to calculate effort, we used density surface modelling to analyse the observation data (as counts). Where this was not possible, or where sampling effort was spatially restricted (as mentioned above) we used the Maximum Entropy Method (MaxEnt), a species distribution modelling approach, to model observations as presence/absence data (Table 1). Some datasets were deemed unusable for either analysis (Table 1).

Dedicated surveys included both vessel-based and aerial line transects conducted in both zigzag patterns and parallel lines perpendicular to coast over the study area which sometimes differed in structure in each year. Tracking data from satellite tags that was collected over three years (2008, 2009 and 2011) was also analysed to provide details of the movement behaviour of whales of known sex and breeding status (cows with calves) to determine areas with highest residence and to document the area of use on each of the northward and southward migrations.

The spatial extent of the modelling was determined by the spatial extent of the surveys and although we refer to 'the Kimberley' throughout this report, it technically refers to the area of the Kimberley surveyed (Fig. 1).

Table 1. Aerial and vessel line transect survey data compiled for the project and the response variable used for modelling. Species distribution modelling (using MaxEnt) was used for presence/absence data and density surface modelling used for counts, RPS = RPS Group, environmental consultants.

Platform	Year	Sample days	Total whales	Survey program	Months covered	Response variable
Aerial	1993	75	805	Coastwatch/CWR	Jun, Jul, Aug, Sept	presence/absence
Aerial	2006	4	279	CWR	Aug, Sept	counts
Aerial	2007	7	1050	CWR	Aug, Sept	counts
Aerial	2008	9	1979	CWR	Jul, Aug, Sept, Oct	counts
Aerial	2008	7	172	CWR	Aug, Sept, Oct	presence/absence
Aerial	2009	9	568	RPS/Woodside	Jul, Aug, Sept, Oct	presence/absence
Aerial	2009	17	905	RPS/Woodside	Jul, Aug, Sept, Oct	presence/absence
Aerial	2009	6	112	RPS/Woodside	Jul, Aug, Sept, Oct	presence/absence
Aerial	2009	8	962	RPS/Woodside	Jul, Aug, Sept	presence/absence
Aerial	2010	10	530	RPS/Woodside	Jun, Jul, Aug, Sep, Oct	presence/absence
Aerial	2010	10	377	RPS/Woodside	Jun, Jul, Aug, Sep,	presence/absence

					Oct	
Aerial	2011	7	490	RPS/Woodside	Jun, Jul, Aug, Sep	presence/absence
Aerial	2012	7	762	RPS/Woodside	Jul, Aug, Sep, Oct	presence/absence
Boat based	1995	39	372	CWR	Aug, Sept, Oct	presence/absence
Boat based	1996	52	667	CWR	Jul, Aug, Sept, Oct	presence/absence
Boat based	1997	58	904	CWR	Jul, Aug, Sept	presence/absence
Boat based	2006	70	534	CWR/Inpex	Aug, Sept	presence/absence
Boat based	2007	27	461	CWR/Inpex	Jul, Aug	presence/absence
Boat based	2008	58	57	CWR/Inpex	Jun, Jul, Oct, Nov	presence/absence
Boat based	2008	13	401	CWR/Woodside	Sept, Oct	presence/absence
Boat based	2009	25	1262	RPS/Woodside	Jul, Aug, Sept, Oct	presence/absence
Boat based	2008	6	131	WAMSI	Sep	*
Boat based	2009	6	380	WAMSI	Aug, Sep	*
Boat based	2010	3	86	WAMSI	Aug	*
Boat based	2011	8	498	WAMSI	Aug	*
Boat based	2010	27	1155	Costin (tourist operator)	Jun, July, Aug, Sep	presence/absence
Boat based	2011	13	907	Costin (tourist operator)	Jul, Aug	presence/absence
Boat based	2013	14	893	Costin (tourist operator)	Aug, Sep	presence/absence
Boat based	2014	6	332	Costin (tourist operator)	Sep	presence/absence
total		691	18031			

* The positions recorded in the data are boat positions, not whale positions and distance and bearing were not recorded thus, whale positions could not be calculated.

2.1 Dedicated surveys

2.1.1 *Aerial surveys*

Aerial surveys by CWR (Jenner & Jenner 2007a, b, 2009) were conducted at an altitude of 305 m (1000 ft) and a speed of 222 km/hr (120 knots) using a twin-engine, over-head wing aircraft (Twin Otter or Cessna 337). The plane followed zigzag transects that operated in passing mode (i.e. the plane did not deviate from the flight path). Surveys were only initiated in wind speeds < 33 km h^{-1} (18 knots), which has been shown to be adequate for spotting whales (Salgado-Kent et al. 2012). Each flight was of approximately 5.5 to 6 hours duration and take-off times varied between 8:40 and 10:55 so that the mid-day period was always sampled and glare would be a consistent factor for all flights. Personnel for each survey included two pilots and two observers. The pilots were responsible for recording the angle of drift of the plane on each transect, so that angles of whale sightings reported from the compass boards (see below) could be corrected relative to the flight path (Lerczac & Hobbs 2006). The observers were linked via a separate intercom system that was logged to a Sony Mini Disk Recorder NH900, allowing the observers to search continuously and voice record all sightings to a time code that was synchronized to the Global Positioning System (GPS) before each flight. A Garmin III Pilot aeronautical GPS was used to log sightings (as waypoints) and coordinates of the flight path, including altitude, for every second of the flight. Observers sighted and recorded positions of whales by measured vertical and horizontal angles from the aircraft to the whales (using Suunto PM-5/360PC clinometers, and a compass board). The location (latitude and longitude) of each sighted whale was later plotted by projecting a new GPS waypoint from the waypoint recorded at the time of sighting (using Oziexplorer ver 3.95 GPS software) from the calculated angle and distance of the aircraft to the whale. The angle was calculated with the formulae:

Angle to starboard = AC + (MHA + DA), and Angle to port = AC + (MHA - DA)

where AC was the aircraft course, MHA was the measured horizontal angle and DA was the angle of drift of the aircraft. Distances were calculated using formulae in (Lerczac & Hobbs 2006). The level and direction of glare (scale 1-3) for each observer was recorded for each transect (leg of the zigzag before a change in direction occurred) along with environmental variables such as Beaufort sea-state (scale 0 - 5), associated wind speed (knots) and direction, cloud cover below 1000 feet (percentage) and overall visibility (scale 1-3). Survey paths in 2006 were inconsistent among flights due to communication issues with the contractor regarding plane endurance and pilot flying hours. Two flights followed the same path, and two flights followed different flight paths. In 2007 and 2008, the same survey path was flown for all survey days (Fig. 1).

Aerial surveys by RPS focussed on James Price Point but extended along the west Kimberley coast and out to Scott Reef using both straight parallel survey lines perpendicular to shore and zigzag transect as per CWR. The surveys were designed with an emphasis on either humpback whales or dugongs but all megafauna were counted. They were conducted with a fixed wing aircraft and although a double count methods and distance sampling techniques were followed, the data were not analysed for abundance and rather used in presence absence models. This was because of the spatial focus of the surveys being at and around James Price Point (the proposed site of a gas plant) rather than being representative of the region used by humpbacks in the Kimberley. Flight altitude for humpback surveys was 1,000 feet flown at a constant speed of 110 kts in Beaufort sea state conditions < 4. For dugong surveys (where humpbacks were also recorded) flight altitude was 900 feet at 110 kts with parallel transect lines (perpendicular to the coast) placed 4.6 km apart (humpback whale parallel line surveys were 13-14 km apart). This meant that some double counting of humpbacks could have occurred (see RPS Environment and Planning Pty Ltd 2010 for details of the survey methods).

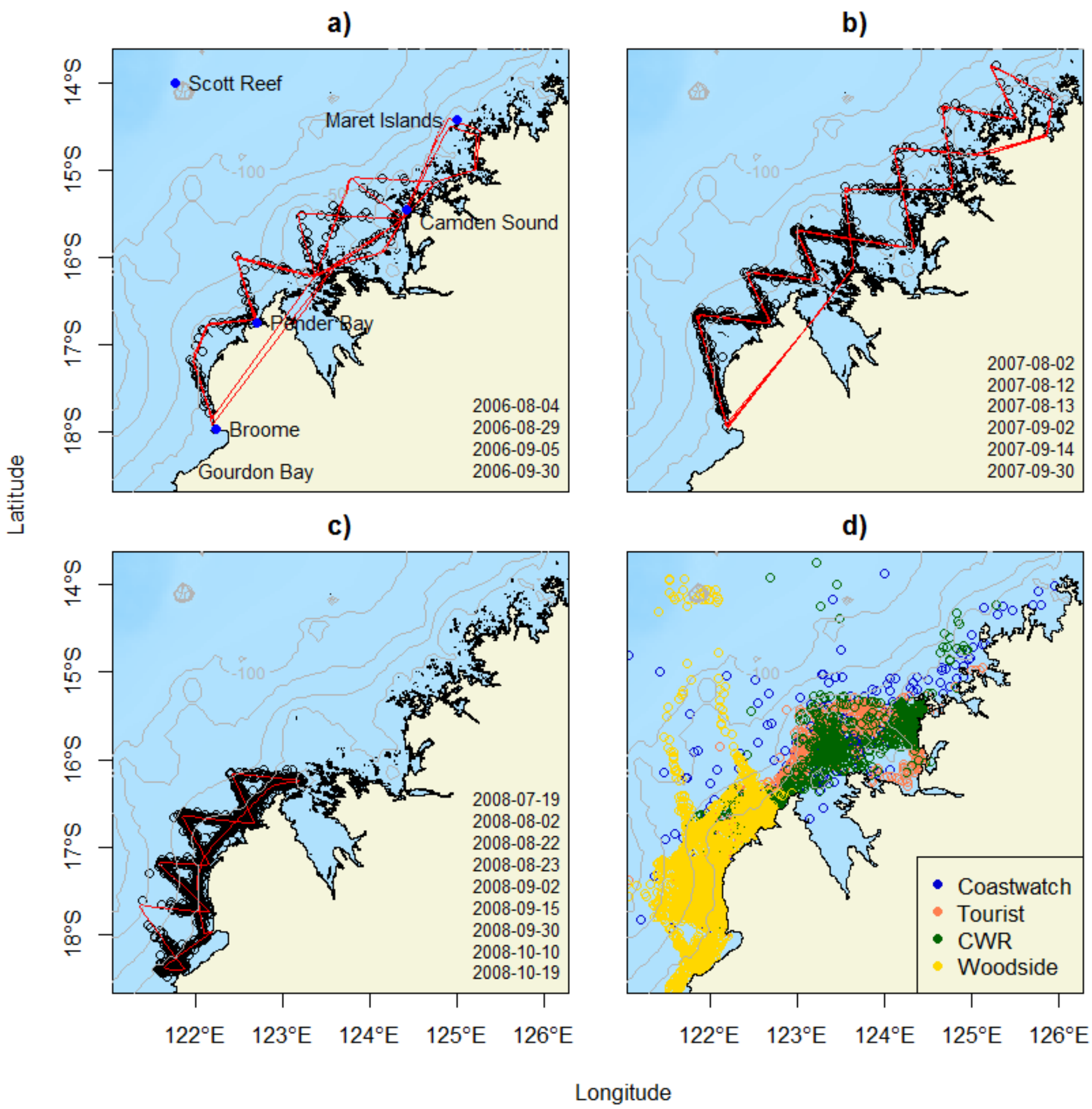

Figure 1. CWR aerial survey data used in density surface modelling collected in 2006 (a), 2007 (b) and 2008 (c). In 2006 two flights followed the same flight path, and two flights followed different flight paths. Flight paths are shown in red and humpback whale pods in black. In 2007 and 2008, the same survey path was flown for all survey days (shown in the right of each plot). Plot d) shows all other aerial and vessel survey data used in MaxEnt modelling (see table 1 for years). Grey lines show bathymetry contours; 100 m, 75 m, 50 m and 25 m. Note that Scott Reef surveys were not included in the analysis as sampling and observations from those locations were rare and may not have accurately represented whale occurrence in those habitats. They are shown here to show that humpback whales occur there.

2.1.2 *Boat based surveys*

A range of vessels were used for boat based surveys and were mostly motorised vessels (20 - 24 m in length) with a 12 m sailing vessel used by CWR in 1995-1997 surveys. Two - three observers (one port and one starboard and one data recorder) scanned the horizon from the upper deck (height of eye above sea surface ~ 5.5 m) of the vessel during daylight hours while the vessel steamed at 6-9 knots along a series of transects. Binoculars were used to identify fauna that were not readily identifiable by eye. An electronic hand-bearing compass was used to determine the bearing of sighted whales and other megafuana and their range to the vessel was estimated. A GPS waypoint was entered for each sighting and the track of the ship was also recorded by GPS as well as group size and environmental variables such as Beaufort sea state and sun glare. Positions of cetaceans were then projected with the appropriate bearing and distance from the sighting waypoint using Oziexplorer software.

2.2 Non-dedicated surveys

Two types of non-dedicated survey data were used in the analysis. The first was from an aerial surveillance program conducted in 1993 by Coastwatch (Australian Coastal Surveillance Organisation). Under the direction of CWR, one of the pilots was asked to record positions of humpback whales as he sighted them during border protection surveillance flights. As GPS was not yet commercially available, the positions were estimates from nearby landmarks in degrees and nautical miles. These were still considered reasonably accurate given that at the time, human navigational skills were not completely reliant on instruments and pilots routinely estimated distances from the plane during flight. Flight paths were unavailable for these surveys due to confidentiality surrounding the Coastwatch program. Another non-dedicated survey was conducted by the operator (Richard Costin) of a whale-watching tourism vessel and spanned the area from Broome to Camden Sound, but did not collect/provide survey path information. We did not have any information on how these data were collected.

2.3 Humpback whale movement

We obtained tracking data of 46 humpback whales that were tagged with satellite tags by CWR and AAD. The custom-designed Spot 5 transmitters (Wildlife Computers, Redmond, Washington, USA) were deployed on whales using a compressed air gun from the RV Whale Song, and its tender vessels in the Kimberley, over three years (Table 2). Six tags provided few or no locations in 2009, whereas in 2011 three tags were lost during deployment and a further four provided too few locations (<5). These data were not included. All tags were programmed to transmit on a duty cycle of 6 hours on, 18 hours off in order to maximise battery life and therefore track length. Two tags had longer deployment durations than shown in the table below (108 and 74 days respectively), but these data were not relevant to this project as one individual migrated from the Kimberley out to the Indian Ocean and the other to Antarctica (see Double et al. 2010, Double et al. 2011 for more details).

Table 2. Annual summaries of satellite tracking data of humpback whales used for analysis.

Year	n	Group type	Median duration (d)	Duration range (d)	Date deployed	Area deployed	Migration timing
2008	6	Cow/calf	25.2	4.6 – 27.6	28th Jul – 1st Aug	James Price Point	Northbound
2009	17	Cow/calf	7.4	0.3 – 60.6	24th Aug – 6th Sep	Camden (3), Buccaneer (6), Pender (8)	Southbound
2011	21	Adult male (10), adult female (2) cow/calf (3),unknown (6)	18.7	0 – 44.3	8th Jul – 23rd Jul	North-West Cape	Northbound
All	46		12.9	0 – 60.6			

2.4 Analysis

2.4.1 *Density surface model*

In these models, distance sampling is coupled with generalised additive models (GAM) to produce maps of whale densities (individuals km^2) predicted from environmental covariates (Miller et al. 2013). In distance sampling it is understood that not all animals are detected; rather the probability of observing an individual declines with increasing distance of the animal from an observer (Buckland et al. 2011). Thus, the first step of the analysis was to fit a probability density function to the distance data (measured distance from the observer to each whale sighting) thereby making it possible to obtain detection probabilities of observing whales. Whale counts were then summarised per continuous segment of survey transect and a GAM was fitted with the per segment counts as the response variable, where the counts (or segment areas) had been corrected for detectability using the probability density function fitted in the first step. This compensated for the proportion of animals missed by the observer (Miller et al. 2013). The explanatory variables in the GAM were environmental variables including water depth and derivatives such as slope and rugosity and sea surface temperature (SST) in order to determine what variables may influence whale spatial density.

Data from CWR aerial surveys during 2006, 2007 and 2008 and were used for density surface modelling (Fig. 1). Distance data were converted to meters (from nautical miles) and the distribution of data was both left and right truncated. Right truncation is commonly done to remove any distant sightings (Buckland et al. 2011), which in this case was defined as sightings at >9000 m from the observer. The data were also left truncated (to 200 m), as observers could not see directly under the plane (i.e. at distance 0). Distance data was binned prior to fitting a detection function at 200, 1500, 2500, 3500, 4500, 7000 and 9000 m from the observer. Different bin sizes were selected until a reasonable fit was obtained (determined by eye). We used the Distance Library (Miller 2017b) in R to undertake all distance analyses. The first step in constructing a model for the detection function is to choose a key function, which determines the basic model shape. There are four key functions available in Distance; uniform, half normal, hazard rate and negative exponential and these can be made more robust by adding a series of adjustment terms (cosine, hermite polynomial or simple polynomial). We tested hazard rate and half normal key functions with no adjustments and with second and third order cosine adjustments and assessed them using AIC – the model with the smallest AIC selected plus considering the principal of parsimony where models were equivalent (AICs within 2 points). We examined the effect of covariates recorded by the observers including group size, Beaufort sea state and sun glare on detection probability prior to fitting the detection functions. As we did not find strong relationships, but did identify some unpredicted effects (e.g. detectability decreased with increasing pod size) we did not fit detection functions with these covariates.

The second stage of the analysis split the survey transects into segments to summarise the counts per segment and correct for detectability. For each survey we iterated through the sequence of points along each transect and split each into approximately 10 km segments. This segment size was selected considering both the truncation distance and the spatial resolution of the environmental data. As these were computed along each continuous section in turn, the actual length could be slightly smaller or larger than 10 km.

We then fitted a generalised additive mixed model (GAMM), with abundance of humpback whales on each segment as the response variable (corrected for detectability using the detection function fitted above) and a range of physical covariates including sea surface temperature (SST), bathymetry (depth), seabed slope and seabed rugosity fitted as individual smooth terms as well as the bivariate smooth of latitude and longitude combined (similar to fitting an interaction between latitude and longitude). As all spatial calculations are done on metres, latitude and longitude were projected to metres with a Lambert Azimuthal Equal Area (LAEA) projection. The models were fit using the density surface package in R (Miller 2017a). The histogram of the slope values were highly skewed to the left and the values were thus log transformed after subtracting each slope value from the maximum slope (90) in order to normalise the data. Given that abundance changes over the course of the migratory season for humpback whales in the Kimberley, we also used date of the surveys (as a Julian day) as an explanatory variable in the models. We set year as a random effect in the models.

In order to understand how the spatial distribution changes over the course of the season, we not only analysed the complete data set, we also split the data into two blocks: 1) August (peak residency); and 2) September and October (egress from the Kimberley). It was not possible to model early season patterns (ingress into the Kimberley) as there were no aerial surveys in June and only limited data for July (2008 only).

The GAMMs were fitted using all possible combinations of the explanatory variables and a null model, using a Tweedy distribution for the response variable. The null model contained the bivariate smooth of latitude and longitude. Modelling all possible combinations allowed for the selection of the subset of predictors that best explained humpback whale abundance. The explanatory variables were modelled with a cubic regression spline with the basis dimension "k" restricted to 5 and a maximum model size of 4 terms to avoid overfitting. We tested for collinearity in the explanatory variables and rather than drop one of the collinear variables, we simply did not include a pair of variables in the same model if they were correlated above a threshold of 0.4 to avoid invalid results and predictions. The models were compared and ranked according to Akaike's information criterion, corrected for small sample size (AIC_c) and by their relative model weight, the AIC_c weight. The AIC_c weight varies from 0 (no support) to 1 (complete support) (Burnham & Anderson 2002). The amount of variance (percent deviance) in the response variable explained by each of the candidate models was used as a measure of goodness-of-fit to the data (Burnham & Anderson 2002). We produced and inspected model diagnostic plots of the top ranked model, including Q-Q plots of deviance residuals and plots of random quantile residuals against the linear predictor to assess the validity of the model and whether the underlying assumptions of the model had been met.

Sea surface temperature data were obtained using the Marine Geospatial Ecology Tools (MGET) for ArcGis10.3 (Roberts *et al.* 2010). Eight day averages of SSTs were generated by the Moderate Resolution Imaging Spectroradiometer (MODIS), Aqua satellite Level 3 with a 9 km resolution. Bathymetry data was obtained from the General Bathymetry Chart of the Oceans Gebco15 database in a 30 arc-second resolution grid (http://www.gebco.net). We also calculated seabed slope and rugosity from this data as a proxy of habitat complexity with ArcGis 10.3 using digital terrain analysis with fixed window sizes (Holmes *et al.* 2008) and a resolution of 1 km to match the bathymetry dataset. We obtained the covariate values for each of the segment centroids with the SST value obtained from the 8-day satellite image that coincided with the survey date. For model predictions bathymetric covariates were resampled to 9 km to match the spatial resolution of SST rasters.

Using the top ranked (by AIC) model, we then predicted density surfaces onto a 10 km grid of the covariates. This grid size was selected given the grid size of the covariates and that it is considered useful by end users. We produced abundance estimates by summing the abundance across the prediction grid, which was delineated as a minimum bounding box encompassing the total area surveyed. We also produced uncertainty estimates using the method described by (Miller et al. 2013) and implemented using the function `density surface.var.gam` in the `density surface` package (Miller 2017a).

Distance sampling assumes that the probability of detecting objects on the transect at distance 0 is 1 (Buckland et al. 2011). Unfortunately, cetacean surveys cannot often satisfy this assumption given the study animals dive and while submerged are not available to be detected ('availability bias'). In order to avoid this problem a correction factor was calculated following Barlow et al. (1988):

Probability of being visible = (s + t) / (s + d)

Where s represents the average amount of time a whale is on the surface (43 s), *d* represents the amount of time a whale is diving (270 s) and *t* represents the time window a whale can be seen during an aerial survey, when taking into account to range of vision and the speed of the aircraft. As the plane travelled at a speed of 120 knots, we calculated that a 120 second (*t*) time window would be necessary to travel 4 nm (Jenner & Jenner 2007b).

2.4.2 *Species distribution model*

The presence-only Maximum Entropy (MaxEnt) modelling approach (Phillips et al. 2006) was used for all other sightings data (Table 1). In order to understand how the distribution changed over the course of the season, we also split the data into three time blocks: 1) June and July (ingress to the Kimberley); 2) August (peak residency); and 3) September and October (egress from the Kimberley) and analysed these three time periods/migration phases separately. In addition, these analyses (full time period and monthly blocks) firstly included all whales (males, females and calves) and then were run on groups containing females and calves only, in order to determine if females with calves had specific habitat requirements.

The MaxEnt modelling approach compares the environment at occurrence (or, presence) localities to the environment at background localities. As there was no true absence data, the MaxEnt approach sampled random points from a background extent (Phillips et al. 2006). The background extent and subsequent model outputs were confined to within 150 km from shore (as sampling and observations from those locations were rare and may not have accurately represented whale occurrence in those habitats), within which 5000 background points were sampled randomly. This presence-only modelling approach included assumptions that sampling within the model extent was relatively structured and that detection probability of whales during the surveys was constant. Care must be taken when interpreting outputs of presence-only models, however only overlapping areas that were consistently sampled were used in the analysis and pre-processing of occurrence points and selection of pseudo-absence positions were conducted to account for sampling biases. Sampling biases in the covariate space were accounted for by pooling occurrence points within each raster pixel, whereas in geographic space, sampling biases were accounted for by selecting pseudo-absences only within the convex hull of occurrence data for each monthly dataset. We used the same set of environmental/biophysical explanatory variables as for the density surface models but with distance from coast and relative distance along shore (south to north) in place of the bivariate smooth on latitude and longitude used in the density surface model. Relative distance along shore ranged from 0 at the southern extent of the model extent to 1 at the northern extent, and was calculated by dividing the distance of each raster pixel to the northernmost point in the extent divided by the sum of distances to the northernmost and southernmost points in the extent (Fabricius & De'ath 2000). We tested for collinearity between the environmental variables as before but with a threshold of 0.7.

The R library `ENMeval`(Muscarella et al. 2017) was used for the species distribution modelling. Specifically, the function ENMevaluate function (Muscarella et al. 2017) was used to construct and tune MaxEnt models by testing all possible combinations of feature classes (determines the potential shape of the response curves) and regularization multipliers (determines the penalty for adding parameters to the model). The model with the best combination of settings was selected on the basis of lowest AICc score and the principal of parsimony.

We used a random 5-fold cross validation method by dividing occurrence and background data into training and 4 testing sets and evaluating each testing set with the trained model. Model performance was evaluated by calculating AUC score based on probability of true presence (for each of the 4 testing sets) falling on model predictions, reported as mean and variance of AUC between the 5 cross validations. The AUC ranges from 0 to 1, with an AUC of 0.5 indicating that model performance is equal to that of a random prediction and 1 indicating perfect discrimination between suitable and non-suitable habitat. We also calculated other evaluation indices including Cohen’s kappa statistic (Kappa) and a True Skill Statistic (TSS). The output of the models is a habitat suitability value for each grid cell (0.01 degree; ~1 km) within the extent (Kimberley region). We also used ‘thresholding’ to convert the continuous (0-1) suitability scale to binary (important/non-important habitats) using the kappa statistic to identify the threshold for each model. The process of ‘thresholding’ considers all output raster pixels with predicted probabilities above the maximum kappa threshold as areas that are statistically suitable habitats (given the occurrence data and MaxEnt output). Thresholding allows for an easier interpretation of predicted outputs and identifies locations of high importance to the modelled species.

2.4.3 *Humpback whale movement behaviour*

The Bayesian state-space switching model developed by Jonsen et al. (Jonsen et al. 2003, Jonsen et al. 2005) was fitted to the ARGOS locations received for each individual whale to account for position error and to provide a classification of the behavioural state of the animals. Briefly, the position error was modelled with the observation equation (assuming *t*-distributed error, with associated variance and degrees of freedom) and behavioural state (transient or resident) was inferred from the autocorrelation to the previous displacement and turn angle. The resident state has low autocorrelation to the previous displacement and high turn angles and the transient state has high autocorrelation to the previous displacement & low or near zero turning angles (directed movement - see Jonsen et al. 2005 for more details). Resident behaviour is commonly associated with resting or breeding (Bailey et al. 2008, Bailey et al. 2009) and also foraging (Kareiva & Odell 1987). This approach is useful as it provides a statistically rigorous approach for the determination of hidden behavioural states underlying animal tracks (Jonsen et al. 2013); (See Costa et al. 2012 for a useful review). The observation error modelled for each ARGOS location estimate was as per the reported (by Argos) error associated with each ARGOS location class (Z, B, A, 0, 1, 2, 3). The first three classes have no accuracy information assigned by Argos and the remaining classes have reported accuracy >1500 m, 500 m < < 1500 m, 250 m < < 500 m, < 250 m respectively. However, accuracy had been measured on marine mammals at 10.3 km and 6.2 km for class B and A and 4.2 km, 1.2 km, 1.0 km and 0.49 km respectively for the remaining classes (Costa et al. 2010). The state-space switching models were fitted via Markov Chain Monte-Carlo (MCMC) implemented in JAGS 3.2.0 (Plummer 2003) called from R: A Language and Environment for Statistical Computing (R Core Team 2017) using the R package, bsam (Jonsen et al. 2013). We ran two MCMC chains of length 120 000, of which the initial 80 000 were discarded, and every 40th of the remaining samples were retained. We used a 6 hour time step for all animals, giving 4 location estimates per day. All models were checked for convergence using the methods outlined by Jonsen et al. (2013).

Using the raw Argos location data we also calculated time spent in a pre-defined grid of each of 10 x 10 km to determine which areas had the highest use both for all whales and for each individual.

3 Results

We compiled 29 survey and 3 satellite tracking datasets from 6 research groups, spanning three decades and encompassing 13 years of sampling, 691 sample days and 18,031 observations of humpback whales (Table 1). Three survey datasets (aerial surveys from CWR from 2006, 2007 and 2008) had the inputs needed for density surface modelling and the others were analysed using MaxEnt. The reason for this was that for many of the surveys (see Table 1), the inputs required for density surface modelling were not provided/collected (e.g. survey paths and distance measurements) or that there was uneven survey coverage across the area known to be used by humpback whales in the Kimberley (most of the RPS/Woodside data) (Table 1). This uneven coverage occurred because the RPS/Woodside surveys were designed to document megafauna distributions around the site of a proposed industrial development (James Price Point gas processing plant) rather than for the purpose of describing broad-scale patterns in abundance across the Kimberley.

3.1 Density surface model

For the data where density surface models could be fitted, the surveys ranged from Julian day 201 (19th July) to 293 (19th October). The detection function with the hazard-rate key function with cosine adjustment term of order 2 had the smallest AIC (Fig. 2).The generalised additive mixed model with the bivariate smooth on latitude and longitude, depth and Julian day had majority support (67% AIC and 99% BIC) and explained 31% of the deviance (Table 3). Relationships between the covariates in this model and abundance are illustrated via plots of marginal smooths shown in Figure 3. Humpback whale abundance was quite variable in the deeper depths (around -80 m), with a peak around -35m and declining in waters shallower than -25 m (Fig. 3a). Whale abundance peaked around Julian day 224 - 228 (mid-August), initially declining slowly to around Julian day 260 (mid-September) and then more rapidly after this time (Fig. 3b). Figure 3c shows the influence of the spatial smooth (note that as the plot is on the scale of the link function, the offset is not taken into account and the contour values do not represent abundance, just the “influence” of the smooth). Predicted abundance of humpback whales increased with sampling year (Fig. 3d), although this is probably related to spatial and temporal differences in sampling rather than population increase (Fig. 1).

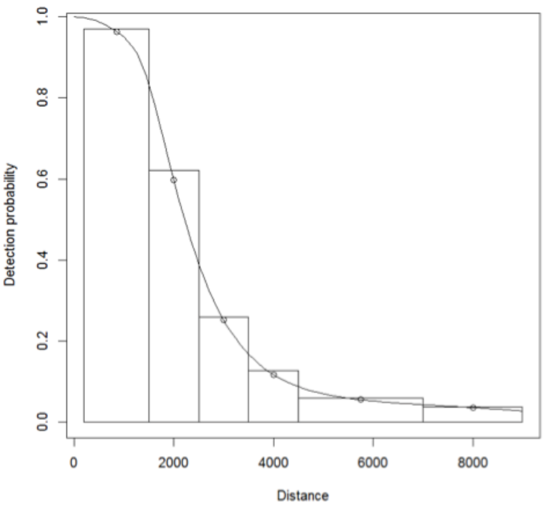

Figure 2. Fitted detection function for pooled CWR aerial survey data showing a hazard-rate key function with cosine adjustment term of order 2.

Table 3. Ranked (by AICc) additive mixed models of humpback whale abundance explained by depth, Julian day (jday), rugosity, slope and the random effect of year. Shown are Akaike's information criterion corrected for small samples (AIC_c), Bayesian information criterion (BIC) change in AIC_c and BIC relative to the top-ranked model (ΔAIC_c, ΔBIC), AIC_c and BIC weights (*w*AIC_c, *w*BIC) and the percent deviance explained (%De). Only the top 6 models are shown, in addition to the null model which contained the bivariate smooth of latitude and longitude (spatial smooth).

Model	**AICc**	**BIC**	**ΔAICc**	**ΔBIC**	***w*AICc**	***w*BIC**	**%De**
All data							
Depth + jday	7919.71	8155.05	0	0	0.67	0.99	0.31
Depth + rugosity + jday	7921.49	8164.00	1.78	8.95	0.28	0.01	0.31
Depth + slope + jday	7925.71	8181.41	6.01	26.36	0.03	0.00	0.31
Depth + rugosity + slope + jday	7926.50	8187.94	6.79	32.88	0.02	0.00	0.31
jday	7958.97	8171.36	39.26	16.31	0.00	0.00	0.29
Slope + jday	7960.97	8179.65	41.26	24.59	0.00	0.00	0.29
null	8242.81	8429.92	323.10	274.87	0.00	0.00	0.21
August data							
SST	3862.135	4042.878	0	10.977	0.26	0.004	0.29
Depth + jday	3862.603	4043.135	0.468	11.234	0.206	0.003	0.289
Depth	3862.627	4037.753	0.492	5.852	0.203	0.046	0.288
Slope + SST	3864.256	4050.352	2.121	18.451	0.09	0	0.29
SST + jday	3864.414	4052.716	2.278	20.815	0.083	0	0.29
Slope + SST + jday	3865.901	4057.902	3.766	26.001	0.04	0	0.29
null	3873.729	4031.901	11.594	0	0.001	0.868	0.279
September and October data							
Depth + jday	3639.392	3831.878	0	2.846	0.511	0.185	0.39
Depth + rugosity + jday	3640.869	3839.077	1.477	10.045	0.244	0.005	0.391
Depth + slope + jday	3641.688	3839.664	2.295	10.632	0.162	0.004	0.39
Depth + rugosity + slope + jday	3643.05	3846.107	3.658	17.074	0.082	0	0.39
jday	3657.464	3829.032	18.072	0	0	0.769	0.374
Slope + jday	3659.438	3836.07	20.046	7.038	0	0.023	0.374
null	3853.358	4002.909	213.966	173.877	0	0	0.237

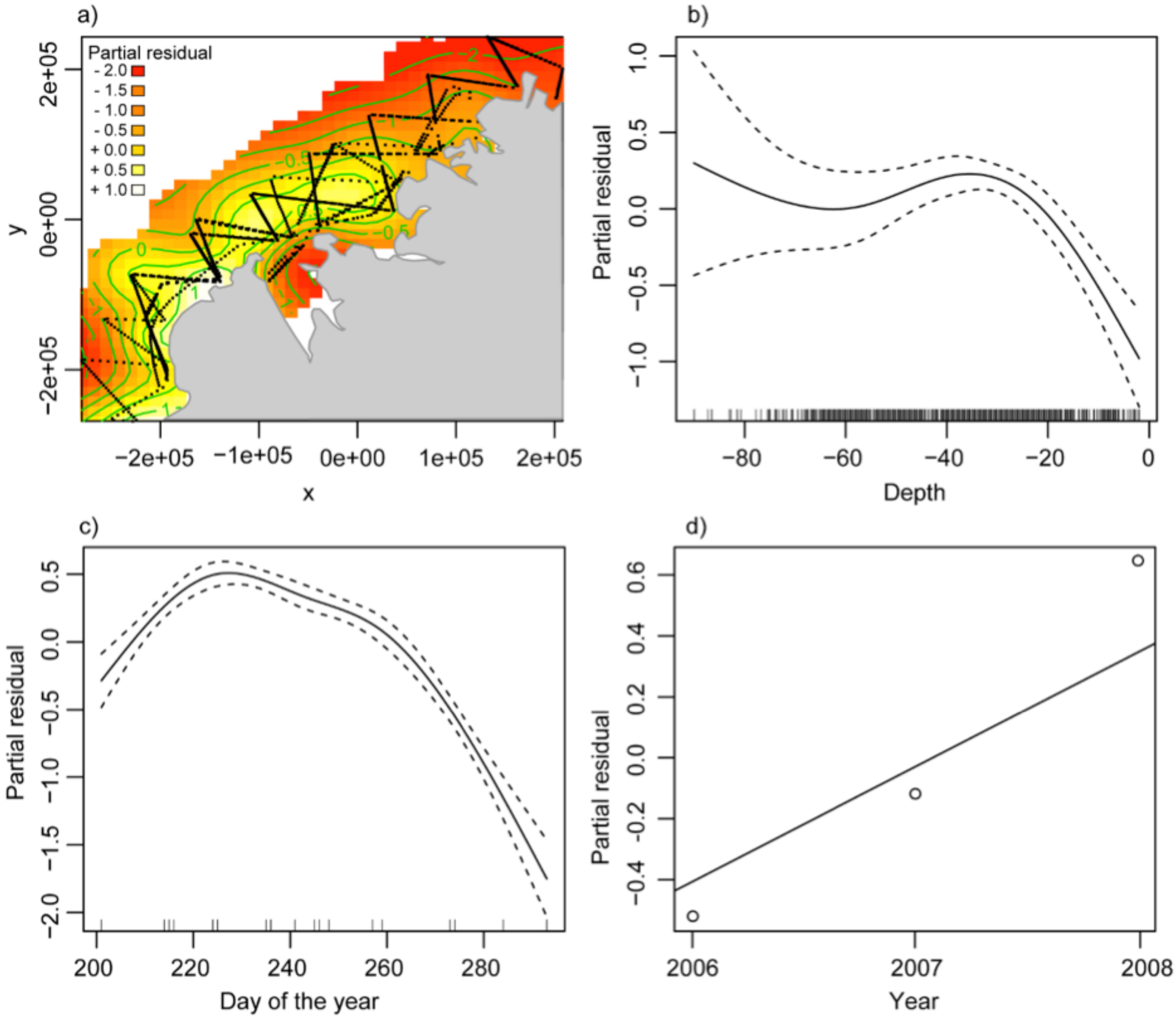

Figure 3. Marginal smooths of the relationships between the covariates in the top ranked model and humpback whale abundance, showing the spatial smooth (a), depth (b), day of the year (c) and the random effect of year (d).

The predicted spatial density of whales for early, mid and late season for all data averaged over the three years is plotted in figure 4a and shows that humpback whale density was highest at Pender Bay. Note that as we did not allow an interaction term with day of the year in the model (because of unequal temporal and spatial sampling effort), the pattern in density did not change with each of these time periods, only the abundance estimate (shown in the multiple legends in Fig. 4a). Using the top ranked model, abundance was predicted on one day for every 2 weeks of the 2007 season (the year with the most representative sampling effort) and is presented in table 4 with the abundance estimates also corrected for availability bias. These two weekly point estimates, were summed to provide a representation of the total number of humpback whales (9558 corrected) using the study region during the time period mid-Jul to mid-Oct. It has been assumed that the average length of stay for a whale in the Kimberley region is approximately 1-2 weeks, based on mark-recapture photo-id data from 35 whales in this area in the mid-late 1990's (Jenner and Jenner, unpubl. data).

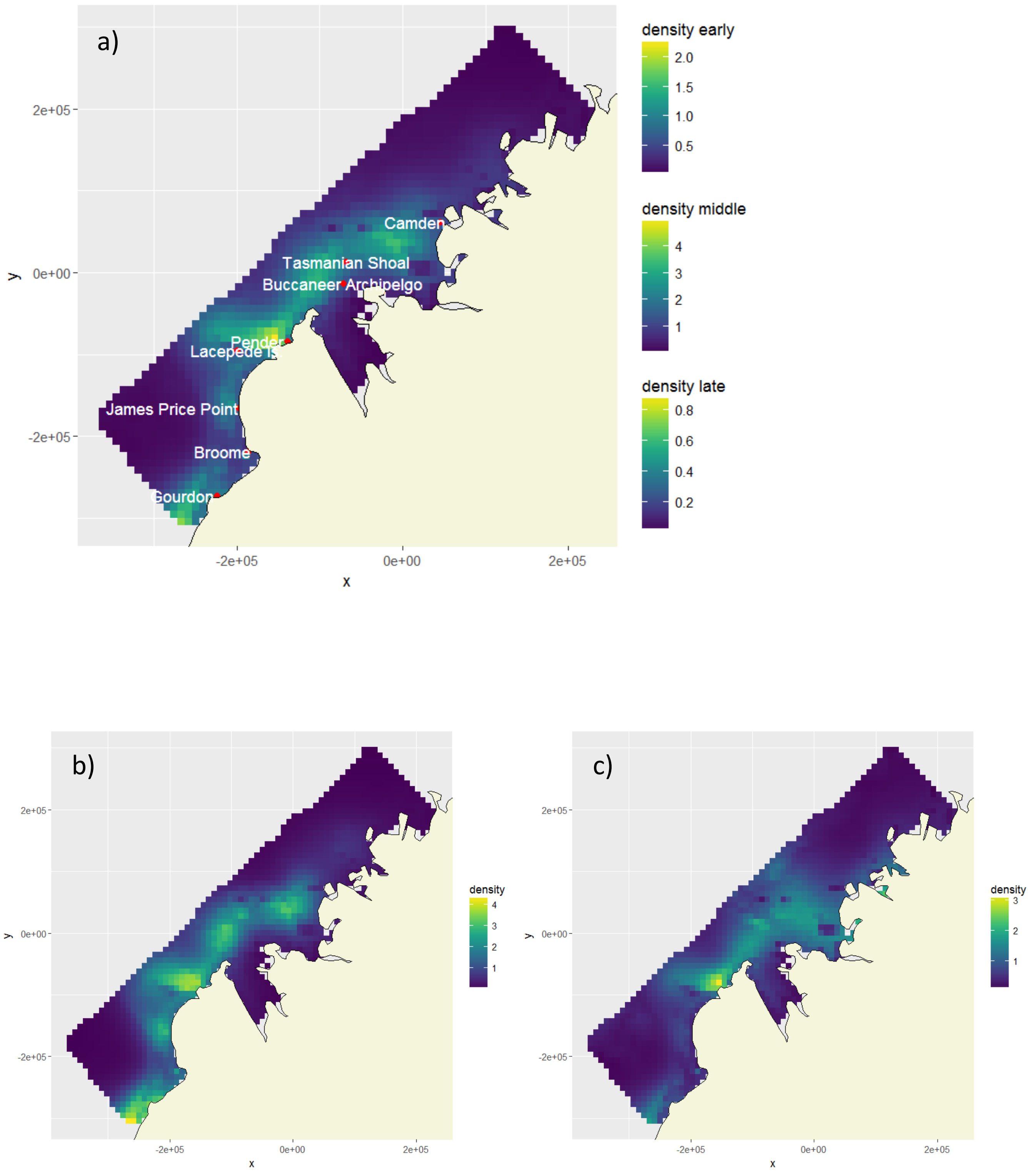

Figure 4. Predicted density (from the top ranked model) of humpback whales averaged across all three years across the full migratory season and with scale bar for peak (middle), early and late season (a) (note that this model could not allow for the spatial distribution to change seasonally, only for density to change seasonally). Locations of place names are denoted with red points. Shown in (b) is the predicted density when the model was run on August data only and September and October only (c). X and y coordinates are in LAEA projection.

Table 4. Abundance estimates (Nhat) from the top ranked model for each 2 week block through the humpback whale season for 2007. Last 3 columns show abundance estimates corrected for availability bias (abundance estimate × 1.92).

					Corrected abundance estimate		
Julian day	**Date**	**Lower CI**	**Nhat**	**Upper CI**	**Lower CI**	**Nhat**	**Upper CI**
201	19/07	405.66	515.54	655.19	778.87	989.84	1257.97
215	02/08	807.65	922.25	1053.11	1550.69	1770.72	2021.97
229	16/08	1000.47	1136.39	1290.76	1920.90	2181.87	2478.26
243	30/08	821.09	956.24	1113.63	1576.49	1835.98	2138.17
257	13/09	673.05	781.22	906.78	1292.26	1499.94	1741.02
271	27/09	395.63	463.28	542.49	759.61	889.50	1041.58
285	11/10	161.85	203.16	255.01	310.75	390.07	489.62
Total		**4265.4**	**4978.08**	**5816.97**	**8189.568**	**9557.914**	**11168.58**

For the August data no single generalised additive mixed model had majority support according to AICc with three all within 2 AICc points (Table 3). The model with SST had the most support, with a weight of 26% (wAICc = 0.26) and the model with depth and Julian day next (as with the model with all data combined) followed by the model with depth alone (Table 3). However, BIC favoured the null model, which included the bivariate smooth of latitude and longitude. As this model accounted for the majority of the deviance explained (28%) and the addition of SST only accounted for another 1% thus it would seem that the relationship was driven predominantly by the former predictor and SST is only a weak driver of humpback whale abundance. Humpback abundance increased with SST up to about 24°C and then became variable with higher temperatures (Fig. 5). The model predicted 1134 whales (lower CI = 983.19, upper CI = 1309.08) for a snapshot in time in August (Fig. 4b).

For the September and October data the results were the same as for the fitted model when all data were combined with the model with the bivariate smooth of latitude and longitude, depth and Julian day having majority support (51% AICc) and explaining 39% of the deviance (Table 3). However, as above, the BIC did not support the same model as AICc with the model with the bivariate smooth of latitude and longitude and Julian day only having majority support. This shows that Julian day and the spatial smooth explained most of the variation in humpback whale abundance with depth only a minor contributor. The model predicted 1134 whales (lower CI = 525.54, upper CI = 810.97) for day 257 (mid- September) (Fig. 4c).

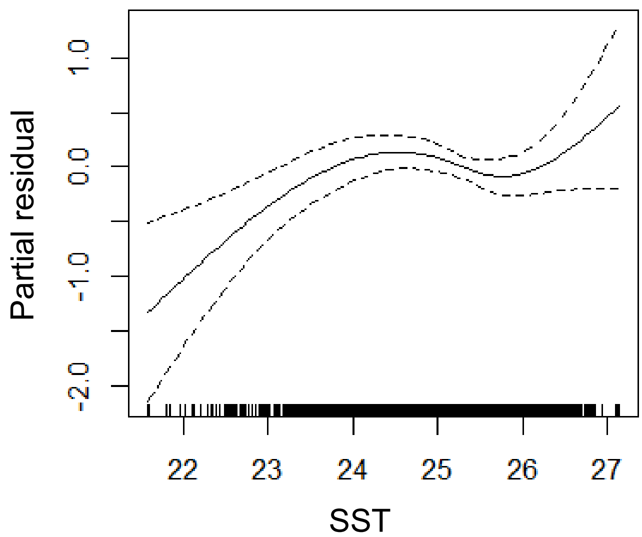

Figure 5. Marginal smooth of the relationships between SST and humpback whale abundance in August.

3.2 Species distribution model

Distance to Coast and Depth were still correlated at 0.7 but they were left in as they both had varying degrees of contribution to the resulting Maxent models and provided meaningful response curves. When all months were combined, the most influential environmental/biophysical predictor of habitat suitability for humpback whales in the Kimberley was distance to coast both for all whales (Fig. 6a) and for females with calves (Fig. 6b). The same predictor emerged for the analysis of the data split into months of sampling (Fig. 6). For pods containing females and calves the percentage contribution of distance to coast was slightly lower in August, with SST making up the difference (Fig. 6b). Probability of presence dropped rapidly as distance to coast increased, with a more rapid decline for pods with females and calves (Fig. 7). During August, probability of presence of all whales and females with calves declined sharply when SSTs were greater than approx. 26°C (Fig. 8a&b). Spatial predictions are shown in Figures 9 and 10. For all whales and for groups containing females and calves only we found a seasonal shift in habitat suitability, which was lower at Camden Sound in June and July (Fig. 9 and 10b) and September and October (Fig. 9 and 10 d) than in other months (Fig. 9b and c). When data sets from all months were pooled, there were three main areas where habitat suitability was highest – the coast of the Dampier Peninsula, Tasmanian Shoals and Camden Sound (Fig. 9 and 10a). The Tasmanian Shoal area was not as important for groups containing females and calves (Fig. 10a). This pattern was more obvious when we converted continuous (0-1) SDM output (habitat suitability) to a binary scale (suitable and unsuitable) using the application of the thresholding method. Although this process results in loss of spatial information and is dependent on the threshold selected (Wilson 2011), it is useful in this context of assessing the difference in habitat use between the two groups. Groups with females and calves preferred habitat closer to the coast at Pender Bay and along the Dampier Peninsula between Pender Bay and Broome, whereas when data for all groups were pooled, suitable habitat extended further from shore and included a much larger area in Tasmanian Shoal and Camden Sound (Fig. 11). Model evaluation showed that the model performed relatively well (Table 5). All models had high mean AUC scores with low AUC variance, high TSS scores indicating predicted probabilities from tuned models fit well with testing datasets, denoting a reliable prediction based on occurrence datasets.

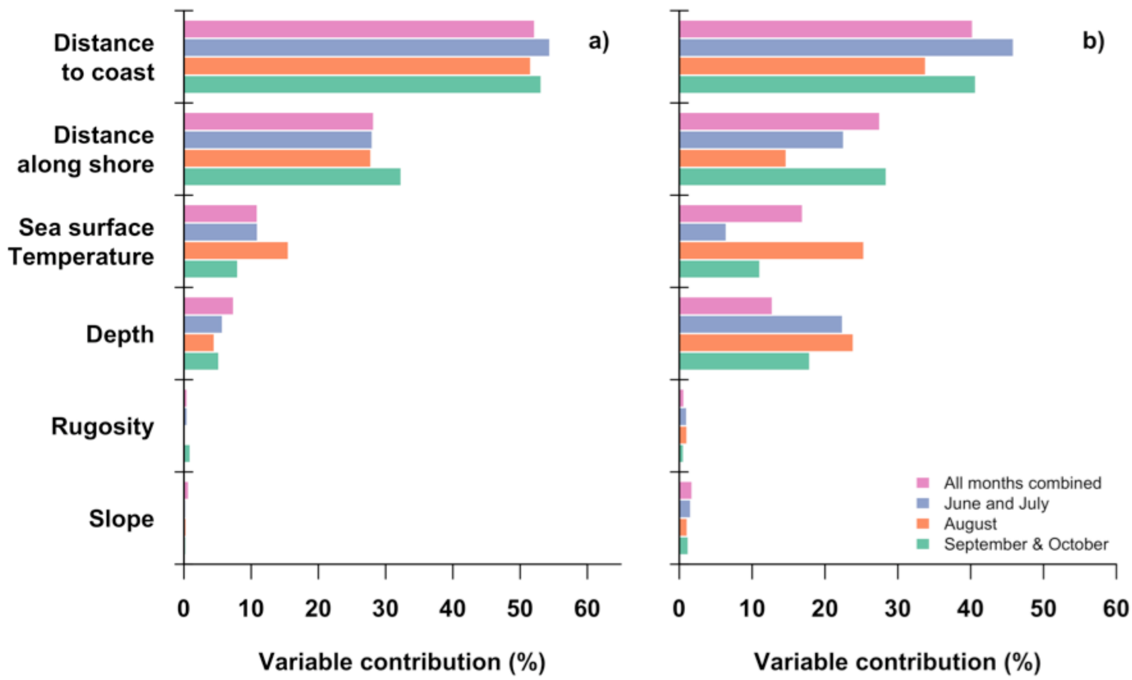

Figure 6. Variable contribution scores from the MaxEnt model on all months combined and each of the three monthly datasets for all whale groups combined (a) and groups with females and calves only (b).

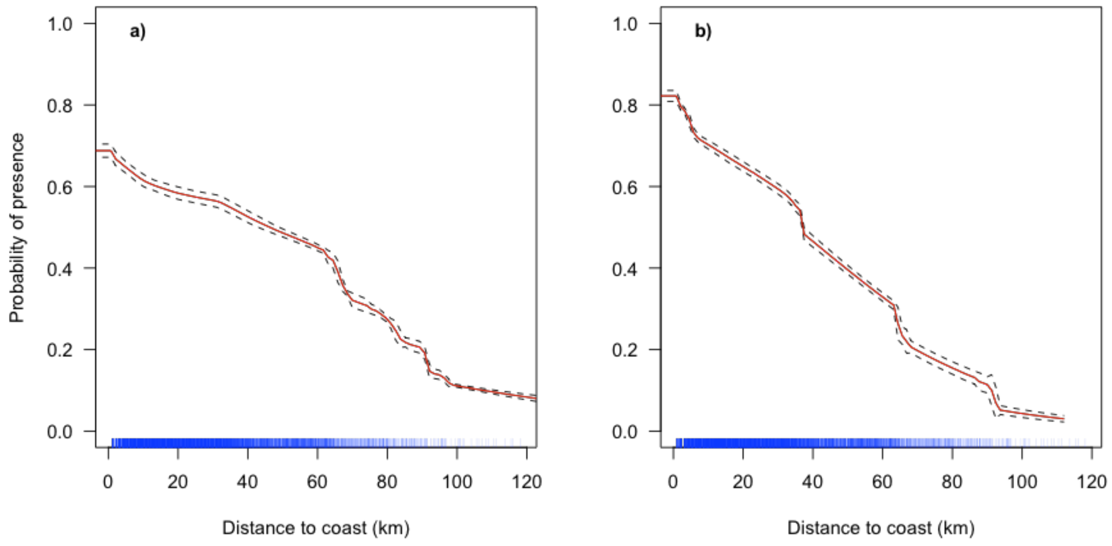

Figure 7. Maxent model response curves for each of the top predictor (distance to coast) in the model for all whale groups for all months combined (a) and for pods with females and calves only for all months combined (b). Response curves represent the change in probability of presence in chosen predictor variable while all other variables are kept at median values.

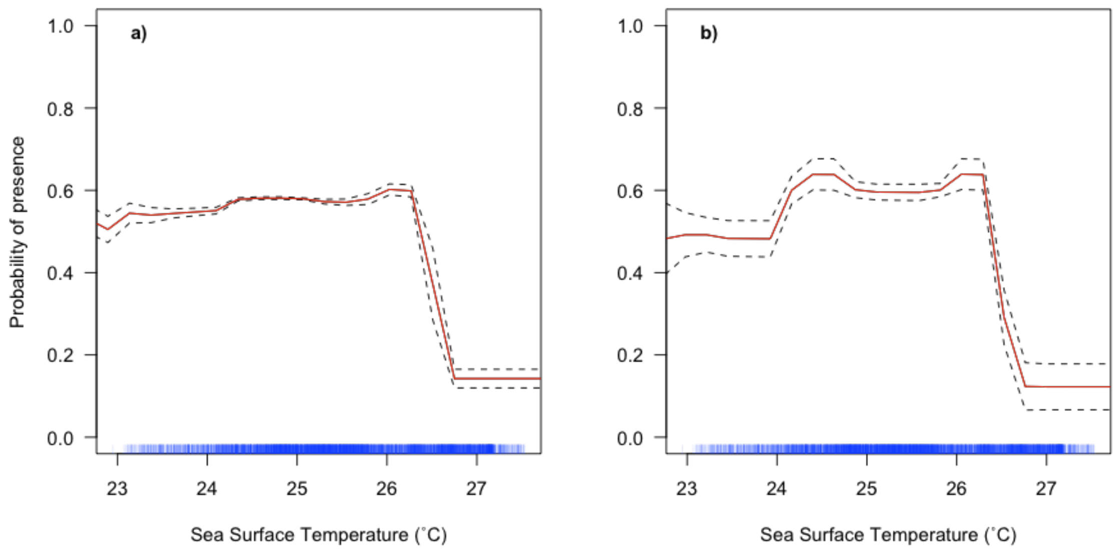

Figure 8. MaxEnt model response curves for SST in August for whale pods combined (a) and pods with females and calves (b). Response curves represent the change in probability of presence in chosen predictor variable while all other variables are kept at median values.

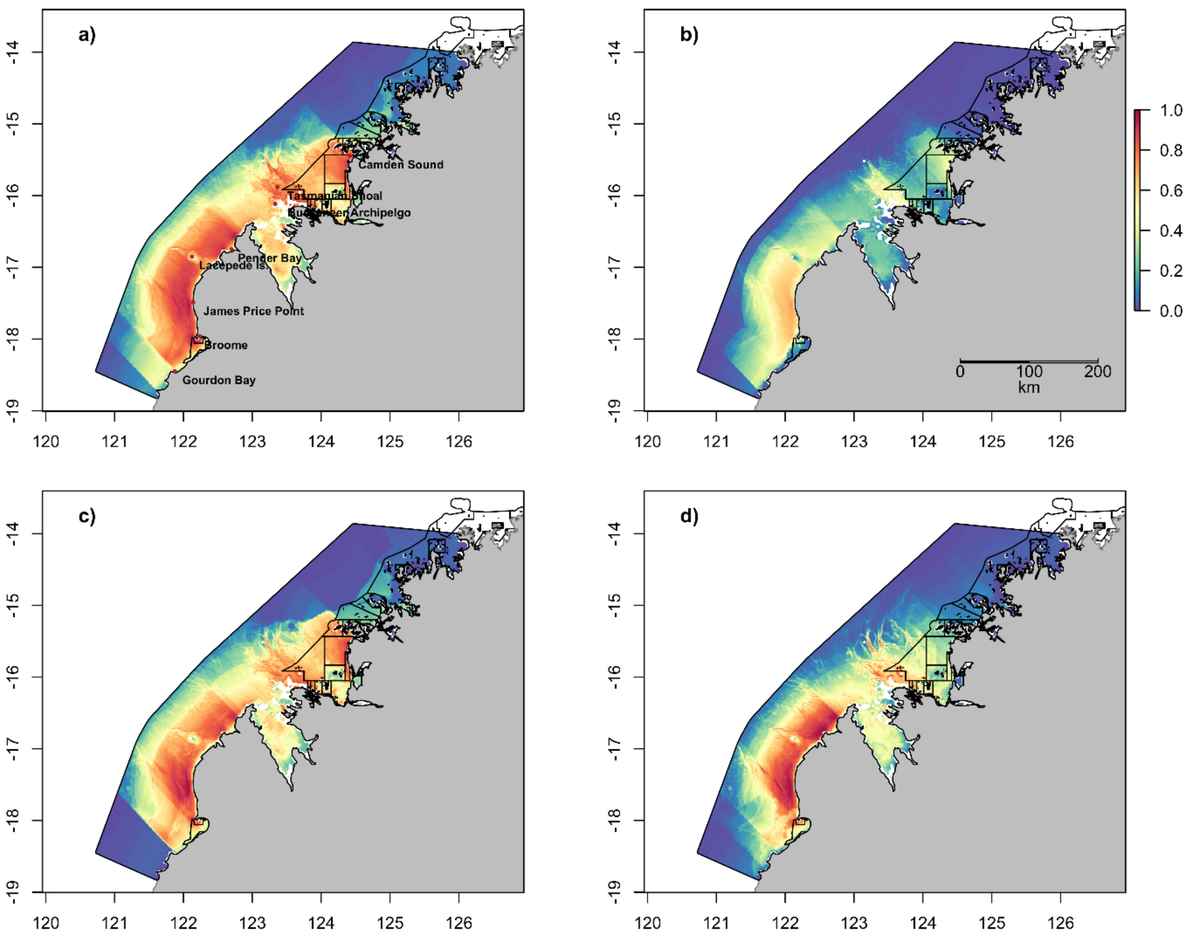

Figure 9. MaxEnt model output (clog-log representation) showing habitat suitability for all whale groups in all months combined (a), June and July (b), August (c) and September and October (d). Black lines show the State of Western Australia's Kimberley Marine Parks. See appendix 1 for the names of each of the parks.

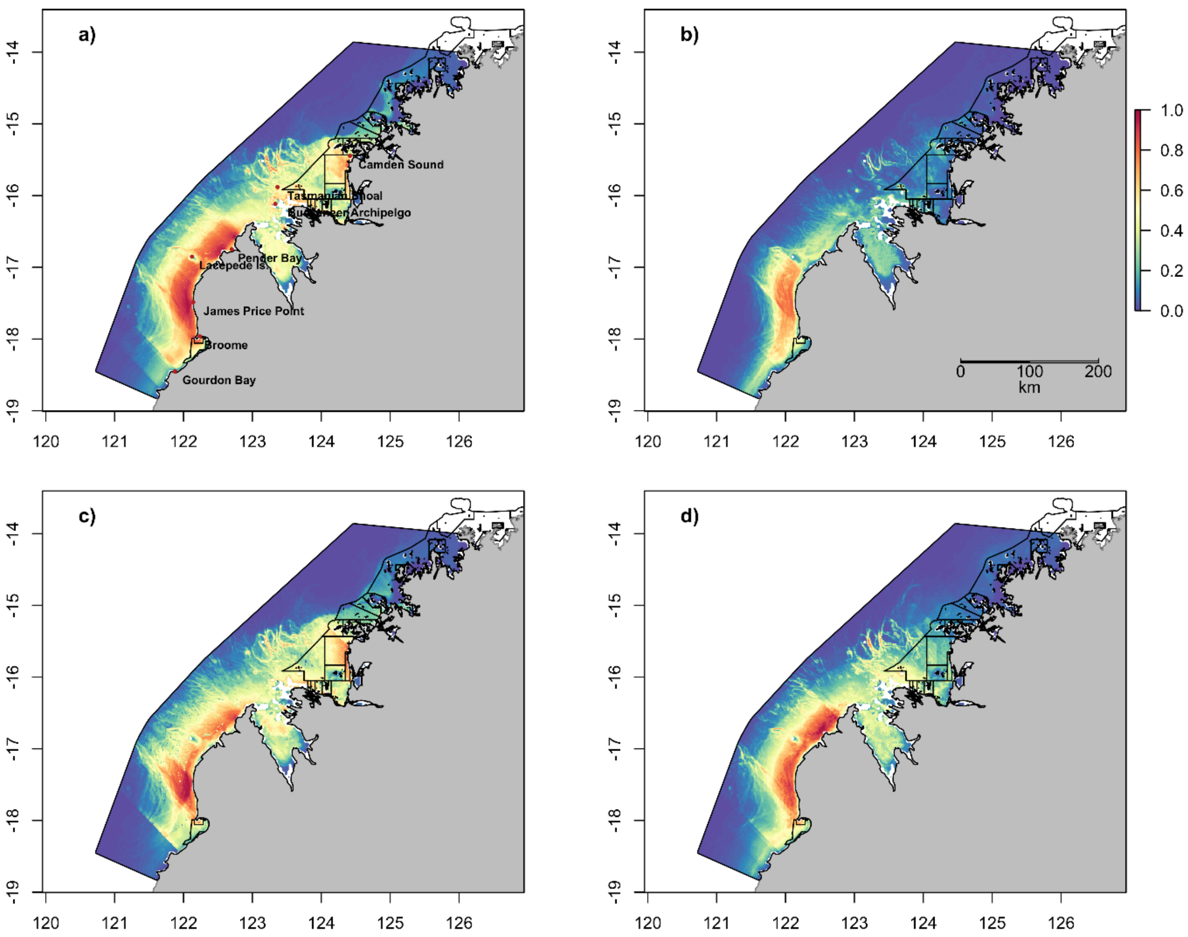

Figure 10. MaxEnt model output (clog-log representations) showing habitat suitability for females and calves in all months combined (a), June and July (b), August (c) and September and October (d). See caption for Fig. 9 for further details

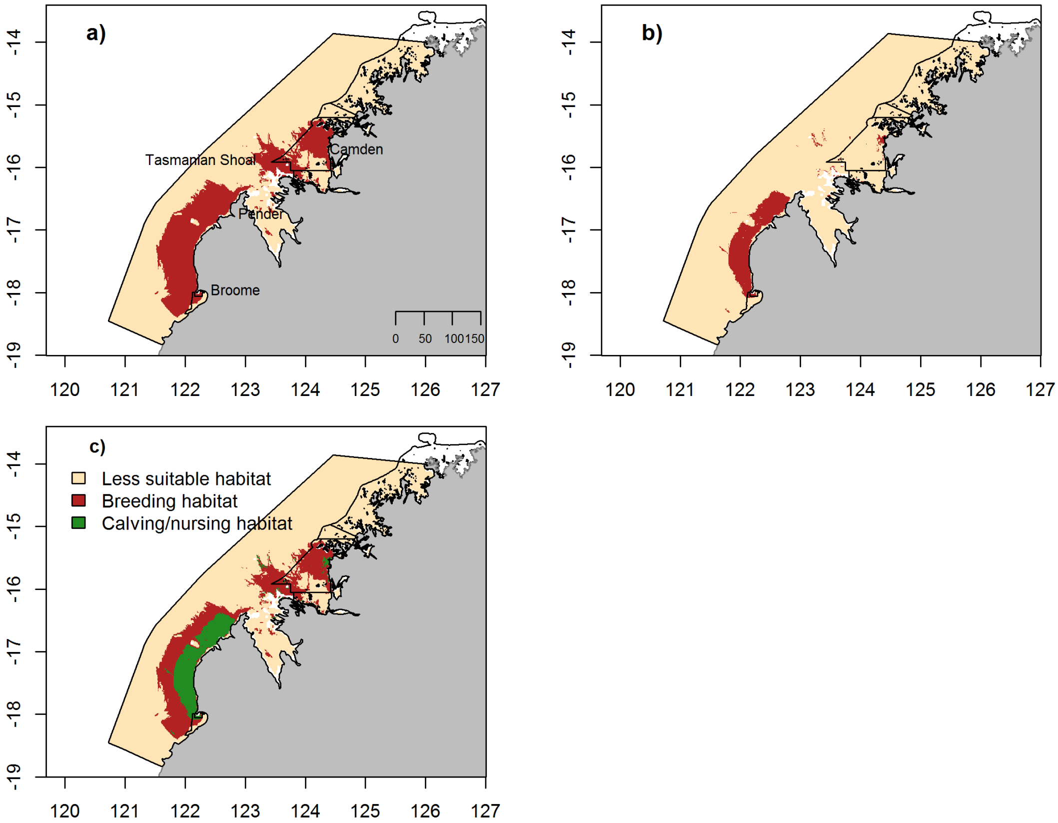

Figure 11. Model estimated suitable and unsuitable habitat mapped for all observations (a), groups containing females and calves (b) and the overlap between these two (c). Thresholding of models were conducted using maximum kappa threshold for all models. See caption for Fig. 9 for further details

Table 5. Model evaluation results. AUC = area under the curve.

	AUC_{mean} ± AUC_{var}	**Kappa**	**True Skill Statistic**
All groups			
All months	0.89 ± 0.01	0.53	0.61
June and July	0.92 ± $2x10^{-2}$	0.49	0.70
August	0.88 ± 0.01	0.46	0.59
Sept and Oct	0.89 ± 0.01	0.46	0.63
Cow-calf groups			
All months	0.88 ± 0.01	0.35	0.59
June and July	0.90 ± 0.04	0.47	0.70
August	0.87 ± 0.02	0.46	0.57
Sept and Oct	0.89 ± $4x10^{-2}$	0.37	0.61

3.3 Humpback whale movement behaviour

The results from the state-space switching model applied to the satellite tracking data for individual whales showed that while in the Kimberley region, humpback whales were almost always in resident mode, i.e. not migrating. Even though some short, transitory movements appeared to be visible in the tracks (e.g. from Camden Sound to Tasmanian Shoal and Pender Bay), the model did not identify a switch in behaviour, which matches with expectations, given that the animals use the area for breeding. However, most of the tracks were very short (median = 13 d, table 2), so that a switch in behaviours between resident and transient modes may have been harder to detect. Only two whales showed a switch to transient mode (96382 and 96389 from 2009), with each of these having deployment durations of 60 and 33 days respectively. This switch occurred around Exmouth and at the end of Eighty Mile Beach respectively. A total of 15 of the individual tracks were too short and some had gaps in the data, resulting in failures of the state-space model. For this reason, we used the raw location data in the analysis of time spent per grid cell (Fig. 12). Northbound whales used areas further from shore (69 ± 71 km) (Fig. 12a) than southbound whales (36 ± 31 km) (Fig. 12 b). When examining the histogram of distances to shore (Fig. A2), northbound whales had a much larger range, and appeared to have two modes; the main one around 30 km and a second smaller one around 225 km (Fig. A2). The most heavily-used areas in the Kimberley region on the northward migration were James Price Point, offshore of the southern part of the Dampier Peninsula and Tasmanian Shoal (Fig. 12a) and Pender Bay and the norther part of the Dampier Peninsula on the southward migration (Fig. 12b). For both migrations Eighty Mile Beach also had some residency (Fig. 12).

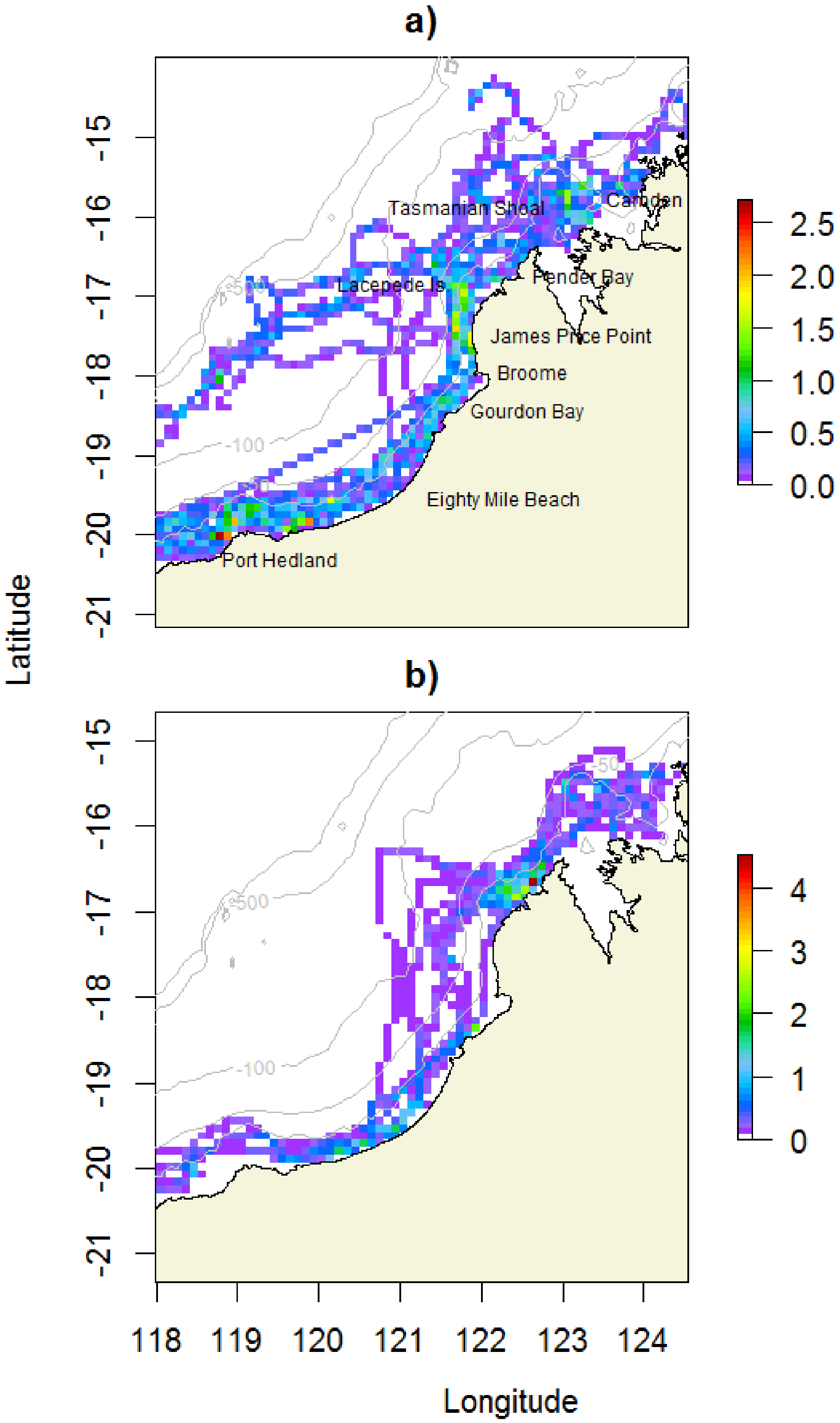

Figure 12. Number of days spent by northbound (a) and southbound (b) humpback whales per 10 km × 10 km grid cell, calculated from raw Argos location data from tagged humpback whales from 2008, 2009 and 2011. Grey lines show the 25 m, 50 m, 100 m, 500 m and 1000 m depth contours. Note that only the Kimberley region is shown, even though time spent was calculated across the whole spatial extent.

4 Discussion

Our analysis of all available survey data for humpback whales across the nearshore waters of the Kimberley region quantified seasonal shifts in abundance and habitat suitability and revealed the importance of inshore areas for females and calves. Importantly, the spatio-temporal distribution maps produced by the analysis will be useful for evaluation of the potential effects of current and proposed human activities on humpback whales in the Kimberley.

Three of the aerial survey datasets were collected with estimation of long-term (multi-year) density distributions as an objective and had the inputs needed for density surface modelling. These data are now almost ten years old and, given a population increase estimated to be in the order of 11% per year (Salgado-Kent et al. 2012), it is likely that current abundance would be higher than the abundance estimates calculated here. However, relative patterns in density among areas will still be useful. The top predictors of abundance were depth and day of year, with the model predicting numbers to increase up to mid-August and to peak in waters around 35 m depth and decline in waters shallower than 25 m. Similarly, humpback whales on the Great Barrier Reef also had a preference for waters between 30-58 m deep (Smith et al. 2012). The decline in abundance in the Kimberley after mid-August concurs with whaling data, which suggests that at this time most animals are migrating out of the breeding grounds (Chittleborough 1965). The model also predicted an increasing trend in abundance with survey year, although spatial and temporal survey effort increased with year so this almost certainly affected this result, as predicted abundances were much greater (up to 40%) than previously reported (11% per annum). The trend is however still consistent with that reported for this increasing population of humpback whales (Salgado-Kent et al. 2012). Our total abundance estimate for the season (~10,000) was much less than the ~30,000 for the total WA population. While there is evidence to suggest that whales calve in other areas along the coastline and do not all travel to the Kimberley (Irvine et al. 2017), it is important to note that our abundance estimates were only for the surveyed region which did not include the entire area used by humpbacks in the Kimberley. The satellite tracking data (and the surveys to Scott Reef) show that the whales occupy a much larger area of the Kimberley than was surveyed by plane and used in the density surface models and given that the season might start in mid-June (Blake et al. 2011) and extend to mid-November but might differ in timing among years by three weeks (Jenner et al. 2001) our estimates (calculated from mid-July to mid-October) are most certainly an underestimate. In addition, our season abundance estimate was based on the assumption that the average length of stay in the Kimberley is two weeks (calculated from mark-recapture from photo ID of 35 whales in the Kimberley). However as there is likely to be variation in the length of stay among sexes and classes of whales (Jenner & Jenner 2007b), our whole of season estimate will further be under-estimated if whales stay less than two weeks.

The abundance model using all data combined identified Pender Bay as a principal core area of habitat for humpback whales, although other areas such as Camden Sound, the Buccaneer Archipelago/Tasmanian Shoals region and Gourdon Bay were also important. When the data for August and for September/October were analysed separately it was possible to detect a seasonal shift in abundance with Camden Sound, Gourdon Bay and the Tasmanian Shoal areas more important in August than in September and October. Interestingly, Gourdon Bay is at the southern end of the survey region so it might be expected that it would be more important later in the season than August, however this was also reported by Jenner and Jenner (2009). Pender Bay became the principal core area in the latter months of September and October. Although these areas have all been previously identified as important (Jenner et al. 2001), our models have quantified their relative importance. This seasonal shift matches the previously reported migration pattern (Chittleborough 1965, Dawbin 1997) whereby mothers and calves are reported to be at the rear of the migration and by the time calves appear in August, much of the non-calving population have already started heading south. As Camden Sound is at the northern extent of the migration for this humpback population (Jenner et al. 2001) it starts to 'empty out' before the more southern locations.

Distance to coast was the most important predictor of habitat suitability for humpback whales, with the majority of individuals sighted within 20-40 km of the coast. This behaviour may offer both respite from the strong tidal currents of the Kimberley and assistance with swimming, and might be especially important for an animal living on a fixed energy budget (humpbacks do not feed during the migration). Distance to coast was also important for abundance patterns of humpback whales on the Great Barrier Reef (Smith et al. 2012), although depth and SST were more important as determinants of distribution on the east coast than the west. Off the Kimberley, SST was only important in August, with whales displaying a preference for temperatures around 24.5 and 26.5ºC, within the range of temperatures (21 - 28ºC) reported for the species worldwide (Rasmussen et al. 2007). This coincides with the peak of parturition (early August) for this population (Chittleborough 1958) and both models (abundance and presence/absence models) showed Camden Sound, an area considered a major calving ground (Jenner et al. 2001), as important during this month. Perhaps the combination of slower tidal currents as evidenced by generally lower turbidity (Fig. A3) mentioned above and the consequent higher water temperatures make Camden Sound an ideal calving ground. Camden Sound is also an important area for all groups in August, not just groups with caves. Mature males also likely to concentrate here since there is an aggregation of successful breeding females in August, particularly since some of these female whales may come into post-partum oestrus.

Sea surface temperature did not emerge as an important predictor of abundance of humpback whales (density surface models) when all data were combined, however when Julian day was not included as a predictor in the models, SST did emerge in the top model. Given that the addition of Julian day forced SST to be dropped from the top model, it suggests that the animals are not basing their movements on SST but instead on some other covariate for which time is a better proxy. It is also possible that they do move explicitly according to time, for example for position of the sun or day length perhaps. Additionally, at local scales, less than optimal water temperature might be selected if those areas offer suitable, shallow protected conditions (Rasmussen et al. 2007), especially for females and calves trying to avoid the attention of males. This might explain why SST was only a weak predictor in the models for August and that requirements might change as the season progresses. For example the relationship between mother-calf pairs and water depth and sea bed terrain changed with calf age (Pack et al. 2017).

The species distribution models predicted similar core areas to the density surface model, however Camden Sound, the Tasmanian Shoal area and the entire coast of the Dampier Archipelago were all equally important across the season. Analysis of each of the three time periods showed that Camden Sound was only important in August, a result consistent with abundance models. Importantly, the models predict habitat suitability of groups with females and calves in June and July south of the Lacepede Islands, and in August, habitat suitability includes the coast of the Dampier Peninsula, not just Camden Sound. This suggests that the calving grounds extend beyond the Camden Sound area. New evidence suggests that calving areas for humpbacks extends along a substantial part of the migratory corridor along Western Australia, rather than being confined to discrete, localised areas (Irvine et al. 2017). As recorded by earlier studies (Craig & Herman 2000, Irvine et al. 2017), habitat preference differed between breeding (those without calves) and calving/nursing groups (those with calves present) with calving areas closer to shore and less extensive than breeding areas. As mentioned above, females and calves may prefer shallower, protected habitat which might also be warmer. In addition, highly competitive groups of males often chase cow-calf groups through and around Camden Sound, such that females with calves may be forced closer to shore or may stay as close to the coast as possible to avoid detection.

Evaluation showed that the species distribution model performed relatively well and that its predictions were reliable. In addition, the areas of importance to humpbacks identified by the model were consistent with satellite tracking data, which showed a similar area of importance across the Kimberley although not extending as far as Broome and with only moderate use of Camden Sound. This latter issue might be more to do with biases in the tracking data than actual patterns of use, since many of the transmitters on northbound whales tracked from NW Cape in 2011 had ceased reporting positional data before tagged individuals arrived in the Kimberley (only 8 of 23 tags were still transmitting on arrival in the Kimberley) and that the southbound whales were mostly tagged south of Camden Sound. However, of the eight whales that arrived in Kimberley in 2011, only four went to Camden Sound and in 2006 when six northbound whales were tagged at James Price Point, only two went to Camden Sound. As suggested previously (Jenner 2001), northbound whales migrated further offshore than southbound whales and the raw Scott Reef survey data that we were unable to model shows that humpback whales use areas beyond what was modelled here. Although the majority of the area used by the majority of the population using the Kimberley has been modelled.

Pender Bay was identified by both modeling approaches to be an important core area for humpback whales in the Kimberley. It is important to note that this may be partly related to Pender Bay being a physical gateway into, and out of, the Kimberley calving area. Humpback whales are not thought to migrate continuously in this region and as Pender Bay is also a shallow area out of the tidal current, whales may rest here before advancing both inbound to and outbound from the Kimberley and Camden Sound. This two-way traffic could create a pattern of higher abundances of whales in Pender Bay across the season. This contrasts with Camden Sound and the neighbouring Buccaneer Archipelago at the northern extent of the breeding grounds, where it is thought that cow-calf groups do not linger for more than 1-2 weeks (Jenner et al. 2001). Tasmanian Shoals also has “two-way traffic”, but to a lesser extent since whales disperse once they are north of Pender Bay and some move slightly south into the islands of the Buccaneer Archipelago. The importance of Pender Bay as a resting area (Jenner et al. 2001) and the very high abundances of humpbacks that occur here over the entire breeding season suggest that it should be given consideration for additional protection measures.

Importantly, there have not been any systematic surveys of the Kimberley region, including Camden Sound since an aerial survey by CWR in 2007. While it is widely recognised that the population has been increasing each year as it recovers from the decimation of whaling, there is no current estimate of the absolute population size nor of how population growth may have affected spatial use in the important breeding grounds of the Kimberley. It is now crucial that a monitoring program be implemented to ensure this population is managed effectively into the future, given the growing pressures of climate change and other anthropogenic pressures in the marine environment. Differences in the spatial and temporal coverage of the datasets compiled and analysed here, prevented valid/robust analysis and detection of trends among years and highlights the importance of having, long-term, repeatable systematic survey data to effectively monitor trends.

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Chapter 2: Detecting humpback whales from high resolution satellite imagery

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1 Introduction

Humpback whales are distributed throughout the length of Kimberley coastal region, surveys are necessarily complicated by the size and remoteness of this region, platform logistics and observer biases. The costs of broad-scale surveys using planes or vessels (the traditional platforms to assess population size and distribution) are high, as is the time required by researchers to analyse the data. These issues are common to many studies and have led some researchers to trial high resolution satellite imagery to detect and count whales and other megafauna (Abileah 2001, Fretwell et al. 2014, McMahon et al. 2014, LaRue et al. 2017). For example, WorldView-2 (operated by Digital Globe) satellite imagery was used successfully to identify and count southern right whales (*Eubalaena australis*) breeding off the coast of Argentina (Fretwell et al. 2014). This satellite orbits at a height of 770 km above the earth and provides a maximum resolution of 1.6 m per pixel in the multispectral bands (includes two infrared bands) and 0.46 m in the panchromatic band (greyscale). The success of this earlier work led our study to trial WorldView-2 satellite imagery as a means to sample humpback whales. Images are now also available from WorldView-3, a newer version of the satellite, which orbits at 620 km above the earth and collects data at a resolution of 1.24 m per pixel in the multispectral bands and 0.31 m in the panchromatic band. The higher resolution of WorldView-3 was considered preferable for detecting whales, but as it was also more costly to source, we sought to first examine images from WorldView-2. The latter satellite also has a more extensive archive as it was launched in 2009, whereas the WorldView-3 satellite was launched in late 2014.

Here we used archived WorldView-2 images and tasked WorlView-3 images to assess whether humpback whales could be detected and counted using visual and automated methods.

2 Materials and methods

2.1 Image selection

We first set out to obtain a WorldView archived image that overlapped with the temporal and spatial extend of the humpback whales survey data (Table 1 in Chapter 1) and preferably obtained around the peak in humpback whale seasonal abundance in the Kimberley. To do this, all the survey data (Table 1 in Chapter 1) was collated into a single GIS dataset and used to define an area of interest (AOI) for the satellite images. The AOI was defined as the 95% kernel utilisation density of all sightings data combined (Fig. 1), which was then used to query Digital Globe's database for the WorldView Archival imagery. The query defined all pre-existing WorldView-2 and WorldView-3 imagery that intersected with the AOI and was downloaded as a shapefile of image footprints. We compared the temporal extent of the footprints to the survey data to search for images that were captured on or close to a corresponding survey date. No suitable WorldView-3 imagery was available that fulfilled these criteria, but three WorldView-2 Images were identified that were captured within a few hours of a survey completed on the 6th of August 2010 off James Price Point. We selected one image (Fig. 1) of the three available that appeared to have the best sea surface conditions (low swell, white caps and glare) based on the catalogue preview, and also overlapped with the survey that had the most observations of whales. We then acquired the 941 km², 8-band multispectral satellite image (10AUG06021738-M2AS-055137769010_01_P0011) on an evaluation license. The size of the image meant it was delivered as a tiled product with each tile provided as a geotiff or as a mosaic through the xml file. We followed a similar approach to that of (Fretwell et al. 2014), with an initial step of visually searching the image to identify some features that were likely to be whales based on size and shape that could then be used to train a supervised automated detection process using spectral image analysis of all bands and thresholding of the panchromatic band. The primary software package used in the analysis was ESRI's ArcGIS package and Exelis's ENVI.

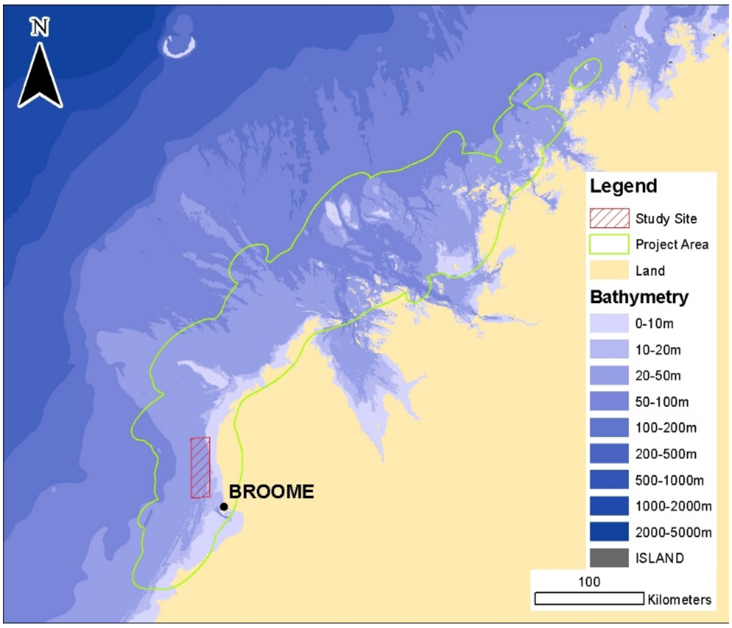

Figure 1. The study area showing the 95% kernel utilisation distribution from all the humpback whale survey data in green and the area where WorldView-2 archived image was captured in red square.

2.2 Spectral image analysis of WorldView-2 image

We classified all surface features found in the visual search including white caps, boats and whales and whale features (e.g. footprints) similar to the categories in Fretwell et al. (2014) in the panchromatic and multispectral bands. We then undertook a spectral analysis to determine whether pixels that contained whales had a different spectral signature to pixels of other non-whale surface features and the surrounding environment so that the spectral signature could potentially be used to automate the detection of whales in the satellite images.

Each visually feature was digitised as a polygon within ArcGIS and to provide the best shape definition and minimise inclusion of non-target cells, the panchromatic band was used, having the highest spatial resolution. To improve definition of the shape of objects a combination of the Dynamic Range Adjustment function and manual histogram stretching within the image analysis tools of ArcGIS were used to enhance their appearance. To provide comparison, additional features were digitised to capture deep water, shallow water, mid water, wave crest white water and boat wakes.

Each pixel's digital number value was extracted by loading the digitised feature polygons into ENVI to intersect with and sample the value ranges represented within each band and calculate the range and mean values for each of the surface feature categories (Fig. 2). For the multispectral bands we used the pan sharpened multispectral image resampled to 0.4m pixels in an attempt to reduce the sampling of non-target values (Fig. 3). We then used a supervised classification using the pixel values from each class to automatically classify the image. We also tried an unsupervised classification to classify surface objects in the image based only on information held within the image and using a clustering algorithm to determine the groupings. We also used an iterative process to formulate threshold pixel values to that maximised the signal of the 'whale' features and reduced the signal noise on non-whale surface features.

Following examination of the spectral profiles, separability tests were run using ENVI and the Gram Schmidt Pan Sharpened Multispectral image and all 8 bands. Jefferies-Matusita (JM) and Transformed Divergence (TD) scores were calculated from these tests, where values over 1.9 indicate the features are separable and values between 1.7 and 1.9 may be separable.

2.3 Tasking and analysis of WordView-3

Since there was no archived WorldView-3 data from our region, we tasked the WorldView-3 satellite to provide two images to be taken on two different days (early and mid-August) in 2016. The area over which the images were to be taken was based on the 25% kernel utilisation density area centred on Camden Sound (425 km^2 area). We then identified and counted the whales in the resulting images by eye. Each of three people counted the images independently and the results were cross checked for the final count. We also worked with Toyon Research Corporation to trial a semi-automated detection process using shape previously developed for detecting gray whales in remotely sensed imagery. We provided a subset of the grayscale, panchromatic WorldView-3 imagery that contained whales as input to this algorithm. Later, we provided the spatial locations of these whales in the imagery to validate their process. The algorithm ran a sliding window over the image and saved any image chips that met whale shape criteria. Then a human reviewed the chips generated by the algorithm and identified those that actually contained whales.

Given the high cost of tasking the WorldView satellites, we also conducted a cost-benefit analysis for the use of this technology to monitor humpback whales in the Kimberley region and compared costs to traditional surveys to achieve the same goals.

3 Results

3.1 WorldView-2

From the visual search of the WorldView-2 image a total of 59 surface features related to whales were identified including possible submerged whales, surfaced or partially-surfaced whales and footprints from tail beats or landing marks of breaches (Table 1). Additionally, 6 vessels where identified ranging from only a few meters to 35 m in length. We were not able to reproduce these images here as the image was obtained using an evaluation licence, however they were of similar to poorer quality to those shown in Fretwell et al. (2014). Only one of the surface features was able to be classified as ‘whale certain’. For the actual vessel survey that coincided with the day of image capture there were 66 whales observed over the entire 941 km^2 footprint of the image or 7 whales per 100 km^2, however sufficient information was not available to determine whether the survey was representative of the entire footprint.

Table 1. Results of the visual search of WorldView-2 image.

Classification	Feature	Count
Certain	Whale	1
	Boat	6
	Total	7
Probable	Whale	3
	Footprints etc	4
	Submerged whale	12
	Total	19
Possible	Whale	21
	Footprints etc	10
	Submerged whale	2
	Total	33
	Grand total	59

Examination of the spectral signals on the panchromatic band (Fig. 2) shows that minimum values are relatively common and is most likely because all features have water in common which is difficult to completely exclude from the pixels. Within the maximum values there are spikes, with Boats having the highest maximum values followed by, Boat-Wakes, then Whale-Certain and Whale-Related features. Boats also have the highest mean values followed by Boat-Wakes, Whale-Related features and Whales-Certain. However, with the exception of the Whale-Related features, mean values for whale categories are not significantly higher than mean values for water features, with Whales-Certain having a mean value of 153 compared with 145 for Water-Shallow.

When whale features were re-examined using the pixel inspector tool we were able to tighten the range of the pixel values to 200-810 and boat features to 300-1978. Although the maximum value of boats allowed them to be selected and removed, there was still overlap with whale features and boat wake (which was found to vary greatly), and shallow water (Fig. 2).

Surface disturbance believed to have been caused by whales was difficult to isolate from white water and sun glint with thresholding alone, and a significant amount of noise and false targets remained. It was noted that white water and sun glint both associated with swell had a distinct orientation which possibly could allow it to be filtered out from target features. Shape of whale related surface disturbance varied but could be of use in further separating surface features. In addition to overlaps with other surface features, shallow waters with seemingly reflective sea floor returned high values that overlapped with whales, whale related features and whitecaps making it difficult to rely on thresholding alone to extract whale features.

Submerged whales had no overlap with other features but had varying values, presumably based on varying depth and could not be distinguished from deep water areas. While other bands may help distinguish submerged whales from deeper waters, low resolution of other bands and poor distinction of submerged features prevents this from being a suitable option for thresholding alone.

We tried reclassifying based on threshold values of 200 and greater than 810, however this did still not allow discrimination of whale related features from boat waked and neither did the use of minimum bounding geometry calculated along with the geometry attributes and a filter applied to exclude all features with a length of less than 4m and a length of greater than 18 m leading us to conclude that thresholding in the panchromatic even with the use of basic geometry measures to filter was not adequate. However, the process did successfully filter out the boats, water and the majority of the white water.

We found similar results with the spectral analysis of the multispectral bands, with whale features not being able to be distinguished from the surrounding water (Fig. 3). The primary draw back of the multispectral bands is they have a maximum resolution of 1.6 m or 2.56m², this represents 16 of the 0.4 m pixels in the panchromatic band, and larger pixels result in more overlap with non-target features such as water, providing a mixed signal which when identifying relatively small features makes it difficult.

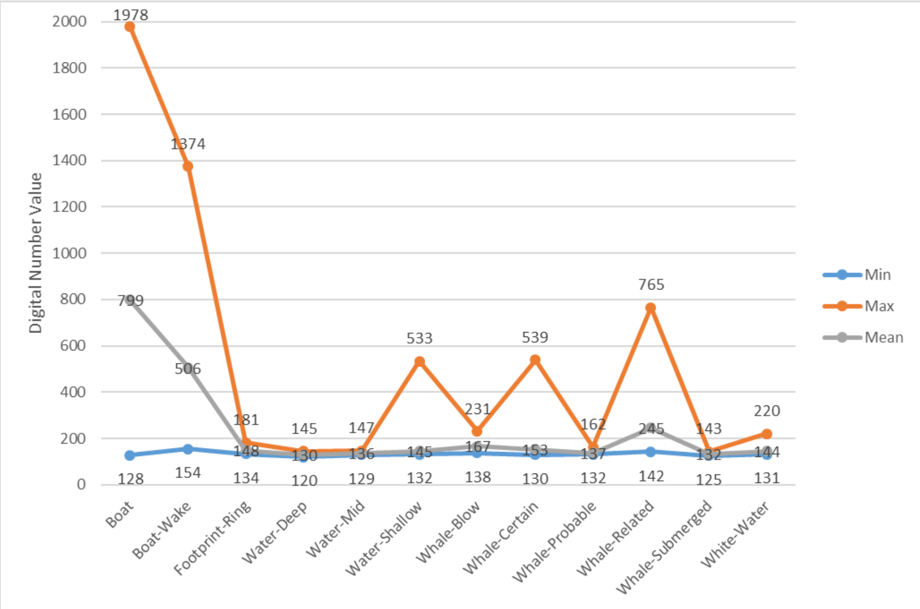

Figure 2. The minimum, maximum and mean values within the panchromatic band for each of the identified surface features and the surrounding environment.

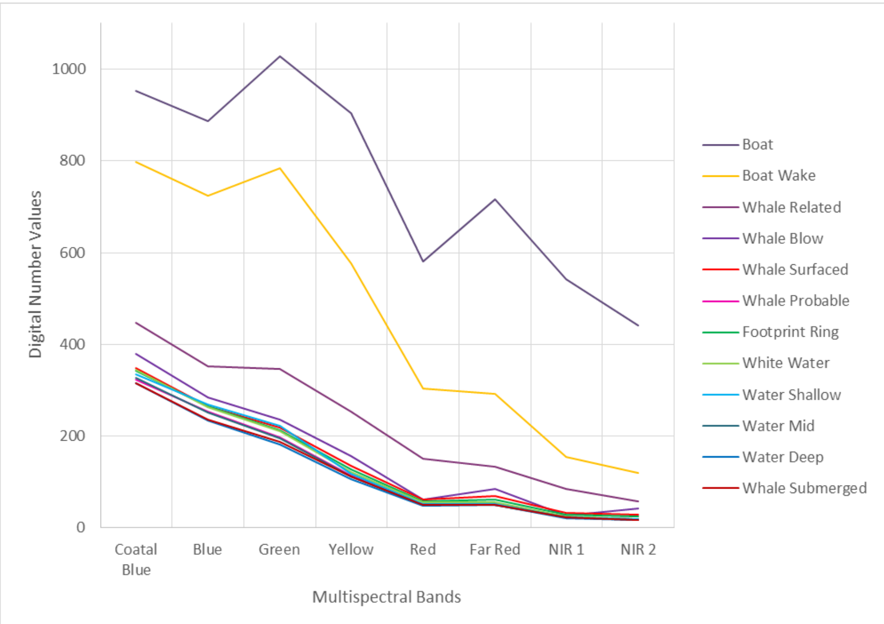

Figure 3. Mean values within the multispectral bands (from sampling a pan sharpened multispectral image) for each of the identified surface features and the surrounding environment.

The Jefferies-Matusita (JM) and Transformed Divergence (TD) scores resulting from the separability tests indicated that white water and whale footprints cannot be spectrally separated with a JM score of 1.333 and a TD score of 1.543. The TD Test suggested all other features were separable while the JM tests suggested a number of features were either not separable or not well separable. Submerged whales were one of these showing poor separability from Mid Waters with a score of 1.656 and surprisingly poor separability from White Water at 1.694, while possibly being separable from Deep Water with a score of 1.79. Whale related surface features were not separable from Boat Wake in the JM test with a score of 1.668. Surfaced whales where highly separable from most features but less separable from Footprint Rings with a JM score of 1.865 and White Water with a JM score of 1.848, though these scores are sufficiently high enough to suggest separation can still be achieved.

Despite promising results from the separability tests, the supervised classification of the pan sharpened multispectral image did not provide adequate separation with identified classes having significant overlap in feature identification.

3.2 WorldView-3

For the WorldView-3 tasked images captured at higher resolution we manually counted 33 adult whales, and eight calves on Aug 06, 2016 and 23 adult whales and seven calves on Aug 12, 2016 (Table 3). Unlike with WorldView-2 (Table 1), the majority of these were in the 'certain' category (Table 3). Figure 4 shows a selection of these images and one of a boat, demonstrating that WV3 had sufficient spatial resolution to discern size differences in humpback whales and to thus identify some calves (potentially not all). For the semi-automated detection algorithm using shape, 100% detection rate was achieved (Table 2). There were a high number of false identifications of whales (max of 128) at times, and these took a total of 20 mins to resolve visually by an observer. Two of the positive identifications obtained from visual searches were not whales. Visual searching with three replicates (three people searching independently) of one 425 km^2 image set took 24 person-hours (eight hours per person).

Table 2. Results of the semi-automated detection algorithm of a selection of the WorldView-3 images of Camden Sound.

Image name	Whale ID	Detected?	No. False positives	Algorithm time (mins)	Chip review time (mins)
16AUG12022217-P2AS_R1C4-055488310050_01_P002.TIF	1	Yes	14	7	<1
	2	Yes			
	3*	No			
16AUG06022458-P2AS_R5C3-055488310050_01_P001.TIF	4	Yes	128	20	2
	5	Yes			
16AUG12022217-P2AS_R2C2-055488310050_01_P002.TIF	6	Yes	0	7	<1
	7	Yes			
	8*	No			

Note: Whale IDs 3 and 8 were confirmed not to be whales

Table 3. Results of the visual search of WorldView-3 image.

Classification	Feature	6 August	12 August
Certain	Adult whale	18	11
	Calf	5	2
	Total	23	13
Probable	Adult whale	6	6
	Calf	2	3
	Total	8	9
Possible	Adult whale	9	6
	Calf	1	2
	Total	10	8
	Grand total	33A + 8C = 41	23A + 7C = 30

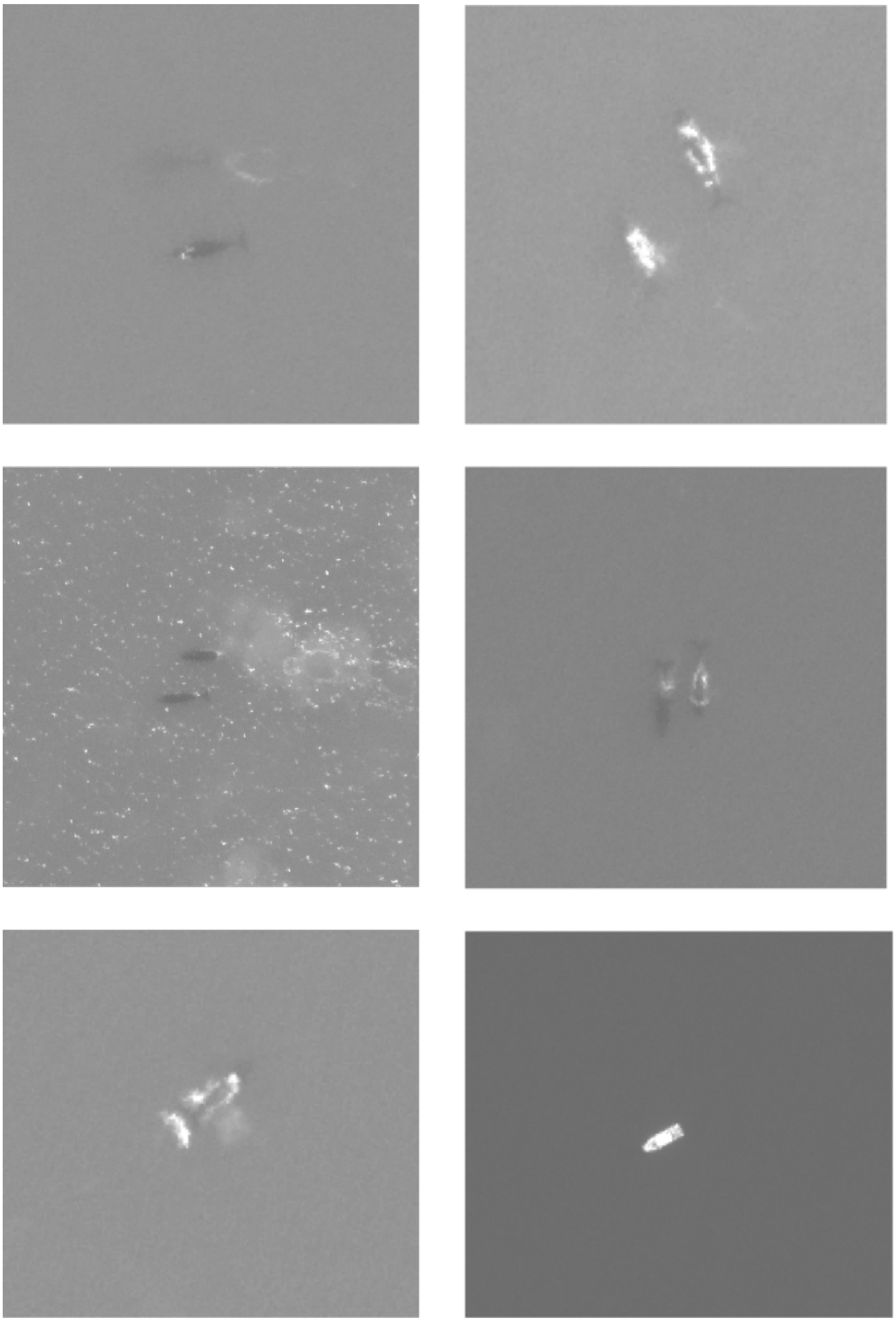

Figure 4. Humpback whales and boat (bottom right) captured in WorldView-3 satellite imagery.

4 Discussion

We have shown that it is possible to visually detect humpback whales in images collected by the WorldView satellites but that the higher spatial resolution of WorldView-3 is needed to provide more confidence around whale identification and thus have robust input information for successful automatic classification algorithms.

Analysis of the WorldView-2 spectral signatures found that there was no clear distinction between whale related features and surrounding water but that boats could be distinguished from whales. To detect whales successfully, a strong contrast between the whale and the surrounding environment is needed (LaRue et al. 2017). This was challenging for the WorldView-2 imagery as whales were always partly submerged and thus it was difficult to completely exclude water from the 'whale pixels'. In addition, although the image acquired was selected considering minimal swell, this assessment was based on examination of the quick look image on the catalogue website, however when the image was delivered there was significant swell across the image. This meant there was a significant number of whitecaps and few clearly distinguishable whales could be identified on the surface visually. In addition to the surface swell, examination of the acquired image showed bright areas which coincided with shallow bathymetry and other variations that appeared to be related to turbid water. Bright areas decrease the contrast between the background environment and the target features. As a result, when using unsupervised classification techniques these bright areas tend to fall in the same classes as whale features. This problem meant that only approximately 70% of the image could be classified with the remaining area having to be excluded due to background noise.

The lack of contrast might have also been related to the behaviour of the whales, i.e. that they might not always be positioned parallel to the sea surface where visibility would be highest. Such body position is likely more indicative of travelling rather than when resident on the breeding grounds as was likely the case here. In addition, the resolution of WorldView-2 likely contributed to the problem of obtaining pure whale pixels and resulting lack of spectral separation. It made visual detection difficult with only one whale identified as 'certain' and majority of whale related features classified as 'possible'. The supervised classification of right whales from WoldView-2 imagery also showed no meaningful results, however their unsupervised classification gave reasonable results as did simple thresholding of the panchromatic and band 5 (Fretwell et al. 2014). This might be due to right whales having a larger surface presence than humpback whales. However the WorldView-2 images in Fretwell et al. (2014) show similar poor resolution as found here.

Although we could have tried object oriented feature extraction using the shape of the surface objects to detect whales in WorldView-2, the issues we highlight above meant that the observed features lacked clear shape definition suggesting object orientated classification would have a low chance of success. Whereas, the higher resolution of imagery captured by the WorldView-3 satellite allowed humpback whales to be easily detected by eye and also by the semi-automated, shape-based detection algorithm. The algorithm made the detection of whales in the image very efficient, with an average review time for researchers of three minutes for each of the three images, compared to two days for the visual (by-eye) search of the entire area. We thus recommend WorldView-3 over WorldView-2 for the remote sensing of humpback whales and the use of shape/object oriented analysis rather than pixel based analysis in automated classification algorithms. In addition, unsupervised classification is preferable as it does not require prior visual identification of the image. Although the time taken for visual detection of an image is relatively low for small images (as we had here), this might not be efficient and cost effective with larger images.

At present the high cost of WorldView-3 means that it would be prohibitive as a tool to monitor the entire distribution (as shown in Fig. 1), which we estimate at a cost of Approx. $4M. and this is only for one snapshot in time, whereas given the annual variability in the peak season (Jenner et al. 2001), more than one capture would be needed over the season. Although projections infer that costs are rapidly reducing over time, it is still likely to be five years or more before this would be reduced to an affordable level to management agencies. This means that it is only affordable to monitor small, targeted areas such as hotspots like Camden Sound and Pender Bay.

The counts made using satellite telemetry have bias, similar to traditional methods such as availability bias (whales not able to be counted as they are underwater), however would not be subject to observer bias (whales on the surface but missed by the observer). Thus while traditional methods extrapolate from counts made along line transects to the larger area they are representative of, by correcting for these and other biases, counts made from a satellite image of an area require no extrapolation (as the whole area has been counted), just correction for availability bias. But more work needs to be done to understand bias (such as how deep whales can be detected) and whether counts from images can be used as a reliable index of population size (Fretwell et al. 2014). Our rough calculations of how many whales were counted on a vessel survey that overlapped with the area of the WorldView-2 image turned up a higher number of whales. We suggest that this is related the fact that the image is taken by the satellite instantaneously, whereas during a vessel survey, the observers have greater time to make their observations.

Even if costs are reduced in the future to be able to survey the entire Kimberley area with very high resolution satellite imagery, we still suggest there would be some drawbacks including: 1. Limited opportunities for successful capture, 2. Low chance of ideal conditions across entire area, 3. Limited chance of capture in same day and 3. Greater difficulty in detection in low density whale areas especially with swell.

We thus recommend the use of high resolution satellite imagery for the targeted monitoring of smaller areas where whale density is high. In these areas higher densities of whales facilitate easier detection and can be processed in a shorter time period. Smaller targeted areas provide more flexibility in finding a suitable window that meets time, satellite position and environmental conditions and where unavoidable, manually analysing imagery captured in adverse environmental conditions becomes more manageable.

We also recommend investigating the capture of high spatial resolution but lower spectral resolution imagery from an aircraft platform. Use of an aircraft would not only allow the capture of higher resolution imagery but would also increase the level of control over the capture time and environmental conditions accepted. In this case panchromatic resolution of 10 or 20 cm may be sufficient but the capture of Red, Green, Blue and Near Infra-red should also be considered.

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Chapter 3: Monitoring of humpback whales *(Megaptera novaeangliae)* at Pender Bay, south Kimberley region

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Executive Summary

Humpback whales (*Megaptera novaeangliae*) migrate annually along the coast of Western Australia (WA) from their summer Antarctic feeding grounds to warm tropical waters in the Kimberley for breeding (Jenner et al 2001). While the population has been increasing in size since the cessation of whaling in Western Australian waters by 1963, it is important that we have a good understanding of their habitat use, in particular in critical areas, for their long term sustainable management. Key sites have been identified as important breeding grounds and high use areas for humpback whales in the Kimberley including Camden Sound, Tasmanian Shoals/Buccaneer Archipelago and Pender Bay (Jenner et al 2001, Jenner et al 2014). The Lalang-garram/Camden Sound Marine Park, including several sanctuary zones specific to humpback whales, was established in 2012 by the WA State Government largely in recognition of this (Department of Parks and Wildlife, 2013).

Given the remote nature of the Kimberley marine environment and the very large range of humpback whales across known breeding and resting areas, it can be difficult to gather sufficient data to assess their distribution and to monitor population health. A four year project underway at Two Moons Whale and Marine Research Base at Pender Bay, WA (McKay and Thiele 2008, Blake and Dapson 2011) offered an opportunity to assess the value of using a land based site manned by volunteers as a cost effective means of gathering suitable data. The purpose of this project was to evaluate the data collection methods used at this research station, extend data collection for an additional year and evaluate the 5 year dataset to understand humpback whale use of Pender Bay.

The data collection methods were evaluated and amended slightly for the whale migration season in 2013 and an appropriate field manual and training material prepared. A team field leader coordinated data collection by a group of volunteers from 1 July 2013 – 10 October 2013. Data collection included counts of all humpback whale groups (noting size and presence of calves) observed at 20 minute intervals from a cliff top viewing platform. Additional information was recorded on environmental variables (tide, sea state, weather) and the presence of vessels. These data were evaluated to assess the timing of the migration season, including peak in the number of individuals and the number of calves across the season and the distribution of whales within the Bay and adjacent waters.

Overall a total of 3,695 groups of whales (5,521 individuals) were sighted over the 88 days when observations took place throughout the season. Calves were observed in 187 of these groups. While the peak in number of groups with calves occurred in mid August to September, there was a higher proportion of groups with calves early in the season. This may indicate that calves were being born near Pender Bay, however this has not been further explored. Whales were sighted between 400m and up to 15 km from shore, however were most commonly sighted at 3-4km from shore, potentially in association with particular water depths or benthic features, though more data would be needed to evaluate this. Both observer and environmental variables were found to have an effect on the number of whales detected in each scan. For example, more whales were detected when 4 observers were present than when there were fewer observers. Similarly, more whales were detected when visibility was better (ie based on sea state and weather).

Implications for management

Land based viewing platforms can provide a cost effective means of acquiring data on whales that can be used for management and other purposes. Most important though is to have a clear question in mind and to ensure that the data that can be collected can meet this purpose. The land based site at Two Moons Whale Research Base can be used to collect data that will inform regional managers about the timing of the humpback whale migration season, as this can vary annually, including the timing and density of mother and calf groups. It can also be used as an indicator of the extent of use of Pender Bay by humpback whales, including changes in timing and whale density throughout the migration season.

The modifications to the sampling design and methodology led to additional information (animal general location and distance from shore), better temporal distribution of data across the day and reduced observer fatigue. While this information cannot be used to calculate humpback whale abundance in the Kimberley, it can give a relative understanding of the use of Pender Bay and of the timing of the annual migration season which can vary slightly each year.

Products and Tools

This project has produced a field manual describing the methodology for land observations at Two Moons Whale and Marine Research Base. It has also produced a set of presentation slides to be used in conjunction with the manual for training volunteers. These tools would be useful for interaction with community groups as well as volunteer groups that would participate in a cliff-based survey of whale distribution.

Key residual knowledge gaps

Additional research would be useful that could link the relative abundance and density of humpback whales sited at Pender Bay with the broader Kimberley so that this land based site could be used as an indicator of population health across the broader region. Other specific research projects that would add value to our understanding of whale use of Pender Bay would include assessing whale distribution in relation to water depths or bottom features in the vicinity of Pender Bay and experimentally testing the effect of some of the environmental and observer variables including sea state, number of observers and observer experience, so that these could be accounted for in a standardized methodology and analysis.

1 Introduction

The population of humpback whales (*Megaptera novaeangliae*) known as Group IV migrate annually from Antarctic feeding grounds in the summer months, along the coast of Western Australia to warm tropical waters in the Kimberley for breeding (Jenner et al 2001). The population has been increasing in size at a rate of approximately 10% per annum since the cessation of whaling in Western Australian waters by 1963, however has not yet fully recovered. It is important for the long term sustainable management of this species to ensure we have a good understanding of their use of habitat in Western Australia as the population continues to grow. This is particularly important for the north western waters identified as important breeding and resting areas. Jenner et al (2001) identified three areas of high use by humpback whales in the Kimberley breeding grounds, including Camden Sound, Tasmanian Shoals/Buccaneer Archipelago and Pender Bay. More recent surveys have confirmed that these areas continue to be of primary importance to this increasing population (Jenner et al 2014) and noted that behaviours recorded at these sites were consistent with these areas being used for resting and nursing.

The establishment of the Lalang-garram/Camden Sound Marine Park in 2012 by the WA State Government was largely in recognition of the importance of the area as a key breeding ground for the Group IV Humpback Whale population at the northern extent of their annual migration (Department of Parks and Wildlife, 2013). In particular, four Marine Park zones have been created to minimise disturbance to whale mothers and calves in the area: Camden Sound Special Purpose Zone (Whale Conservation); Montgomery Reef Sanctuary Zone; Champagny Sanctuary Zone and the adjoining western Shoals General Use Zone. It should be noted however, that the area south of the Lalang-garram/Camden Sound Marine Park remains unprotected and yet is a very important region for this species, especially the region around Pender Bay.

It is widely reported that the Group IV population of humpback whales is the largest natural breeding population in the world with current estimates of more than 20,000 (Hedley et al., 2011; Salgado Kent et al., 2012). As the population continues to increase towards its pre-whaling estimates, questions arise as to the carrying capacity of the region and the importance of known staging areas such as Pender Bay, just south of the Camden Sound region.

Whilst humpback whale surveys have been undertaken in the Kimberley region over the past two decades, there is very little publicly-available data on the population size and the use of the region for calving, mating and resting. To date research has mainly been industry led and thus site specific. There has not been a regional assessment of habitat use by humpback whales across the Kimberley nor have potential correlations between relative annual and inter-annual whale abundances and geographic spread with major climate and oceanographic drivers been explored. Given the anthropogenic pressures of increased activity from the resource sector and tourism in the Kimberley combined with a warming ocean from climate change and changes to primary productivity, it is important to have a strong understanding of the critical habitat for this species and changes in their patterns of distribution and habitat use across the Kimberley. The remote nature of the Kimberley coupled with the wide-scale distribution of whales across available habitat make establishing a cost effective program for long term monitoring a priority. Land based observations can provide a useful and cost effective tool for specific research and monitoring questions where appropriate sites exist.

A study was initiated in 2006 from a land based research station, Two Moons Whale and Marine Research Base, run by the Goojarr Goonyool Aboriginal Corporation (GGAC), to better understand humpback whale use of Pender Bay (McKay and Thiele 2008). While the research project was not able to continue beyond 2008, the GGAC contacted the Western Australian Marine Science Institution (WAMSI) to develop a joint ongoing monitoring and research program between the local aboriginal community and WAMSI. This partnership relied on WAMSI to provide scientific advice and leadership for the annual field work and Two Moons Whale and Marine Research Base to provide volunteer support. WAMSI continued the collaboration with the GGAC from 2009-2013 with the intent to use the "citizen science" research at Two Moons Whale and Marine Research Base to examine factors influencing the timing and use of Pender Bay by humpback whales (Blake et al 2011;

Blake and Dapson 2013). A land based site offers the potential for a unique and cost effective means of monitoring this population over the long term in light of important anthropogenic and natural pressures on this recovering species (Coughran et al., 2013). In particular, community monitoring programs offer a low cost means of capturing important information for management while also building conservation interests and skills in the community.

The main aim of this WAMSI project is to complete a 5 year dataset for the community program that can be evaluated to assess the effectiveness of this land based program for monitoring humpback whales. This project is a subset within the broader WAMSI project 1.2.1a which is evaluating humpback whale use of the Kimberley and exploring suitable cost effective techniques for detecting trends over time.

The specific objectives for this subproject were to use data collection and analysis in 2013 to:

- Estimate the relative abundance of humpback whales using Pender Bay;
- Investigate the distribution of humpback whales in Pender Bay in relation to other variables;
- Estimate relative proportion of adult females and calves and the timing of their use of Pender Bay; and
- Evaluate the methods and protocol for producing useful monitoring information in humpback whales in Pender Bay and the Kimberley, more broadly.

2 Materials and Methods

2.1 Study Area

The study was undertaken at Pender Bay, an open embayment at the northern end of Dampier Peninsula located north of Broome in the Kimberley region of WA (122°38'E 16°45'S). The embayment is typically 12-15 m deep with gently sloping seafloor and freshwater input mainly during the wet season (Blake and Dapson 2013). The extreme tidal range of the Kimberley is evident here, with a tidal range within the bay of up to 9m during spring tides. The Two Moons Whale and Marine Research Base serves as the base camp for the field research team and is situated 1km from the field observation site. Field observations were conducted from a cliff top 34m above MSL at the southern end of Pender Bay, (122°36.546' E 16°45.939' S). This site offers a 190º visibility including panoramic views of Pender Bay with observers recording whale sightings up to 8 km offshore (Figure 1). Facilities at the field site include a cement pad for observers to stand during observation periods and a caravan with windows along the ocean facing side and ends to provide shelter during field observations.

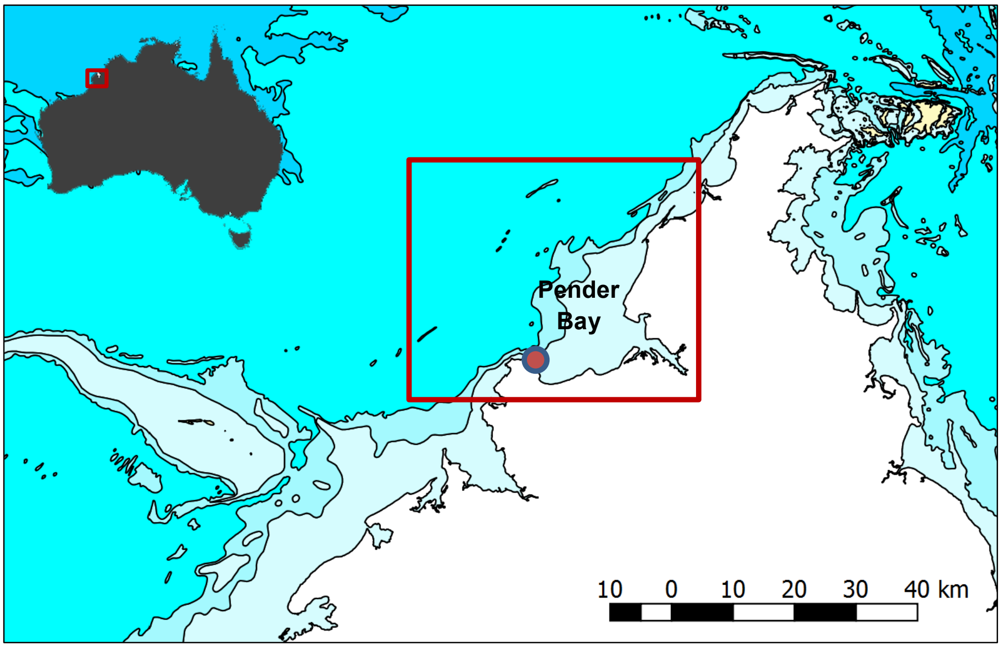

Figure 1. Location of Pender Bay (demarcated with a red square) and land-based observation location (red circle), within the Kimberley region in northwestern Australia.

2.2 Data collection

Data were collected each whale migration season for four years from 2009 to 2012 using the field methodology described by Blake et al (2011). The methodology was reviewed for the 2013 field season by the project team and, while the same basic methodology, comprising visual counts of whales within the study area was used, minor changes were made to enhance data collection and analysis. The field season for 2013 was conducted from 30 June to 10 October 2013. The research team consisted of a lead scientist and between one and four additional volunteer observers. The lead scientist was recruited from the marine science community, and was chosen based on experience with remote field work, team leadership and marine mammal research. Two Moons Whale and Marine Research Base provided the additional volunteers, the majority of whom were interested international travelers and/or local community members. Curtin University provided training of the lead scientist in the research protocol and field work expectations. It was then the role of the lead scientist to train all volunteers and establish a daily field observation schedule. The lead scientist was also responsible for overseeing the volunteers during observations and recording all data into a purpose designed data entry spreadsheet. A Field Training Manual and powerpoint presentation for volunteers was developed by the project team and provided to the lead scientist and all volunteers (Appendix 1). Blake et al (2011) and the Field Training Manual provides specific detail on the conduct of field observations, however a summary is provided below, in particular noting where changes were made in field methodology for the 2013 field season.

Sampling was stratified into morning (07:00 to 12:00) and afternoon observations (13:00 to 17:00). To manage observer fatigue only a morning or an afternoon shift was conducted in a given day and this was determined on a random allocation basis to ensure that over a 7 day period 3 morning and 3 afternoon sessions were conducted. This is a change to previous years where observations were typically undertaken each morning with afternoon sessions included only occasionally throughout the season.

During the field observation sessions the field team recorded the number of whales observed in the study site over a 5 minute period at 20 minute scan intervals. This is a slight deviation to previous years' data which was collected using 5 minute scans every 15 minutes. Reticule binoculars (rather than standard binoculars used in previous years) were used by observers to locate whales and to record information on estimated distance and compass bearing. The binoculars used had a set of vertical reticule lines that could be used to determine distance by aligning the cross-hairs with the point on the whale at the water surface. The observer then counted the number of horizontal lines from that point to the horizon (Figure 2). This information was used to calculate the position of the whale.

Scanning effort was divided depending on the number of observers present (Figure 3). These divisions are slightly different to those used in previous years and were based on dividing up the study area into shore to horizon viewing by each observer with the size of their section depending on the number of observers available. Double counting of whales was minimised by observers talking to each other to identify any overlap near the boundaries of their respective sections and by the team leader who had oversight of the full survey area and could resolve any doubts on overlap.

During the scan sample periods all observers were stationed on the cement pad in accordance with their section to view. Observers began scanning their respective sections and called out the following information when a new whale was sighted:

- ’cue observed’ (behaviour);
- number in group;
- if there was a calf in the group;
- distance (reticules down from the horizon); and
- bearing.

This information was entered by the lead scientist into a spreadsheet along with other data on presence of vessels in the area, and a range of environmental conditions: beaufort (sea state), wind speed (km, wind direction, glare (score 0-3; 3 being severe), cloud cover (8ths), visibility (km), ambient temp. (˚c), wind direction (deg), humidity (%), pressure (hpa), solar radiation, rainfall (mm), dew (deg c) and tidal height (m).

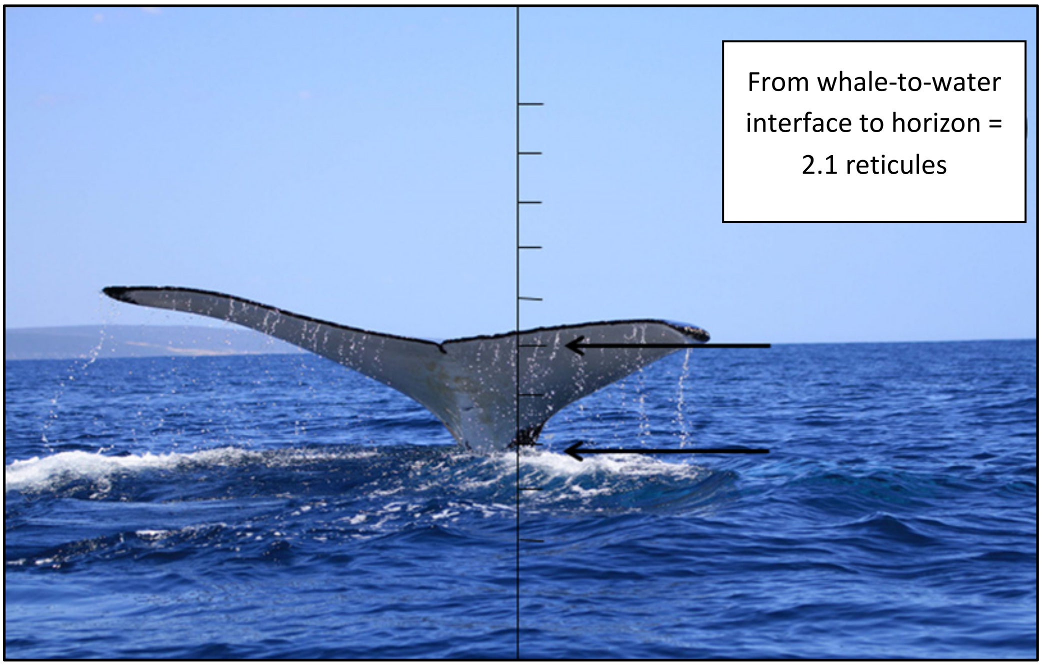

Figure 2. View of reticule cross hairs in the binocular field of view used to estimate distance the distance between the observer and the whale.

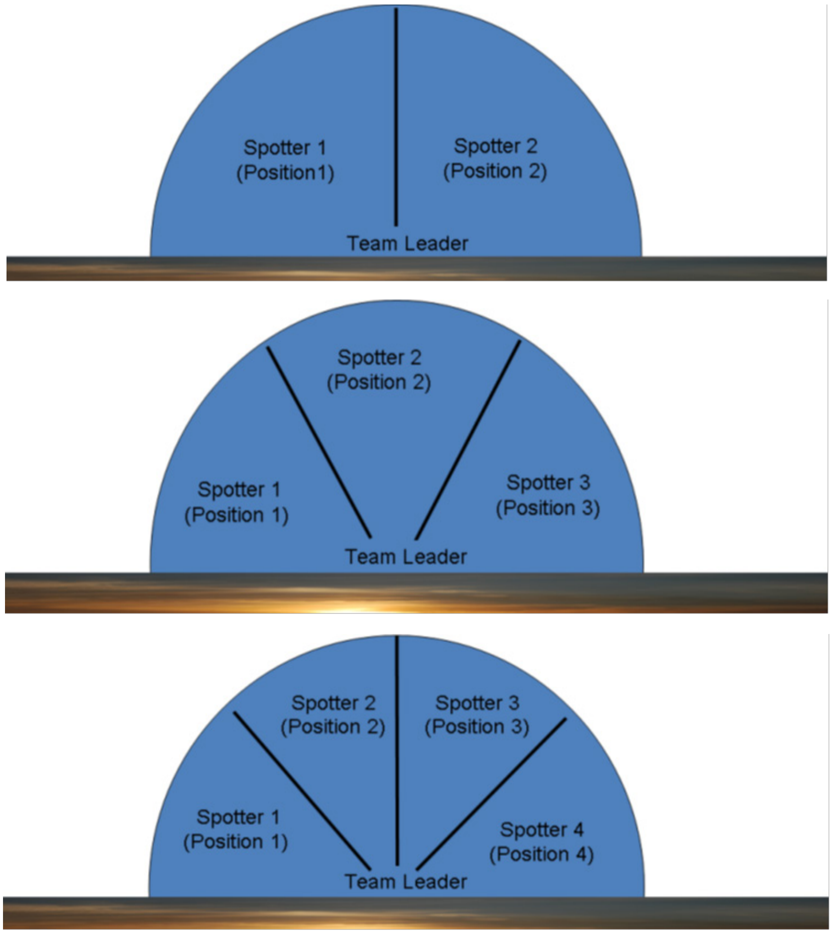

Figure 3. Example of teams with two, three, and four spotters, respectively.

2.3 Data analysis

Data were analysed to estimate the duration of the 2013 humpback whale breeding season, and the intensity of use of Pender Bay by whales, including cow-calf pairs. Observations from the first two weeks of July differed from the rest of the season as they only included estimated distance and angle measurements by eye (rather than reticule binoculars) associated with the whale sighting records. This period also consisted of a 'training' period. Thus, the broad overview of trends presented in the results include the first two weeks of the study (30^{th} June to 14 July) in the dataset, however detailed cow-calf pairs and distributional information presented in the results exclude the first two weeks of the season.

Summary statistics were determined, including the number of whale groups and individual animals sighted across the entire period, and the mean number of total groups, groups of different sizes and groups with cow-calf pairs sighted per day. Since the duration of residency of whales is unknown, and counts were made every 20 min, sightings included recounts of groups and/or individuals observed in different scan samples. Hence, 'intensity of use' of Pender Bay is reflected by relative numbers counted during a scan sample (and not the total over a day). For this reason, the number of sightings are summarised briefly at the beginning of the results, however emphasis is placed on mean relative numbers observed in 5-min scan samples.

The effect of weather conditions and survey team number (explanatory variables) on the number of whale groups (response variable) observed was assessed. The effects of time (days) over the migratory season, sea state (Beaufort condition), glare, cloud cover, and the number of observers (which varied between 1 and 4 observers) on the number of whale groups sighted were modelled as all of these variables can potentially change the visibility and therefore the detection of whales. The association between the response variable, whale group counts, with explanatory variables listed above was assessed using a log-link functions (for poisson distributed data) applied to Generalized Estimation Equations (GEE) using R (R 3.1.1, Core Team, 2013) run through RStudio (Version 0.98.501, © 2009-2013 RStudio, Inc.). A CReSS-GEE (Scott-Hayward et al., 2013a) framework was used to estimate smooth terms in the models for fitting to GEEs, since a linear fit was not expected for all explanatory variables. The packages MRSea (Scott-Hayward et al., 2013b) and geepack (Yan, 2002) were used for fitting smoothed explanatory variables to GEEs. Smoothness of covariates was selected using the function 'runSALSA1D' in the MRSea package. GEEs were used since residuals were temporally autocorrelated (Staley, 2013). The longitudinal order of the data (needed to define the autocorrelation structure in the model) was defined by a vector of the day and time in which the observations were recorded, which was expressed as 'decimal day'. Values for the vector ranged sequentially from 1 to the last date of the survey period. All models (and submodels) were run with AR-1, independent and exchangeable correlation structures, and compared using Quasi Likelihood Information Criteria (Pan, 2001). All resulting QIC were the same, therefore, AR-1 was selected since the data were time ordered (Zuur et al., 2009). The time-block used for clusters in the models (ID) was selected by identifying the period of time in which residuals autocorrelated approximated zero. The result was that single day blocks were defined as Clusters.

Explanatory variables were first explored by plotting these to ensure that there was a robust spread of samples taken over the range of values. At the extreme ends of the Beaufort and Glare scales, the number of samples were few (<20), hence the data were subset to exclude extreme values represented by few observations. This resulted in no more than four possible values for each of these scales. As a result these ordered categorical variables were treated as factors. Also, interactions were not included since many of the interaction levels had few observations (<20). Time (days) was the only covariate found to be fit best with a smooth term. Cloud cover was modelled as a linear term. Covariates were plotted against each other and Variance Inflation Factors (VIFs) were calculated to ensure that none were collinear (VIF < 3; Zuur et al., 2009). For model selection, the data were first fit to a full model, then insignificant explanatory terms were removed one by one. Each time an explanatory term was removed, the data were refitted and the submodel validated. For model validation, observed vs fitted values and fitted values vs scaled Pearson's residuals to assess the mean-variance relationship were plotted. The best submodel was selected by comparing QICu of all submodels (Hudecová & Pešta, 2013) .

Assessment was also made of the relative use of Pender Bay in conjunction with sea surface temperature (SST).

3 Results

3.1 Effort

Between 30 June and 10 October 2013, surveys were conducted on 88 days; 44 during the morning and 44 during the afternoon. The number of scan samples obtained over this period was 1148, with a maximum of 16 and minimum of one scan during a single day.

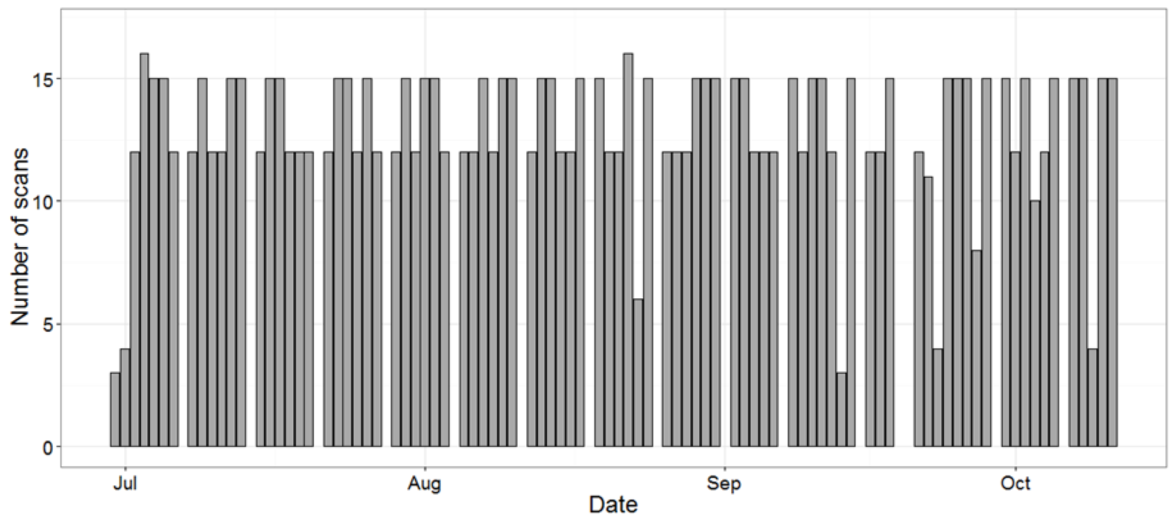

Figure 4. Total number of scans undertaken between end-June and mid-October, 2013.

Reticule binoculars were used from the 17th of July until the end of the survey season during a total of 925 scans. The maximum number of 5-minute scans in one day during this period was 16, and the minimum was one scan. Most often, the number of scans was either 12 or 15 in a day which typically related to whether the observation period was a morning (5 hour) or afternoon (4 hour) session.

3.2 Sightings

A total of 3695 group sightings, including 5521 individual whales, were made across all 5-min scans throughout the season (Table 1). Of these, 187 groups contained a cow-calf pair, and one group contained two cow-calf pairs. It should be noted that sightings include recounts of groups and/or individuals observed in different scan samples. A minimum of 0 groups and a maximum of 18 groups (32 individuals) were recorded during each scan period.

Table 1. Summary statistics for numbers of groups and individual observed, including groups with cow-calf pairs.

Cohort	Statistic		Groups	Individuals (*calves)
All groups	5-min scan samples	Min	0	0
		Max	18	32
		Mean	3.2	6.5
	Total over the season		**3695**	**5521**
Groups with Cow-calf pairs	5-min scan samples	Min	0	0*
		Max	3	3*
		Mean	0.2	0.2*
	Total over the season		**187**	**189***
	Proportion of total		0.05	0.03*

The mean number of groups detected per 5-min scan increased from approximately 2 groups in mid-July to a peak of 11 groups around mid-August, and then slowly decreased to around 1 group per scan towards mid-October (Figure 5).

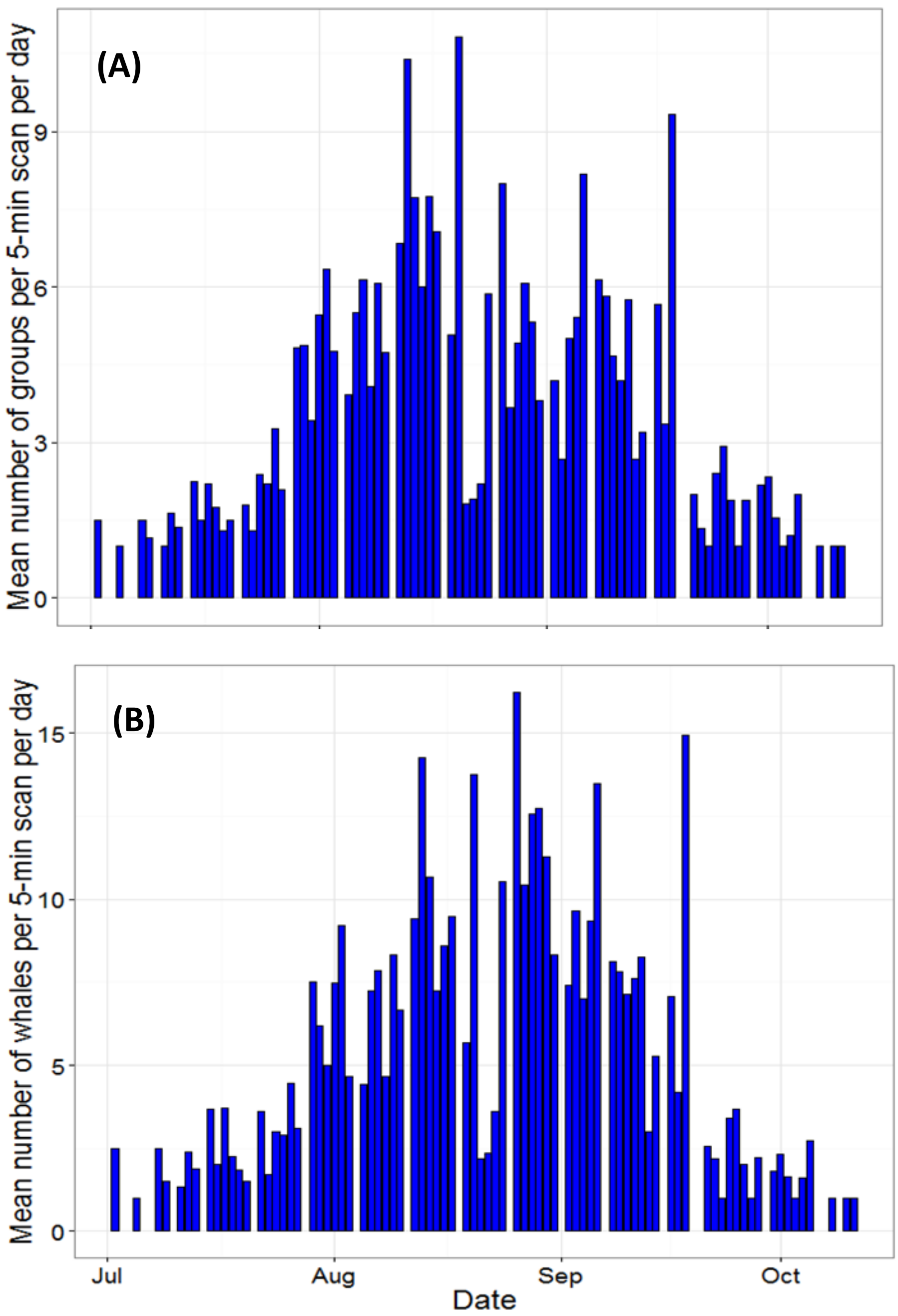

Figure 5. Mean number of groups (A) and whales (B) detected per 5-min scan (bottom panel) over the migration period between July and mid-October, 2013.

The mean number of groups with calves sighted in a 5-min scan per day ranged from approximately 0.1 to approximately 0.6, with the peak coinciding with the overall peak in whales (Figure 6). There was, however, an overall greater proportion of groups identified as having calves in them at the beginning of the migration season (in July, Figure 6). The proportion that could be identified as having calves dropped from 10-50% (depending upon the day) to between approximately 2-10% over the remainder of the migration season. The overall proportion of groups identified as having cow-calf pairs over the migration season was 5%. This was mainly due to the increasing numbers of other non-cow-calf groups as the season progressed.

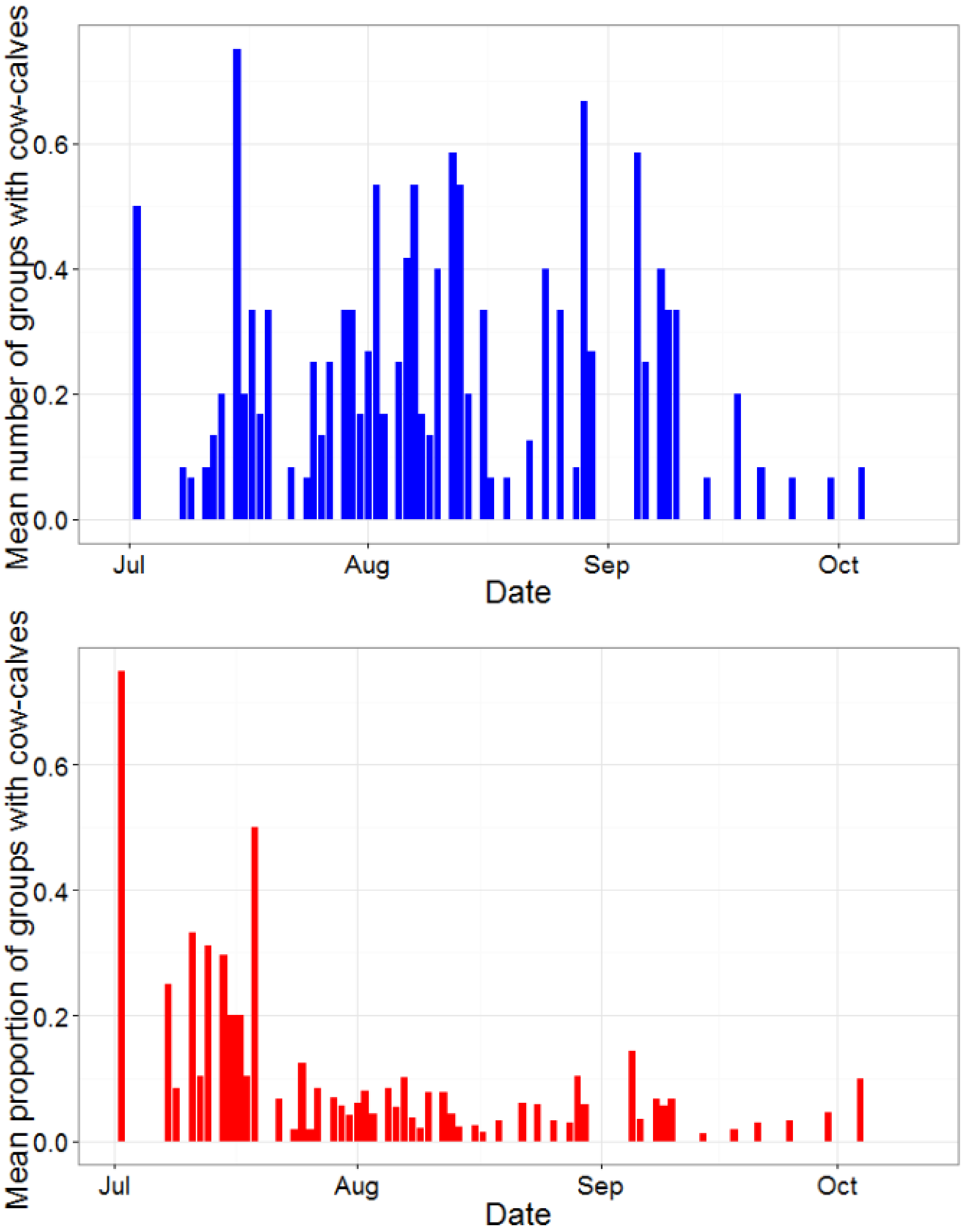

Figure 6. Mean number of groups (A) and proportion of groups (B) detected per 5-min scan with at least one confirmed cow-calf pair over the migration period between mid-July and mid-October, 2013.

The largest groups (>3 individuals) without calves were reported in late August and early September. Groups of at least two individuals (where calves were not identified) had a uni-model distribution with a peak in late August. Numbers of groups reported to have had at least one individual had a bi-modal distribution, peaking in mid-August and again in early September (Figure 7).

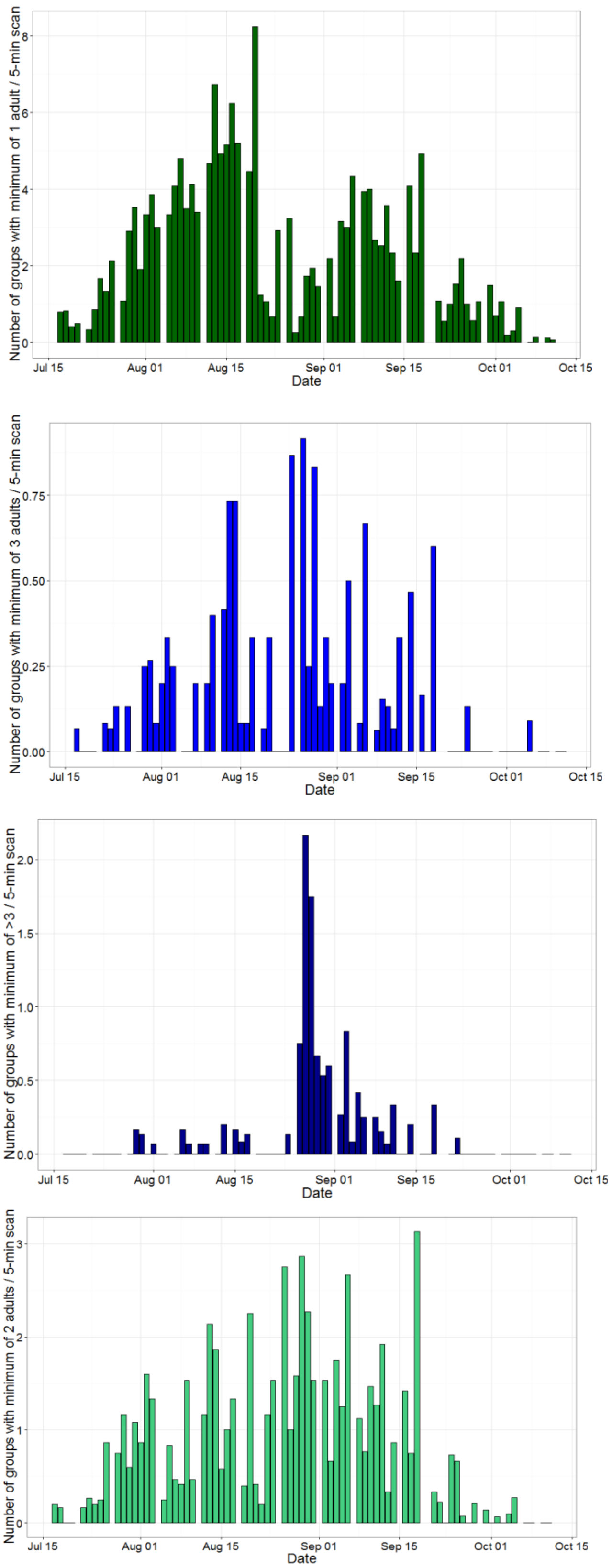

Figure 7. Mean number of groups per scan with different group sizes over the migration period between mid-July and mid-October, 2013 (groups here exclude those with confirmed cow-calves).

The maximum number of whales estimated in one group was 10 animals, and the minimum was one. The 'minimum' mean group size (since many group sizes could not be confirmed) estimates ranged between one and two individuals over the entire study period, with five days in late August/early September having means exceptionally greater than all other times (Figure 8).

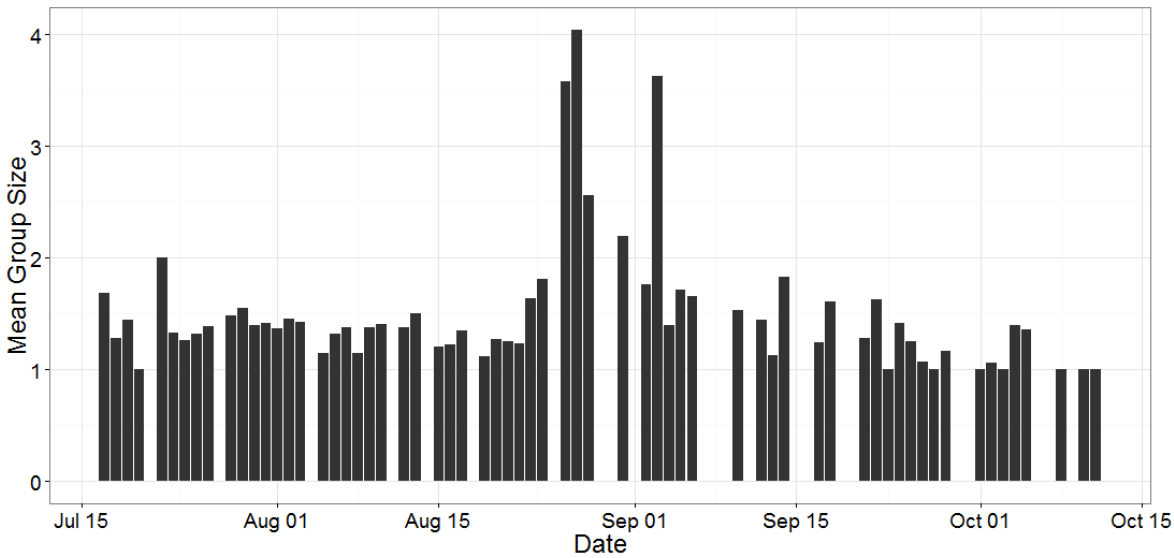

Figure 8. Mean 'minimum' group size estimates per day.

3.3 Effect of Environmental Conditions and Size of Observation Team on Detections

Environmental conditions recorded during scans varied over the survey season. Some surveys after mid-August had Beaufort (sea state conditions) of ≥5 (Figure 9). Surveys with these high Beaufort conditions were not conducted before mid-August. Cloud cover varied from day to day, however no large changes in the trend occurred over the survey season with an overall average of 2 sectors out of 8 having clouds. In contrast, the level of glare recorded during scans changed over the season, with more days of '0' glare occurring during the latter half of the survey season.

The total number of observers in the team varied over the survey season, ranging from one to four. The most notable change in team size was a single individual operating towards the end of August, and greater numbers of scans with a team of two individuals in July (Figure 9).

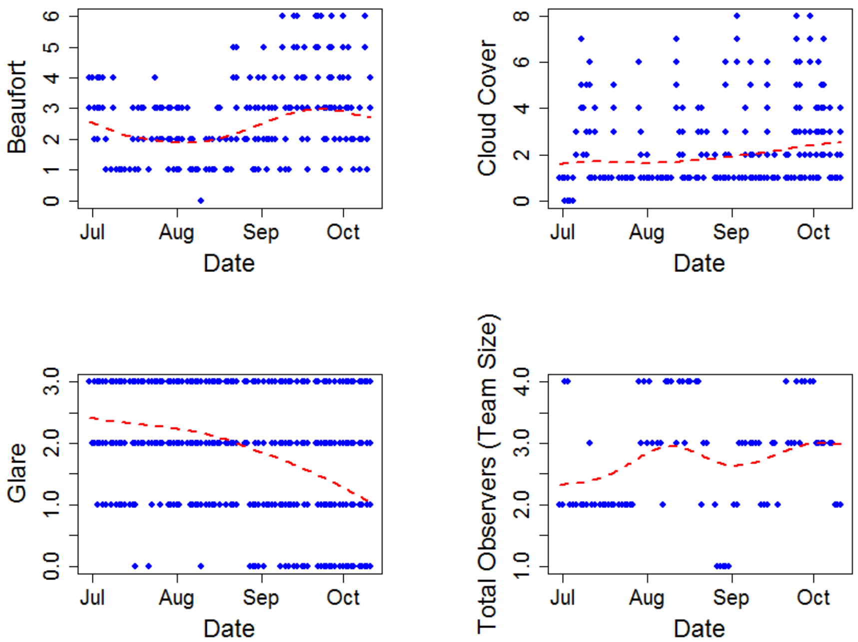

Figure 9. Change in environmental conditions and team size over the survey period (spline fit with a smoothing parameter [spar in the R smooth.spline function] = 0.9).

3.4 Association sightings with environmental variables

As a prerequisite for inclusion of variables in the Generalized Linear Model, collinearity of explanatory variables were checked. Variables (plotted against each other; Figure 10) were not collinear, with Glare and Time having the largest correlation coefficient (r = -0.4). All VIFs were less than 3.

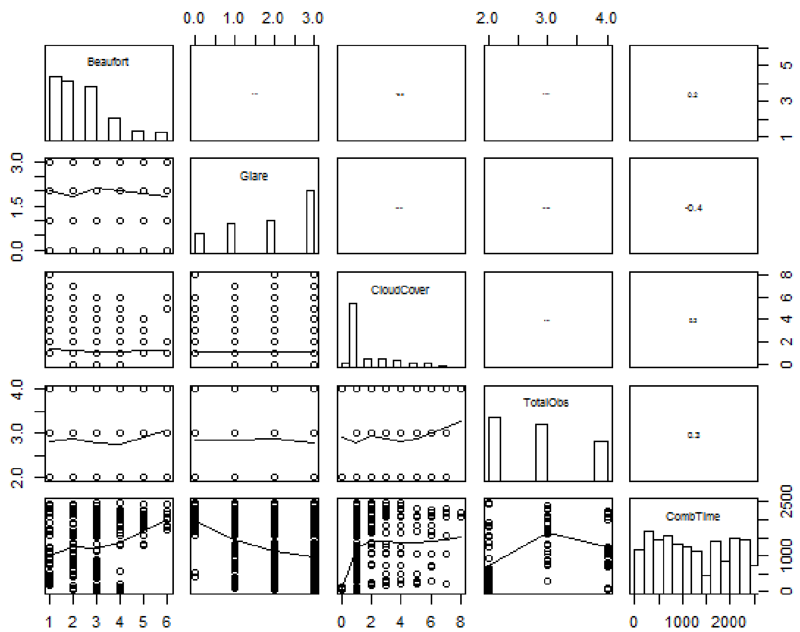

Figure 10. Pairwise collinearity plots of all environmental variables, team size (total observers), and time over the season (Time). The upper panel contains estimated pair-wise correlations. The diagonal panel contains histograms and the lower panel scatterplots with a LOESS smoother added to aid visual interpretation.

For this analysis, we needed to account for heterogeneity (more variation in peak migration period than in earlier and later periods) and temporal correlation. To visualise the heterogeneity through time, a subset of the data was taken, where the first scan for each hour was plotted over the survey day for each date of the survey season. The subset also excluded observations with a single observer (since there were few of these and they occurred at one time during the season), and those undertaken in Beaufort conditions of 0 and of 5 or greater (since these were not distributed evenly across the season). We verified that there was heterogeneity through time (within a day and over days of the season) that would need to be accounted for in the model (Figure 11).

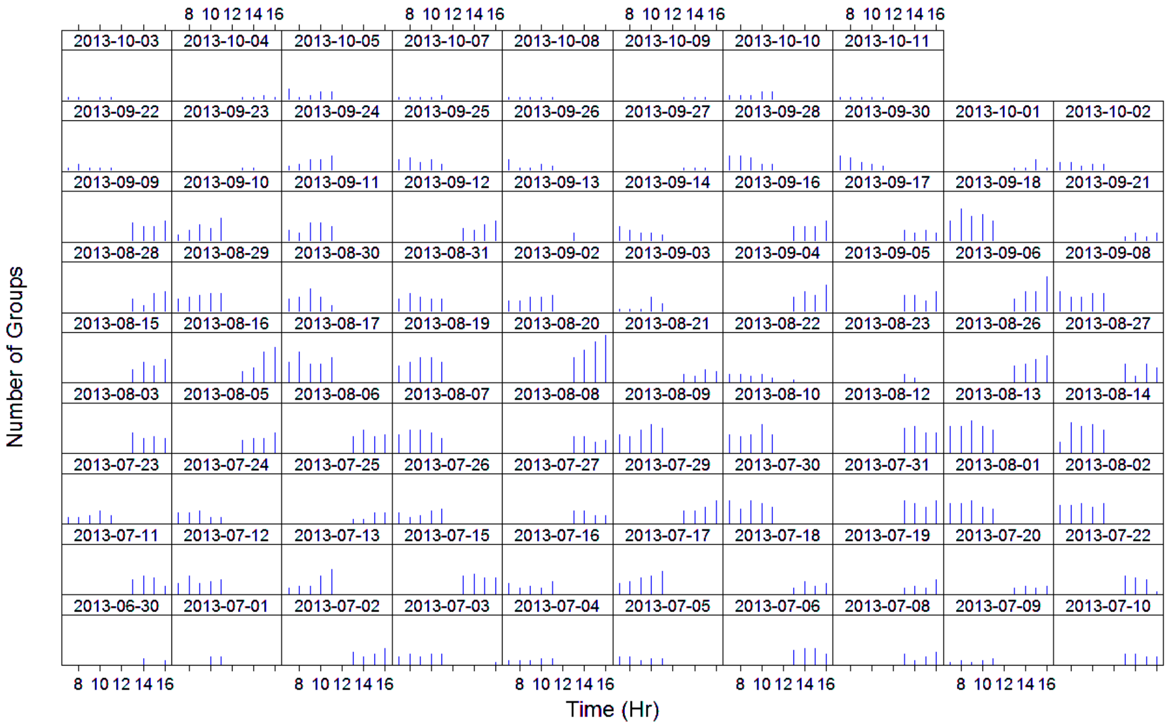

Figure 11. Number of humpback whale groups per 5-min scan during the first scan of each hour over the survey season.

Results of the best fit GEE showed that time (Days) over the season, Beaufort, glare, and total observer all were associated with numbers of groups sighted (Table 2), however cloud cover was not significant.

Table 2. Best fit Generalized Estimating Equations model (significance levels are: *** = ≤ 0.001, ** = ≤ 0.01, * = ≤ 0.05. Wald statistics are included (p-values (Pr (>|W|) were calculated from the Wald statistic). Estimated scale parameter was 1.09.

Formula				
Y = s(Days) + Total Observers + Beaufort + Glare				
Parameter Coefficients	Estimate	Std Err	z value	Pr(>|z|)
(Intercept)	1.5120	0.1759	73.88	< 2e-16 ***
(Days) spline knot 1	-0.0655	0.3272	0.04	0.84141
(Days) spline knot 2	1.2926	0.3318	15.17	9.8e-05 ***
(Days) spline knot 3	-0.4759	0.3982	1.43	0.23200
(Days) spline knot 4	-16209	0.2762	34.44	4.4e-09 ***
Total Observers 2	0.2594	0.1565	3.04	0.08128
Total Observers 3	0.2594	0.1080	5.76	0.01636*
Total Observers 4	0.4842	0.1064	20.69	5.4e-06***
Beaufort 2	0.0467	0.0766	0.37	0.54169
Beaufort 3	-0.2357	0.0743	10.07	0.00151**
Beaufort 4	-0.5589	0.1295	18.61	1.6e-05***
Glare 1	-0.2774	0.0956	8.42	0.00370**
Glare 2	-0.4146	0.1106	14.06	0.00018***
Glare 3	-0.2905	0.0925	9.86	0.00169**

The smoother for 'time' shows a significant trend with a slight increase in sightings at the beginning of the season, and then a relatively steep drop in numbers observed towards the end of the season (Figure 12). Beaufort showed a decrease in numbers of groups sighted with increasing Beaufort. All values of glare (above 0) had reduced numbers of sightings associated with them. Total observers (team size) shows greater sightings recorded when teams included more than a single individual. The numbers of sightings are similar when the team sizes were 2 and 3, but increased when the team was composed of 4 observers (Figure 12).

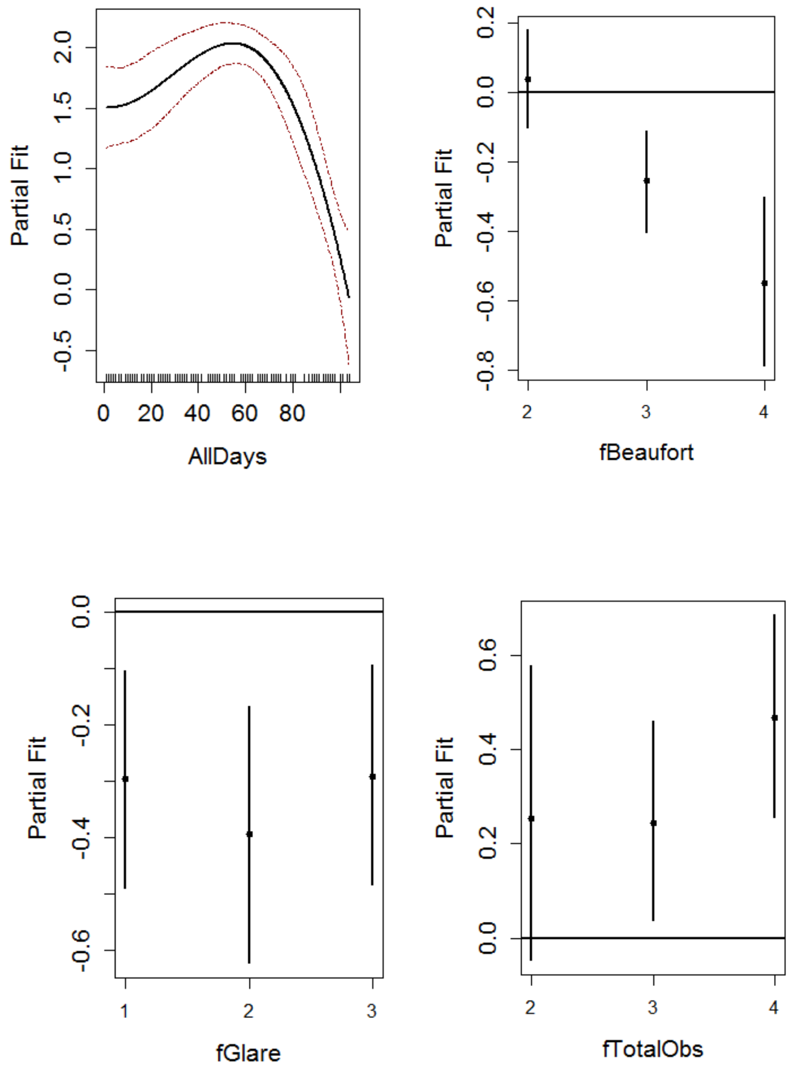

Figure 12. Partial residuals for number of groups sighted in Pender Bay as a function of Days, Beaufort condition, Glare, and Total Observers (Team size).

3.5 Distribution of Whale Groups detected

The distance from the observation site to the whale groups detected ranged from 400m to 15.57km (Figure 13). Only three observations, however, were made with calculated detection ranges beyond 10km. Detections of groups of whales were most frequent at ranges between 3 and 4km. Detections dropped off at closer distances likely due to a combination of a smaller area being sampled at close range and the decreasing water depth close to land. Detections also dropped off at ranges further than 4 km likely due to a decrease in visibility at range.

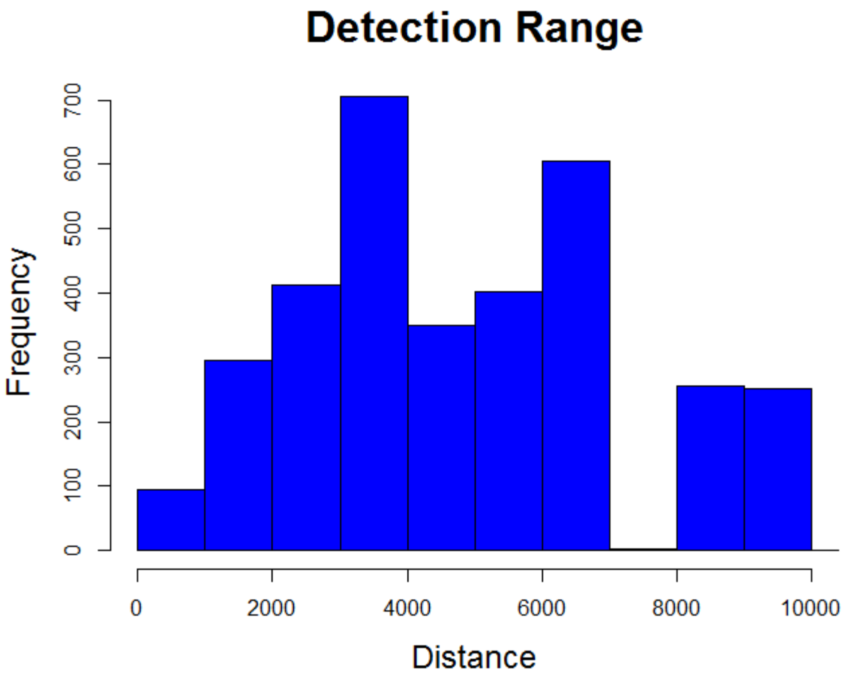

Figure 13. Detection range for first detection of all groups sighted in which the bearing and binocular reticules (down from the horizon) were reported.

The angle of detection was approximately a 180° view from the observation platform (Figure 14). Because of the limited level of precision using reticules at larger distances, 'lumping' is apparent in 'bands' of sightings (Figure 14), however, the information is useful in giving a general representation of distribution, and in particular within 4km of the land station (given the drop-off in detection with range). From the distribution of groups of whales plotted on the map, there is a clear decreasing trend in numbers towards the inside of Pender Bay (towards the east) (Figure 14).

Sightings of whale groups were almost entirely limited to water depths greater than approximately 5m at LAT (Lowest Astronomical Tide chart datum) (Figure 14). This appeared to be fairly consistent, although the subset of dates (equal number of dates selected for each 15 day block) show a higher density in close to the land station in August than in other months, and perhaps a slightly increased relative number further inside the bay towards the second half of August (Figure 15). Sightings of groups containing confirmed cow-calf pairs were observed to have a similar general distribution as other groups, ranging into the shallow waters of 5-8 m LAT (Figure 16).

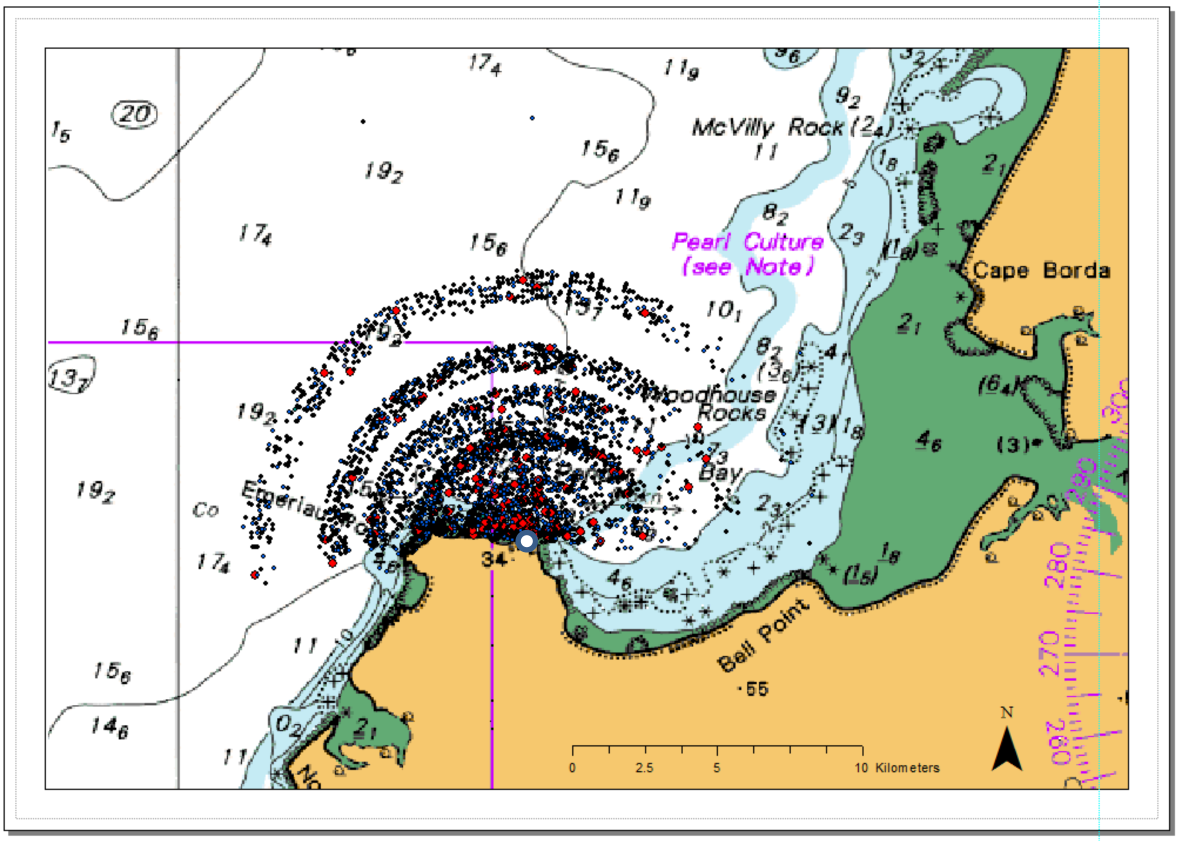

Figure 14. Detections of whale groups and estimated positions using reticule binoculars and compass from the observation platform (white circle). Black circles represent groups with at least one animal, blue circles are groups with confirmed multiple animals, and red circles are groups with cow-calf pairs. Obvious outliers (groups positions located on land) were removed.

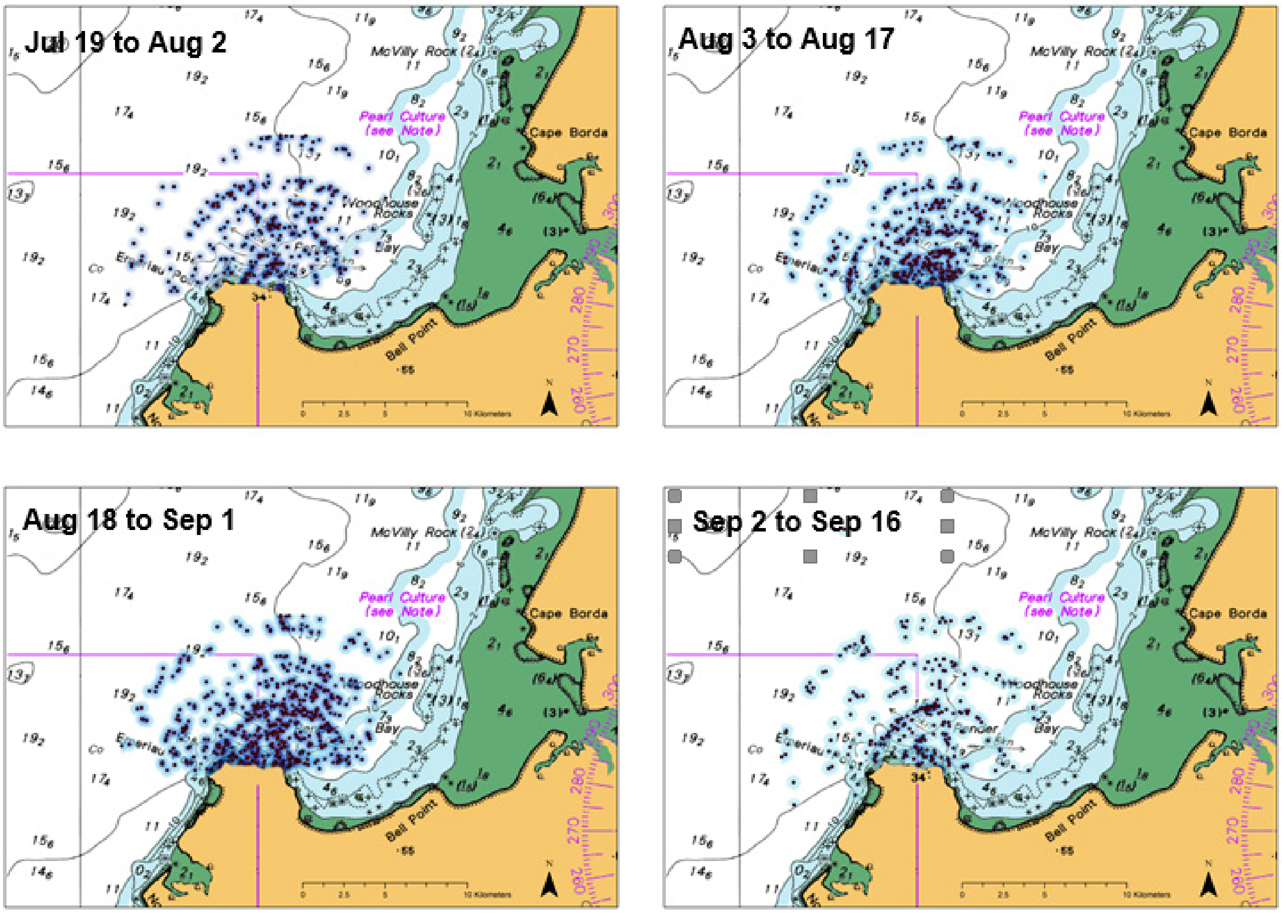

Figure 15. Detections of whale groups and estimated positions using reticule binoculars and compass from the observation platform (dark red dots) during 15-day blocks throughout the season. Kernel densities are overlayed in blue shading. Obvious outliers (groups positions located on land) were removed.

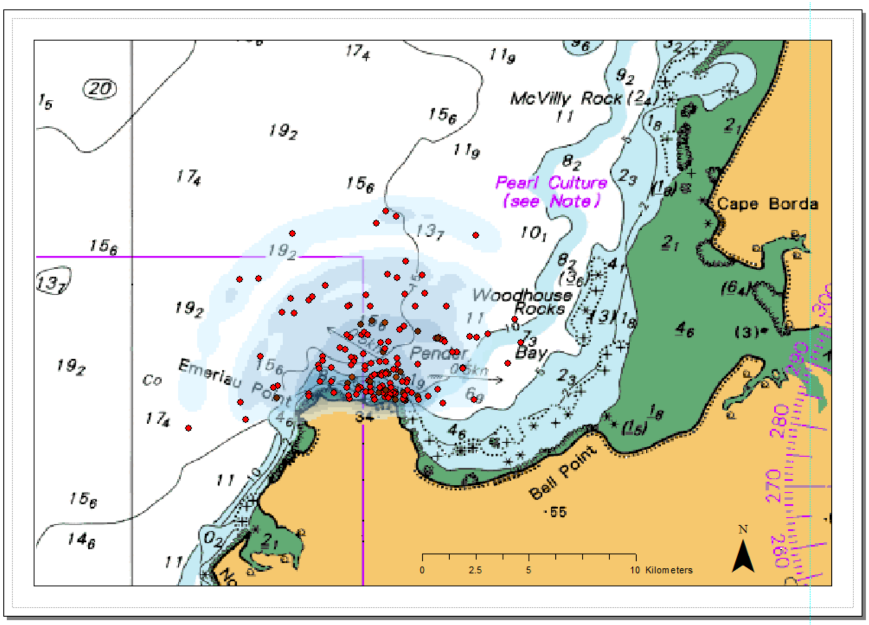

Figure 16. Detections of groups with cow-calves and estimated positions using reticule binoculars and compass from the observation platform over the entire season. Kernel densities are overlayed in blue shading. Obvious outliers (groups positions located on land) were removed.

Sea surface temperature increased steadily over the migration period from approximately 22 to 27°C. During the first half of the season, there was a steady rise in the mean number of groups of whales detected per 5-min scan. During the latter half there was a decrease in numbers of groups of whales detected (Figure 17). These data were not analysed further due to the limited number of days sea surface temperature was sampled.

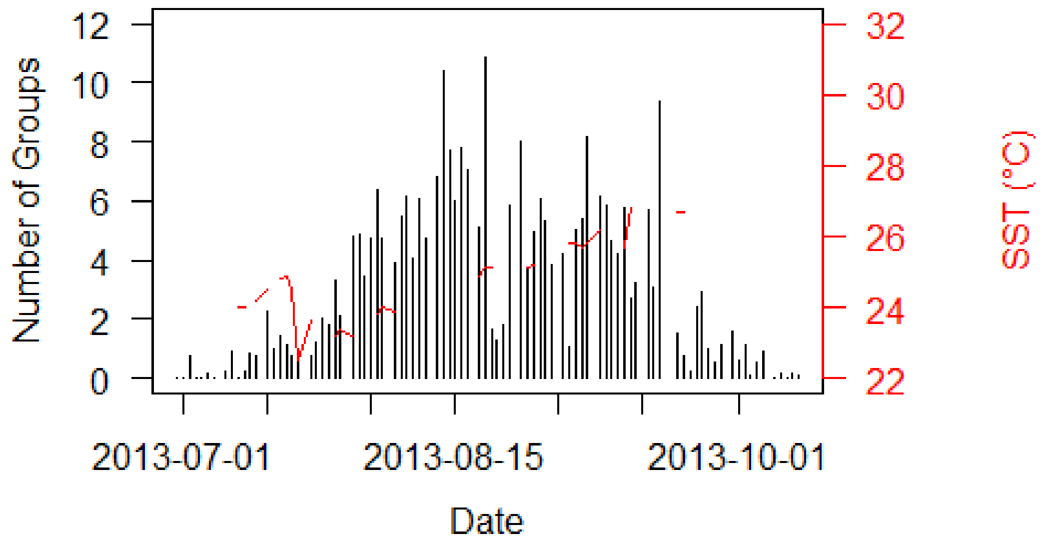

Figure 17. Mean number of groups of whales per day (over five minute scans, bars) overlayed by mean sea surface temperature in Pender Bay (SST, red line).

4 Discussion and Conclusions

4.1 General results for the season

Counts of groups of humpback whales peaked in late winter and early spring (between mid-August and September) in Pender Bay, of which the maximum number of groups of whales reported at any one time (a single scan count) was 18. This peak in the whale season is consistent with previous years' data (2009-2012) as reported by Blake and Dapson (2013) and with that reported by How et al (2013) using commercial whale tour operator data. There was a peak in reports of groups with cow-calf pairs and in the largest groups at the same time. Whereas groups containing single animals peaked just before and just after the peak in groups with cow-calf pairs. An overall greater proportion of groups contained calves at the beginning of the migration season (in July). This is early in the northern migration season and may suggest that calves are being born near Pender Bay. Some care must be taken in the interpretation of these patterns as, for example, a sighting of a single whale could have been in reality a group of 3 whales with only one whale in the group detected. Given the distance of the land based station to many of the sightings and the smaller size of calves making them more difficult to detect than adults, calves may also be under represented. The relative pattern observed could be due to the real pattern in numbers of the various group types, or a shift in distribution and/or behaviour of the different group types so that they have a greater detection probability (either they are at a closer range to the observers or the individuals are at the surface for longer periods and/or more visible). Overall, for this study, whale groups with calves are a minimum representation of calves that could have been present. The largest groups were detected in September which may be indicative of increased social activity, including mating, as well as an increase in the number of whales migrating south.

While the analyses showed that the general trend in whale presence over time was the most significant, the number of groups observed was also influenced by the variability in team size, and environmental conditions. An increase in number of observers only resulted in an increase in the number of whale groups sighted when the team size was 4, meaning that the increase in groups detected does not have a linear relationship with team size. There was likely an effect related to observers themselves (as a function of experience and skill), however this could not be tested as different observers were present at different times during the season for short periods. As expected, with decreased visibility (an increase in sea state) the number of whale groups detected also decreased. To carry the analyses to the next stage (i.e. correcting for the effects of environmental conditions and predicting numbers given constant conditions), an experiment would be required designed specifically to test for these effects. Standardising a methodology to correct for such effects in 'citizen' science observations would allow for more robust analyses with seasons and among years for trend detection.

The relationship between sea surface temperature and number of whales was briefly explored, however these data were not analysed further due to the limited number of days that sea surface temperature was sampled. Interestingly the peak in calves sighted coincides with SST of 25° SST. Over the migration there is a 5° difference in SST between the beginning (22°) and end (27°) of the migration. Water temperature may be a trigger for migration, however a long-term dataset would be required to test such hypotheses. The majority of sightings were within the 10-20 m water depth range. There were fewer sightings of whale groups where the water was shallower than 5m or less in the Eastern part of the bay. A long term data set of water temperature and fine scale bathymetry would allow for a better understanding of habitat use. Furthermore simultaneous observations conducted on a vessel will provide information on distribution further offshore.

4.2 Changes to data collection methods and how this will improve understanding

Minor changes were made to the data collection method that should improve the confidence in data collection and its utility an application to appropriate analysis techniques. For example, the interval between sampling periods was extended to reduce observer fatigue throughout the survey session. Sampling design, in particular decision making about morning vs afternoon sampling, was also standardized to ensure an even distribution of data throughout the day so that temporal patterns in distribution could be explored. Overall these changes should add value to the citizen science style project by providing a straightforward and not too onerous data collection methodology that, with a good team leader, should result in consistent and quality data collection. Given that this research is undertaken in a remote region under often taxing conditions (heat and sun exposure) means of minimizing additional stress to the observers is important to ensure confidence in the data.

4.3 Recommendations for future research or monitoring

Land based viewing platforms can provide a cost effective means of acquiring data on whales that can be used for management and other purposes. Most important though is to have a clear question in mind and to ensure that the data that can be collected can meet this purpose. The land-based site at Two Moons Whale Research Station can be used to collect data that will inform regional managers about the timing of the humpback whale migration season, as this can vary annually, including the timing and density of mother and calf groups. It can also be used as an indicator of the extent of use of Pender Bay by humpback whales, including changes in timing and whale density throughout the migration season.

Additional research would be useful that could link the relative abundance and density of humpback whales sited at Pender Bay with the broader Kimberley so that this land based site could be used as a broader indicator of population health across the broader region. Other specific research projects that would add value to our understanding of whale use of Pender Bay would include assessing whale distribution in relation to water depths or bottom features in the vicinity of Pender Bay and experimentally testing the effect of some of the environmental and observer variables noted in section 4.1 above so that these could be accounted for in a standardized methodology and analysis.

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6 Acknowledgements

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7 Appendices

Appendix 1. Pender Bay Humpback Whale Monitoring: Field Manual 2013

Pender Bay Humpback Whale Monitoring: Field Manual 2013_WAMSI KMRP Project 1.2.1_Chapter 3_ Salgado Kent et al._2018. (*Manual being updated. Will be online shortly)

Chapter 4: Strengths and weaknesses of humpback whale survey techniques in the Kimberley and recommendations for future monitoring

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1 Introduction

In this WAMIS study we have analysed data from a range of survey platforms and using a range of survey methods and included an emerging technique to count whales – very high resolution satellite imagery. Here we assess the strengths and weaknesses of each technique and attempt to assist in determining options for monitoring humpback whales in the Kimberley that provide the best approach to achieve the main management objectives while considering costs.

2 Methods

We costed each of the survey types used in the analysis here with costs based on the most recent survey of each type. Only data collection costs were included and not those for data analysis. Other strengths and weaknesses were also assessed but not on monetary terms. We assessed each of the methods in relative terms on degree of expertise required, ability to answer key management questions, the spatial coverage and any additional pros and cons. The resulting assessment is presented as a table and is designed to assist natural resource managers and decision makers to determine the best approach to achieve their specific management objectives while considering costs.

Rather than assess methods on a technique basis generically (i.e. boat survey versus aerial survey) we assessed the combination of the technique and the suggested sites and spatial coverage for such a technique to be used for humpback whales in the Kimberley. These included: 1. Aerial survey of abundance of the entire humpback whale area of use in the Kimberley, 2. Vessel survey of abundance using areas of high humpback whale density in the Kimberley, 3. Vessel survey of whale presence (direct counts) using areas of high humpback whale density in the Kimberley, 4. WorldView-3 survey of areas of high humpback whale density in the Kimberley, and 5. Land based survey at the humpback whale area a high density at Pender Bay. These are explained below.

Justification of assessed methods

Although aerial surveys can be done on variable spatial scales, here we specifically assess aerial surveys over the whole Kimberley region found to be used by humpback whales in this report (Eighty Mile Beach to Camden Sound) using a zigzag pattern similar to Figure 1b. This assessment is based on the use of systematic sampling and distance sampling methods (Buckland et al. 2011) so that absolute abundance can be calculated and trends monitored over time. Even though such surveys are high cost and need a high level of expertise, they are considered the best from the perspective of being able to address all the key management objectives. Such a survey would ideally be conducted at two weekly intervals over the humpback whale season (mid-July to mid-October). However, as cost will often be a deciding factor, smaller spatial extents might need to be considered in addition to cheaper (and safer) platforms. For example, aerial surveys may be made safer by replacing observers with digital cameras and/or with the use of long range drones (See Hodgson et al. 2013), however these options are not always more cost effective.

From the work done in this report, there are several locations predicted to be the most densely used areas within the Kimberley region and systematic sampling of these areas can reduce costs compared to surveying the entire region. These include the region in and around Pender Bay (including along the Dampier Peninsula), Camden Sound and Tasmanian Shoal region and Eighty Mile Beach. Of these, two locations have been identified as being of particular interest to ongoing management based on the large numbers of mother calf pairs and likelihood that they are breeding or nursery areas – Camden Sound and Pender Bay. Camden Sound has a whale sanctuary zone within the Lalang-garram/Camden Sound Marine Park, thus requires management; while the Pender Bay region was found to have the highest densities of whales in this study. Consequently, these two locations are recommended as priority locations for future monitoring, where resources limit broader coverage. Although these surveys could equally be done with an aerial platform, we assess them based on the use of boats and VHR satellites.

The Western Australian State Government owns assets in the form of survey vessels (Department of Fisheries, Department of Biodiversity, Conservation and Attractions) which could be used to reduce costs. We have assessed vessel surveys based on the use of systematic sampling and distance sampling methods (Buckland et al. 2011) in order to have the ability to correct for bias and calculate an abundance estimate. These methods involve measuring the range and bearing of observed whales from the vessel. Range and bearing can be determined from measures of distance down from the horizon and compass bearing obtained from marine binoculars fitted with a compass and reticules. These methods are strongly recommended where they can be implemented, but we also assess a simpler version of vessel surveys (direct counts of whales without recording range and bearing, Fig. 1). While such surveys cannot monitor trends in abundance they can be used for monitoring relative abundance and recording other things such as calf presence, whale behaviour, boat traffic, etc, all of which will inform different management questions.

Continued monitoring at Camden Sound and the Pender Bay region will also benefit from comparisons to previous work conducted there; including the recent satellite imagery in Camden Sound and a 2008 vessel survey and long-term community land-based monitoring program at Pender Bay. The latter two survey techniques were also assessed here.

3 Results

3.1 Cost and assessment of each survey method

In comparison with previous aerial and vessel surveys, the costs associated with tasking the WorldView-3 satellite appeared relatively high. The cost for both the panchromatic and 8 multispectral bands is US$56 per square kilometre. The lowest cost option for the panchromatic band, which does not include all spectrums (no infrared) for WorldView-3 was US$51 per square kilometre, giving a total cost of US$21,675 per sample day. These have been converted to Australian dollars in table 1.

In comparison, costs of an aerial survey in 2007 (the most recent sampling event) that was flown over the entire Kimberley region were much lower per square kilometre than satellite imagery (~ AUD$1.13/km^2 vs. ~ AUD$75/km^2). The costs per square kilometre to fly a distance sampling survey was inclusive of plane, pilots (2), observers (4), landing fees, accommodation and equipment. This allowed for 1444 km of linear trackline to be flown at a speed of 220 km/hr for 6.5 hour, about the longest aerial observers can be expected to be able to maintain concentration and included a one hour break on the ground in the middle of the flight. A day of flying cost AUD$18,000 (including data transcription costs) plus an initial investment of $15,000 to set the observers up with intercoms, GPS, laptop, clinometers.

Vessel surveys have cost structures that are variable and dependent mainly on the size of the vessel, whether the survey is dedicated or piggybacked (costs shared) and usually require more personnel and for longer periods of time. A typical day rate for a 24 m vessel capable of operating for 2 weeks at a time in the Kimberley with up to 10 personnel onboard may be AUD$12,000 per day including fuel and wages (including time on survey and later for data transcription) and would be capable of surveying 2200 km^2 per day (Table 1). However, if an existing State Government asset and observer team (rangers) can be utilized, these costs become negligible and the vessel surveys become an obvious choice for long term planning.

The season cost to get the management answer considered the number of surveys that would be required in a season to provide a quantitative assessment of the whale population relevant to management, aerial surveys were the most expensive (based on 10 surveys), followed by satellite surveys (based on 5 samples), and then vessel surveys (10 survey days).

The assessment of each of the methods is presented in table 2 and ranked by our recommendations if cost was not a consideration.

Table 1. Costs for each of the three survey platforms, based on the most recent aerial and vessel surveys of the Kimberley conducted by CWR. The satellite survey was based on the costs of tasking the WorldView-3 satellite here.

Item	Satellite	Aerial	Vessel
Cost/Day (AUD)	30,000	18,000	12,000
Coverage/Day (km^2)	425	14,400	2,200
Rough Cost/km^2 AUD	71	1	5
Season Cost to get management answer	$150,000	$180,000	$120,000

Table 2. Assessment of each of the survey methods in relative terms.

								Ability to answer key management questions/concerns				
Method	**Cost**	**Spatial coverage**	**Expertise for study design**	**Data analysis skill required**	**Data collection degree of difficulty**	**Pros**	**Cons**	**Monitor abundance trends**	**Model distribution & environmental associations**	**Identify areas of importance (hotspots)**	**Record behaviour and calf presence and diagnostics**	**Monitor temporal trend in numbers throughout season**
Aerial survey (abundance) e.g. zigzag survey similar to 2007 survey (Fig. 1b from Chapter 1) but extending from Eighty Mile Beach to Camden Sound every 2 weeks during the season.	High	Large	High	High	High	Can obtain absolute abundance over the whole Kimberley area used by humpback whales	A high level of expertise is required	Yes	Yes	Yes	No	Yes and will be absolute abundance
Boat survey (abundance) Using red and blue transect lines over hotspot area of Camden Sound and/or Pender Bay (fig 1) and conducted at peak season and 1-2 weeks either side (minimum)	Medium	Medium	High	High	Medium	Opportunity for other sampling (e.g. record other species, genetics, health status, mark recapture)	Limited spatial and temporal coverage	Yes but only in hotspot areas and use may not be consistent over time	No (unless expand to other areas besides hotspots)	No (see left)	Yes	No (but can monitor relative abundance if data collected regularly through whole season)

Very high resolution satellite imagery using snapshots of WV3 of peak and either side of peak season at Camden Sound and/or Pender Bay hotspots separated by 1-2 weeks.	High	Small	Medium	Low to medium	Low	Can be mobilised relatively quickly. Low effort for data collection as done remotely. Counts can be done by automated methods.	Only feasible for small spatial scales. Rough sea and cloud cover at time of image capture will obscure whales.	Potentially (but still work to be done to determine this and count only relates to the area where imagery was captured)	No (unless expand to other areas besides hotspots)	No (see left)	No	No (unless imagery collected regularly throughout entire season)
Boat survey (presence/direct counts) using priority (red) survey lines (Fig. 1) over hotspot area of Camden Sound and/or Pender Bay and conducted 1-3 times around peak season separated by 1-2 weeks.	Medium	Small	Medium	Medium	Medium	Opportunity for other sampling (e.g. record other species, genetics, health status, mark recapture)	Non-systematic survey design so cannot monitor trends in abundance	No	No (unless expand to other areas besides hotspots)	No (see left)	Yes	No (but can monitor relative abundance if data collected regularly through whole season)
Land-based survey at Pender Bay conducted over the entire humpback season	Low	Small	Medium	Medium	Medium	Ability for community involvement	Only small spatial scale, with only partial coverage of the Pender Bay hotspot.	No	No	No	Yes	Yes but relative abundance

3.2 Vessel survey recommendations

An example of transects that could be used to survey Camden Sound and Pender Bay have been included here (Figure 1). Survey transects have been designed as the main 'priority' transects (thick red zigzag transects in Figure 1). These could be done as direct counts rather than as abundance surveys, however the latter are recommended. The Camden Sound priority transects intersect the 'suitable habitat' for cow/calf groups (thin green line, Fig. 1) and the length of recent satellite imagery, while the Pender Bay priority transects cover the area with both high habitat suitability and high whale density were predicted and with the past 2008 vessel surveys by CWR. Survey transects that can be performed opportunistically (either the entire transects, or partial coverage of transects) have also been included (blue transects in Fig 1). These will allow for greater coverage and replication of transects and can be undertaken when the vessel is transiting the region.

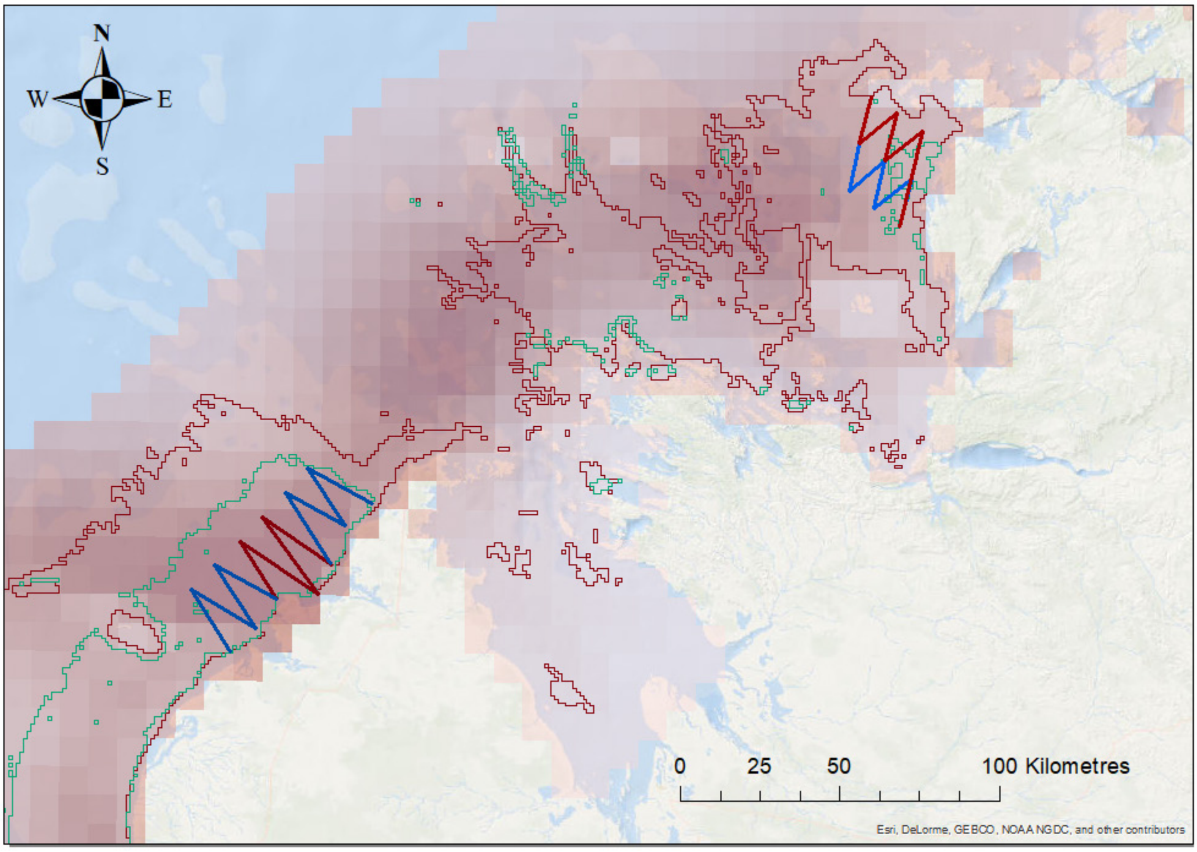

Figure 1. Suggested line transect design for humpback whales in Camden Sound and Pender Bay for state government survey vessels transiting the Kimberley region. Thick red lines show priority surveys and thick blue lines show expanded surveys to be undertaken opportunistically. Predicted whale density from the density surface model is shown in pink colours, thin red line and green line shows the predicted suitable habitat from the Maxent model for all whale groups combined and for groups with calves respectively.

A zigzag design has been suggested to reduce the time required in box-end designs to transit between transects, thus enabling an additional transect in the design that would otherwise not be possible to include. Transects in the zigzag design are 10 km apart at their widest distance. The maximum detection range of whales should be determined for each survey vessel; which is generally ~2-3 km (for far-off breaching whales) from low observation platform. The maximum detection range can be obtained by estimating the distance to the horizon from the vessel using the observer's height above the sea surface in triangulation calculations (Buckland et al. 2011). Based on the maximum detection range, the length of converging transects that have overlapping areas of observations can be determined. In these sections of the transects, observers can identify whales already observed in the previous transect to ensure that they are not double counted. The length of converging transects having some common overlapping observation areas is anticipated to be less than a fifth of the transects. If high densities make identifying whales observed from both transects prohibitive, adjustments can be made during the analytical stage by reducing the half strip-width to 1 km and clipping the transects to exclude the last few hundred meters.

Priority surveys (CS Survey 1 and PB Survey 1 in Fig 1) are recommended to be conducted as many times as possible during the whale season (mid-July to mid-October), with a minimum of one to three times (three being preferred) in mid-August. Three during the August peak season (say spaced a week or so apart) would allow for more reliable comparisons, since the timing of the peak can vary. In addition, communication with researchers, communities and managers conducting studies elsewhere along the migration path may aid in selecting the most probable peak in the Kimberley (based on trends in abundance at points along the migration). The surveys can be conducted from north to south or south to north for Pender Bay, and east to west or west to east for Camden Sound. The priority Pender Bay survey covers a total of 103 km and the Camden survey 89 km. Surveys should be attempted when wind conditions are 15 knots or less and in daylight hours only, and at vessel speeds of 8 – 10 knots. At these speeds, the priority Pender Bay survey could be covered in 6-7 hours and the Camden Sound priority survey in 3-4 hours. All other opportunistic surveys will take less than 5 hours, with the shortest 54-km opportunistic survey (CS Survey 2) estimated to take 3-4 hours. The location of waypoints at each vertex have been included here for practical implementation (Table 3).

Table 3. Waypoints for the surveys shown in Fig. 1.

Survey	Waypoint	Latitude	Longitude
PB Survey 2	1	-16° 55.50′	122° 25.26′
	2	-16° 44.28′	122° 18.66′
	3	-16° 51.36′	122° 29.64′
	4	-16° 40.38′	122° 22.56′
	5	-16° 46.38′	122° 33.18′
PB Survey 1	1	-16° 46.38′	122° 33.18′
	2	-16° 36.24′	122° 26.76′
	3	-16° 45.12′	122° 40.38′
	4	-16° 32.52′	122° 30.66′
	5	-16° 40.14′	122° 42.48′
PB Survey 3	1	-16° 40.14′	122° 42.48′
	2	-16° 27.72′	122° 34.38′
	3	-16° 33.30′	122° 44.76′
	4	-16° 23.82′	122° 38.10′
	5	-16° 30.00′	122° 49.32′
CS Survey 1	1	-15° 42.96′	124° 18.42′
	2	-15° 26.82′	124° 22.56′
	3	-15° 31.56′	124° 16.14′
	4	-15° 24.12′	124° 18.00′
	5	-15° 28.86′	124° 11.76′
	6	-15° 21.00′	124° 13.62′
CS Survey 2	1	-15° 33.00′	124° 20.46′
	2	-15° 40.26′	124° 14.28′
	3	-15° 31.56′	124° 16.14′
	4	-15° 36.54′	124° 10.32′
	5	-15° 28.86′	124° 11.76′

4 Discussion and conclusions

Future monitoring of humpback whales in the Kimberley will need to be cost effective and likely multi-purpose. Aerial surveys answered the most key management questions/concerns assessed here but cost and expertise required for conducting the surveys was high. If funding and expertise was available we recommend aerial surveys using a similar survey design as the CWR 2007 surveys (Figure 1, Chapter 1) but extending from Eighty Mile beach to Camden Sound. Annual aerial surveys are necessary to monitor trends in absolute abundance of the Kimberley humpback population, but many years of systematically sampled data are required (often decades) to effectively monitor trends. The costs of aerial surveys were cheaper per square kilometre than the other two methods but the season cost to obtain the management answer was the most expensive. Importantly, the costs do not include analysis and for aerial and vessel surveys of abundance these can be high (up to $100K). There are some other important considerations of aerial surveys and that is that key components must already be in place, such as equipment, experienced observers and pilots. Today, workloads are declining and as a consequence experienced personnel are becoming harder to find. In addition, there are a number of safety concerns for aerial surveys with loss of life of researchers and pilots around the world. But the use of cameras over observers may reduce some of the risk and the use of drones with ability to cover large distances (See Hodgson et al. 2013) may also be a low risk option. However, such long range drones will likely be as or more expensive than planes. In addition, the choice of study type and platform becomes complicated for situations where long term planning is not possible. For example, if it was known that funding was available to monitor whales in the Kimberly for five years, then planning aerial or vessel surveys may be the best options. However, if funding is intermittently available, then satellite imagery might be the best short term solution.

Satellite imagery has the advantage of being able to be analysed by one or two people and tasked at very short notice (10-14 days although success depends on commitments), so can be flexible in response to available funding. It can also be cancelled at short notice so that budgets can be deferred until the next season, something that is problematic once an aerial survey team is mobilised. A transition from aerial survey to satellite imagery is the next step in remote area management, but given the current very high costs of satellite surveys per square kilometre, they are only currently suitable for smaller areas (e.g. Camden Sound and Pender Bay). But costs will decrease over time and it may be that this becomes the best long term solution for population monitoring. It may take 5-10 years for the technology to become cheap enough to obtain imagery over the entire region used by humpback whales in the Kimberley, which is what is required to be able to have an abundance estimate for the whole region as there are so far no methods to extrapolate abundance from smaller to larger areas as is the case with systematic sampling from aerial or boat platforms.

While budgets for satellite surveys are presently difficult to identify from year to year, the WA State government is required to monitor the Marine Park and, as such, employs rangers and funds vessel patrols. These patrols can be used to undertake surveys, but in order to be able to monitor trends in abundance, a systematic sample design is required including measurements of range and bearing to each whale observed recorded (See Buckland et al. 2011). Observer training is paramount to ensure that this is done in a robust manner. If funds or expertise are not available for this to be successful then relative abundance estimates might be all that is provided from vessel surveys via direct counts along the track line. Although these direct counts are much less reliable for monitoring abundance trends, in the absence of anything else they might provide an early warning system of change in the population and can also provide other important information on calf presence and diagnostics. This is important information for distinguishing between calving and nursing/breeding areas which is important data needed for future management.

The last systematic survey of the abundance of humpback whales in the Kimberley region occurred in 2007 (CWR aerial survey). This combined with the growing vessel use of the marine environment of the Kimberley through both industrial development and tourism, highlights that this data is in urgent need of updating and to effectively monitor trends, many years of systematically sampled data are required (often decades).

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