Modern and historical data identify sperm whale (*Physeter macrocephalus*) habitat offshore of south-western Australia

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Declaration

This project thesis is derived from my own research.

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Abstract

The distribution and use of pelagic habitat by sperm whales (*Physeter macrocephalus*) is generally poorly understood in Western Australia. However, a variety of data are becoming available via online portals where records of historical expeditions, commercial whaling operations, and modern scientific research voyages can now be accessed. Crowdsourcing these online data allows collation of presence-only information of offshore animals such as sperm whales and provides a valuable tool to help augment areas of poor research effort and fill in the gaps. Four data sources were examined, the primary one being the Voyage of the *Odyssey* expedition, a five-year global study of sperm whales and ocean pollution. From December 2001-May 2002, researchers surveyed 5200 nautical miles off Western Australia including historical whaling grounds off Albany and the Perth Canyon, an area previously known for pygmy blue whale distribution, using acoustic techniques and obtained 57 tissue biopsies. To augment areas not surveyed by the RV Odyssey, historical Yankee whaling data, commercial whaling data, and citizen science reports of sperm whale sightings were used. Using Maxent, a species distribution modeling tool, we found that the submarine canyons off Albany and Perth provide important habitat for sperm whales. Recent management measures implemented by the Australian government in this region were evaluated with respect to the sperm whale distribution model and only 1.8% of their predicted habitat occurs within a designated IUCN marine protected area restricting offshore activities.
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1. Introduction

Sperm whales (*Physeter macrocephalus*) inhabit and forage in deep offshore areas around the world and were hunted extensively across all oceans for two centuries (Whitehead, 2002). Historical whaling records indicate that, until 1978, sperm whales were hunted in Western Australia for commercial purposes (Townsend, 1935; Chittleborough, 1956; Bannister, 1968; Bannister *et al.*, 1996). However, little data exist from Western Australia on sperm whale abundance and distribution, and indeed, worldwide, offshore distribution of sperm whales and their habitat use is poorly understood (Whitehead, 2003).

In the southern hemisphere, females and young male sperm whales inhabit warmer waters north of 45°S, while adult males travel to and from the colder waters of Antarctica to mate with females. Currently, sperm whales are listed as ‘vulnerable’ under the World Conservation Union’s (IUCN) Red List of endangered species (Taylor *et al.*, 2008) because of selective take resulting in depletion of males in the population off south-western Australia, and the subsequent lack of information on possible recovery since then (Bannister *et al.*, 1996).

Under the Australian *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), all cetaceans are protected throughout the Australian Whale Sanctuary which includes all Commonwealth waters from the three nautical mile state waters limit out to 200 nautical mile boundary of the Exclusive Economic Zone (EEZ). In addition, all states protect cetaceans within three nautical miles of the coast. Further, informed by the EPBC Act, and to meet its international and national policy commitments, the Australian Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) promulgated marine protected areas within various marine bioregions of the EEZ around Australia. In the South-west marine bioregion, 13 key ecological features such as canyons, upwelling areas, rock lobster
distribution and fish communities have been identified and the subsequent plan has demarcated fourteen marine reserves within the bioregion (Figure 1). Each protected area has been assigned an IUCN reserve category and together with the EPBC Act these broadly determine what activities can and cannot be conducted within them (Australia. Director of Parks, 2013).

Figure 1. The South-west marine bioregion with protected areas demarcated based on various IUCN categories (Australia. Director of Parks, 2013).

The submarine canyons (steep-sided valleys on the continental slope) off south-western Australia have been identified as key ecological features in the South-west marine bioregion as they are linked to localised, periodic upwellings that enhance productivity and attract aggregations of marine life including cetaceans (Rennie et al., 2009). Their higher productivity leads to marine megafauna often inhabiting or feeding in them thereby making them important areas to consider in systematic conservation planning (Hooker et al., 1999; Hooker & Gerber, 2004).
1.1 The Voyage of the Odyssey expedition

The primary dataset in this study is from the Voyage of the Odyssey — a five-year, global, scientific expedition studying sperm whales and ocean pollution led by Dr. Roger Payne and Dr. Iain Kerr of the United States non-profit research group, the Ocean Alliance (Bohannon, 2004). From 2000 - 2005, the research vessel Odyssey, a 28 m motor-sailing ketch equipped for open ocean cetacean research, collected tissue biopsies from sperm whales throughout the Pacific, Indian, and Atlantic Oceans and Mediterranean Sea (Wise Sr. et al., 2009; Savery et al., 2013a; Savery et al., 2013b). Although primarily a toxicology voyage, other opportunistic research was conducted and included sightings surveys in regions with little or poor cetacean research effort (Anderson et al., 2006; Clark et al., 2012; De Vos et al., 2012) and acoustic studies on individual species (Madsen et al., 2002b; Madsen et al., 2004).

From December 2001 - May 2002, the RV Odyssey surveyed areas off the Perth Canyon, Albany Canyon, and offshore in the traditional Yankee whaling area (New Holland Grounds) in transit to the Cocos Keeling Islands. Additional data collected by the expedition included acoustic detections, audio recordings, sightings of animals and environmental conditions.

1.2 Western Australia – a whaling past

Sperm whales were hunted off the Western Australian coast as part of two major historical phases of sperm whaling – the open boat hunt conducted under sail by whalers from the United States, Britain, France and Germany (1712-1920) (Bannister et al., 2008), and the commercial, mechanised hunt (1904-1999) (Whitehead, 2003).

American Yankee whalers focused hunting effort on seven species of whales including the sperm whale (Smith et al., 2012). Men undertook long voyages of several years on sailing vessels in order to hunt sperm whales specifically for the spermaceti oil contained in their noses (Beale, 1835). This oil was primarily used for making candles.
and lamp oil and the commercial demand sent Yankee whalers across the globe in their
hunt. Townsend (1935) compiled whaling records and logbooks kept by the Yankee
whalers from 1761-1920 (Figure 2). Yankee whalers made it to the waters off Western
Australia, primarily hunting both sperm whales and southern right whales until the early
1900s (Townsend, 1935; Torres et al., 2013).

Figure 1. Charts detailing sperm whale kills across the globe during the months of April-
September 1761-1920 (Townsend, 1935).

Antarctic whaling commenced in 1904 and was based in South Georgia Island in
the South Atlantic. The ‘pelagic’ mechanised whaling era operated on the high seas and
by 1924, floating factory ships were the norm (Hjort, 1937; Whitehead, 2003). Stocks
of large Mysticetes (baleen whales) and Odontocetes (toothed whales), including sperm
whales, declined rapidly around the world during this time.

Sperm whales were hunted commercially off the Western Australian coast
primarily off the continental shelf near Albany and in the New Holland grounds off
Carnarvon (Chittleborough, 1956) and to assist whalers, aircraft were often used to spot
sperm whales (Bannister, 1968). In the era of pelagic whaling, there was no
management or regulation of whaling until the formation of the International Whaling
Commission (IWC) in 1946. In Australia, commercial whaling ceased in 1978
(Bannister et al., 2008) and then globally in 1986 (Whitehead, 2003). Modern whaling
methods of the 20th century reduced the global population of sperm whales significantly and remain the greatest influence on their current conservation status with an estimated global population of approximately 360,000 animals (Whitehead, 2002).

1.3 Sperm whales – a global distribution

Females, calves, and juvenile male sperm whales inhabit tropical and temperate waters of the world’s oceans. At the onset of puberty, males leave their natal groups, and head for polar waters where groups of males contain fewer, but larger, individuals. When mature, males then return to the tropics where they encounter and mate with groups of females (Whitehead & Weilgart, 2000).

Around the world, typical sperm whale foraging habitat is along continental slopes and ridges including areas of high bottom relief (Jaquet & Whitehead, 1996a; Hooker & Whitehead, 1999; Pirotta et al., 2011), coastal upwelling of cold, nutrient-rich waters (Rendell et al., 2004b), thermal fronts (Griffin, 1999) and areas of high primary productivity (Jaquet & Whitehead, 1996a). These features lead to concentrations of prey for sperm whales, mainly meso- and bathypelagic squid (Hooker & Gerber, 2004), though fish contribute to their diet in some regions (Clarke, 1996; Whitehead, 2003). In southern Australia, there is evidence that the diet of sperm whales is dominated by oceanic subtropical and muscular cephalopod species demonstrating a high degree of individual variability (Evans & Hindell, 2004).

Sperm whales are highly acoustic animals that use echolocation, a process whereby they emit powerful, regular, highly directional clicks of frequencies of 8-26 kHz almost continuously to navigate and find prey (Gordon, 1987; Gordon, 1995; Jaquet et al., 2001; Møhl et al., 2000; Madsen et al., 2002b; Walhberg, 2002). On average, they spend more than 72% of their time in foraging dive cycles with durations that can last up to an hour to depths averaging 400-1200 m and up to 2000 m (Watwood et al., 2006).
Sperm whales can maintain and regulate acoustic outputs, and the sound-generating mechanism has a bimodal function that allows for the production of clicks suited for biosonar, and clicks more suited for communication (Madsen et al., 2002b). Codas are echolocation sequences of 3-40 broadband clicks generally lasting < 3 seconds that serve as unique identifiers for whales (Watkins & Schevill, 1977a; 1977b) and indicate social structure and culture in the species (Whitehead, 2003; Rendell & Whitehead, 2004a). Codas are strongly linked to social behaviour of female groups and have been recorded in breeding areas (Weilgart & Whitehead, 1993; Rendell & Whitehead, 2003). Sperm whales have strong social structures that can be classified as vocal clans, concentrations, aggregations, groups, and clusters (Whitehead, 2003). The known horizontal spatial patterns of social structures of females and immature sperm whales and non-breeding males are defined in Appendix 1. Slow clicks can be detected by submerged conspecifics at ranges up to 60 km and may indicate long-range sound communication (Madsen et al., 2002a).

Little is known about how sperm whales capture their prey. Past studies have suggested that sperm whales feed by either using their white jaw as a lure (Beale, 1839; Gaskin, 1964), by touch (Tomlin, 1936, cited in Berzin 1972), through passive listening (Sleptsov, 1952, cited in Berzin 1972), echolocation (Backus & Schevill, 1966), or by sight (Fristrup & Harbison, 2002).

Sound is a critical component in the study of sperm whales as passive acoustic monitoring can be used to identify ‘presence’ and abundance of cetaceans for both scientific research and mitigation activities (Mellinger & Barlow 2003; Cato et al., 2005; Barlow & Gisiner 2006; Zimmer et al., 2008; McCauley & Jenner, 2010; Gavrilov et al., 2011). In particular, sperm whales can be located and tracked using both single hydrophone and acoustic arrays towed behind a boat to listen for their echolocation clicks during foraging dives (Jaquet & Whitehead, 1996a; Gordon et al.,
1.4 Species distribution modeling

Species distribution models (SDMs) can provide quantitative predictions of geographic distributions and have been used to model historical whaling data (Gregr & Trites, 2001; Elith et al., 2006; Torres et al., 2013). Knowing where the animals are, what characteristics influence their choice of habitat, and how this choice changes with time, is important in understanding the ecology of the species, identifying critical habitat, assessing the overlap with human activities and, ultimately, guiding appropriate conservation and management efforts (Redfern et al., 2006). SDMs can be used for conservation and policy planning as they are able to predict where species are likely to occur in areas that have not been surveyed, or with poor survey effort, based on environmental and physical variables.

Presence-only records of animal sightings from sources such as museum collections, herbaria, or online databases are becoming increasingly available and provide valuable resources for modeling efforts (Graham et al., 2004; Pearce & Boyce, 2006; Elith et al., 2011). Maximum entropy modeling (Maxent) is a presence-only modeling technique that has been applied to ecological (Phillips et al., 2006; Phillips & Dudik, 2008; Elith et al., 2011) and cetacean studies (Edrén et al., 2010; T.D. Smith et al., 2012; Thorne et al., 2012). Maxent software is suitable for this study as it can model ‘presence-only’ data of various sample sizes, incorporate interactions among environmental variables, account for spatial bias in the presence data and identify areas that fall beyond the range of environmental conditions (Phillips et al., 2006).

1.5 Study objectives

The overall objectives of this study are to:

1.) examine datasets from the RV *Odyssey* including biopsy locations and acoustic monitoring to determine the locations of sperm whales off Western
Australia;
2.) use historical datasets of Yankee and commercial whaling activity, and other data available through online portals to fill the knowledge gaps, examining the abundance and distribution of sperm whales off WA;
3.) collate this ‘presence-only’ data to identify critical habitat for sperm whales in the region testing predictive species distribution modeling using Maxent, and;
4.) evaluate recent management measures implemented by the Australian government in this region relative to sperm whale distribution. Literature reviewed for this study is outlined in Appendices 2, 3 and 4.

2. Methods

2.1 Study area and time frame

The study area is offshore WA (20° S to 38° S and 100° E to 128° E). Four datasets of sperm whale ‘presence’ from 1735-2003 were examined, the primary one being the Voyage of the Odyssey expedition from 2001-2002 (Figure 3).

![Timeline of the data used in this study of sperm whale distribution off Western Australia.](image)

2.2 Data

2.2.1 Voyage of the Odyssey (2001-2002)

From December 2001- April 2002, the RV Odyssey surveyed 5,200 nautical miles of ocean off the coast of south-western Australia including five research legs in Australian waters and one offshore passage to Cocos-Keeling Islands. The primary
aim was to locate and track sperm whales using acoustic methods while they vocalised at depth, and, when they returned to the surface, obtain a tissue biopsy to later analyse for chemical pollutants (Wise et al., 2009; Savery, 2013a; 2013b).

Acoustic detections of marine mammals were made using a 100 m long hydrophone array, consisting of two Benthos AQ4 hydrophone units with Benthos AQ201 pre-amplifiers 2 m apart (Clark et al., 2012; De Vos et al., 2012). Effective listening range was 1–25 km depending on weather conditions, vocalising species, and whether the vessel was motoring or sailing (Clark et al., 2012; De Vos et al., 2012). The output signal was connected to headphones and a pair of stereo speakers located in the pilothouse. While the vessel was underway, the helmsman monitored sounds from the array continuously. When not actively tracking or biopsying sperm whales, listening stations using headphones were conducted every half hour. An acoustic stop was made on the hour with the engine turned off and thirty minutes later, the vessel was brought to a speed of less than one knot for a minimum of five minutes with the autopilot engaged. Acoustic contacts, or detections, with marine mammals were entered in Logger 2000 v 2.05, a computerised database in Microsoft Access 2000 format developed by the International Fund for Animal Welfare (IFAW). The ‘strength’ of ‘presence’ (vocalisation) was recorded on a scale of 1-5; 1 was very loud and 5 was listed as no contact.

Incoming acoustic data from the array were automatically scanned and processed in real time by the software Rainbow Click v. 1.03 (IFAW). Sperm whale clicks were recorded as a detection (or ‘presence’) using different algorithms depending on background noise levels. The ‘automated detections’ were recorded every 4 minutes in Logger 2000 along with the GPS location of the vessel every 10-30 seconds. Once sperm whales were detected, the helmsman maneuvered the vessel to derive the bearing of vocalising animals relative to it. Rainbow Click analysed the stereo signal using time
of arrival differences between the same clicks on the two channels to estimate a bearing to each click source (Clark et al., 2012; De Vos et al., 2012).

A visual watch was maintained during daylight hours (~0600 to 2000) from an observation platform located 4.6 m above water level, with a maximum sighting distance to the horizon of 4 nautical miles (7.5 km). One or two observers surveyed the area 180° forward of the vessel to the horizon by naked eye and with 7x40 binoculars (Clark et al., 2012; De Vos et al., 2012).

Observers recorded all marine mammal sightings into Logger 2000. Data included species identification, geographic position (from GPS), estimated number of animals, behaviour, water depth, bearing and distance to the vessel. Every 30 minutes, while searching for animals, environmental data were recorded including sea surface temperature and weather conditions relating to sighting ability (sea state, swell and meteorological conditions). Visual effort was suspended during times of heavy rain and sea state over Beaufort 6. Sightings within 2 km of the vessel’s track were approached to obtain species identification, photographs and to estimate group size (Clark et al., 2012; De Vos et al., 2012).

Sperm whales that were observed to be less than half the length of an accompanying animal were classified as calves; animals more than half the length of an accompanying adult, but less than full size, were classified as immature animals; and mature males were determined by their large size (estimated at > 12 m) (Clark et al., 2012; De Vos et al., 2012). Sexually mature female sperm whales were classified by the presence of callosities on their dorsal fin (Kasuya & Ohsumi, 1966; Whitehead & Gordon, 1986).

Biopsies were collected from free-ranging sperm whales with standard methods using a crossbow and a 50 mm stainless steel cylindrical biopsy dart with a floatation tip (Wise et al., 2009). Samples were taken from the whale’s flank, a location that has
been shown to elicit the least reaction (Brown et al., 1991). Photographs of individual whales were taken to minimise duplication. Samples were removed from the biopsy dart and divided into two pieces at the interface between skin and blubber. These two pieces were stored separately for later genetic and metal analysis. All tissue samples were frozen at -20°C within a few minutes of collection and the samples were later shipped frozen to the Ocean Alliance laboratory in the United States. To ensure that there was no contamination of the sample by the biopsy dart, these tools were rinsed extensively and cleaned between each use (Wise et al., 2009).

DNA was extracted from a piece of whale skin using standard methods (Alijanabi & Martinez, 1997). Gender was determined by PCR amplification reactions in which the SRY (male determining factor) gene was amplified according to published methods (Richard et al., 1994). The keratin gene was used as an amplification control for all samples and males show both the keratin band (~311 bp) and SRY (male) band at ~152 bp and females show only the keratin band at ~311 bp (Wise et al., 2009).

### 2.2.2 Datasets from historical whaling, commercial whaling and platforms of opportunity (1761-2003)

To examine areas in the study region where the RV Odyssey did not survey, three datasets were sourced from online portals to augment sperm whale ‘presence’ data. These data are available as downloadable GIS layers that display presence data from museum collections, citizen scientist programs, and ‘platforms of opportunity’ (Williams et al., 2006). They include location of a sighting from a ship, a biopsy sample taken from an animal, a location where an animal was heard using underwater hydrophones, or the location of a ‘take’ or kill recorded during whaling operations (Torres et al., 2013).

OBIS-SEAMAP (Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations), is one such online tool (Figure 4). In OBIS-
SEAMAP, spatially referenced data of marine mammal, seabird and sea turtle observations from across the globe are available to view and download for research purposes (Halpin et al., 2006; B.D. Best et al., 2007; Halpin et al., 2009).

The Townsend charts indicate that sperm whales were found around the globe, although only representative of locations to where the Yankee whalers ventured (Figure 5). The global charts are covered in an array of coloured dots, each representing the position of a whaling ship and the locations and months where whales were caught (Jaquet & Whitehead, 1999; T.D. Smith et al., 2012). The Wildlife Conservation Society (WCS) digitally captured the Townsend Whaling Charts (Townsend, 1935) in 2002 and these data are available online on the OBIS-SEAMAP website as an ESRI shapefile (Halpin et al., 2006; Halpin et al., 2009). The original Townsend Yankee whaling chart show the locations of 36,908 sperm whale kills from around the globe and, overall, 616 records were sourced for the study area off WA (Figure 5).
In 2012, the Australian Marine Mammal Centre in Hobart, Australia which hosts the National Marine Mammal Data Portal, and International Whaling Commission catch data (Individual catch database v. 5.0) for the southern hemisphere, launched a tool to visualise the whaling operations of Australia, Japan, USSR and USA which occurred off WA from 1936-1978. It is available online at: http://data.marinemammals.gov.au/ The dataset was provided in .csv format, with date of catch (presence), location, gender of the animal and country of whaling ship. Overall, 16,080 data points were sourced for this study, each representing a whale take or kill.

The OBIS-SEAMAP data portal hosts a number of sperm whale datasets from a variety of research institutions, government organisation, and citizen science programs from around the globe. Within the study area, a total of 16 sightings of sperm whales were available from 1996-2003 via the Australian National Whales Sightings and Strandings database (https://data.aad.gov.au/aadc/whales/).
2.3 Data processing

In summary, ArcGIS 10 (ESRI) was used to process, visualise, and analyse geographical and temporal data stored in multiple formats including Microsoft Access databases. These included position of the research vessel, presence / absence, acoustic stations and locations, and sex from biopsy samples taken. Bathymetric data (depth) were sourced from Australian Bathymetry and Topography Grid DVD (Geoscience Australia, 2009). The data were plotted to display ‘presence’ of historical whaling ‘takes’ and OBIS-SEAMAP sightings records. All map layers were converted to the WGS 1984 Zone 50S Transverse Mercator projection. Figure 6 outlines the workflow of how data were sourced, processed and analysed for the study.

Average monthly sea surface temperature (SST) data were obtained from the NOAA Advanced Very High Resolution Radiometer (AVHRR) Pathfinder version 5 data set at 4.8 km resolution using the Marine Geospatial Tools plugin (MGET v. 8a48) (Roberts et al., 2010). A SST layer was generated for the RV Odyssey study season (December 2001 – May 2002). Using the Cell Statistic plugin in ArcGIS, the average SST was calculated for the 6 months the RV Odyssey conducted research off WA.
1. Sourced data

- **RV Odyssey data** in MS Access, queries to .csv;
- **Historical data** (.csv, Excel) downloaded from online portals.

- **Bathymetric, SW Marine region** – Geoscience Aus, SEWPaC.
- **Environmental data (SST / Chl α)** - NASA & NOAA via MGET plugin

2. Processed data in ArcGIS 10

**Projected data layers** to WGS1984 UTM 50S

**Created environmental layers** –
- Depth – calculated slope, aspect
- SST, Chl α – 2002
- Dist. to land, -200m, -1000m & -2000m isobaths

**Created GRID cells** of 20, 15, 10, & 5nm using Hawth’s tools (GME) & R and centroid points using Xtools Pro.

**Extracted values of environmental layers to points**, values applied to grid using *Spatial Join*, grids converted to raster files which were exported as ASCII for use by Maxent modeling.

3. Analysis

**Created Point / Kernel density** maps using *Spatial Analyst* tool (15 nm cells) queried by Austral seasons.

**ASCII rasters and species ‘presence’** (.csv) imported to Maxent - species distribution modeling.

**Maxent results imported into ArcGIS 10** over SW marine bioregion layer.

**Xtools Pro** used to calculate area of Maxent sperm whale distribution model within SW marine bioregion layer protected areas.

Figure 6. Flowchart of preparation, processing and analysis of seasonal data visualised in ArcGIS 10 for Maxent analysis of sperm whale distribution data off WA.
Using the definition query in ArcGIS 10, data of historical whaling and sightings were extracted by and plotted as four seasons: austral summer (December – February), autumn (March – May), winter (June-August) and spring (September-November). Topographic information including slope and aspect were derived from bathymetric data as individual values and applied to new raster layers. Additional software extensions including Geospatial Modeling Environment (GME v. 0.7.2.0 http://www.spatialecology.com/gme) based on the statistical package R (v. 2.15.3 http://www.r-project.org/) and XTools Pro (v.9.1 http://www.xtoolspro.com/) were used for creation of grid cells, and exporting data from shape files to .csv files.

Grid cell size was a consideration in how all data were plotted in ArcGIS and Maxent. To deal with the location bias in the Yankee whaling data where the mean vessel location error was estimated to be 0.22° latitude (c. 24 km) and 0.54° longitude (c. 34 km) (T.D. Smith et al., 2012; Torres et al., 2013), point and kernel density distributions of historical data were computed in 15 nautical mile grid cells over the study area using the Spatial Analyst tool.

Box plots were created in ArcGIS to examine sperm whale presence data relative to depth. Other GIS layers were sourced from Geoscience Australia (http://www.ga.gov.au/products-services/data-applications.html) to examine current marine management areas and offshore use of the study area (shipping, oil & gas exploration).

2.4 Sperm whale distribution modeling using Maxent

Along with density plots of past distribution, maximum entropy modeling using the software Maxent (version 3.3.3k http://www.cs.princeton.edu/~schapire/maxent/), was used to provide predictions of sperm whale occurrence based on environmental and physical variables in the study area (Figure 7). The general approach of Maxent is to create a probability distribution for a species by contrasting occurrence data with
background data (pseudo-absences) rather than true absence data (J.N. Smith et al., 2012). Maxent employs a maximum likelihood method that models distributions of species by generating a probability distribution over the pixels in a grid of the study area subject to a set of constraints derived from measurements of assumed suitable habitat values at species occurrence locations (Thorne et al., 2012). The output of Maxent is a probability distribution of environmental suitability for a species, where higher values correspond to a prediction of better conditions and higher probability of occurrence (Phillips et al., 2006; Phillips & Dudík, 2008; Elith et al., 2011).

Environmental layers were created in ArcGIS 10 in 15 nautical mile grid cells to account for the position error in the Yankee whaling data (T.D. Smith et al., 2012; Torres et al., 2013). Spatial Analyst tool was used to calculate and create layers including Euclidean distance to land, distance to -200 m, -1000 m, and -2000 m isobaths. The MGET plugin was used to download chlorophyll a data from the NASA Ocean Color L3 SMI product (Terra 4 km) for 2002. In order to create layers of depth, slope, aspect, SST, and chlorophyll a, grid cells and centroid points were created using the Xtools Pro and values were extracted points in ArcGIS. The Spatial Join tool applied values to raster files, which were then converted to ASCII format for use as environmental layers by Maxent.

The species distribution model was created using a variety of sperm whale ‘presence’ location over two seasons, summer and autumn (December – June) to correspond with the entire effort of the RV Odyssey research survey. These included all RV Odyssey acoustic stations and biopsy data, a random selection of IWC commercial whaling data, Yankee whaling data and OBIS-SEAMAP. In Maxent, 25% of the data were randomly drawn from the dataset for model training over 20 replicate subsample type runs over a maximum of 5000 iterations. Several models were tested in Maxent using a combination of datasets (RV Odyssey only, RV Odyssey and IWC, RV Odyssey
and OBIS-SEAMAP, and RV Odyssey with all samples) with and without bias files for testing purposes as this known to influence model output (Phillips et al., 2009).

Maxent provided both threshold-dependent and threshold-independent measures of model outputs using the area under the curve (AUC) of the receiver operator characteristic (ROC), which evaluates how well model predictions discriminate between locations where observations are present and random background data (pseudo-absence points) (Thorne et al., 2012). Response curves of the environmental variables were conducted and a jack-knife test was undertaken to evaluate the relative contributions of each environmental variable to the model (J.N. Smith et al., 2012). The AUC is one of the most widely used threshold-independent evaluators of model discriminatory power (Fielding & Bell, 1997) and can range from 0 to 1, where an AUC of 0.5 indicates that model performance is equal to that of a random prediction and a value of 1 suggests perfect discrimination between suitable and non-suitable habitat (J.N. Smith et al., 2012).

3. Results

The number of sperm whale ‘presence’ locations analysed in this study are provided in Table 2. For the RV Odyssey data, sperm whales were heard before they were seen, so acoustic detections (both automated and manual) took precedence over sightings from the original dataset. Biopsy locations were also included as presence data for this study.
Table 2 - Number of sperm whale ‘presence’ data points in the study area off Western Australia.

<table>
<thead>
<tr>
<th>Sperm whale ‘presence’ by type</th>
<th>RV Odyssey</th>
<th>Yankee whaling</th>
<th>Commercial whaling</th>
<th>OBIS-SEAMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic stations</td>
<td>87</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Automated acoustic detections</td>
<td>119,570</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(Rainbow Click)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biopsy</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Whale ‘takes’ (kills)</td>
<td>-</td>
<td>616</td>
<td>16,080</td>
<td>-</td>
</tr>
<tr>
<td>Sightings</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td>119,717</td>
<td>616</td>
<td>16,080</td>
<td>16</td>
</tr>
</tbody>
</table>

3.1 Voyage of the Odyssey

Fifty days were spent on acoustic and visual searches off WA under various conditions (conditions for research regarded as borderline for about half the time). The track of the research voyage and the automated acoustic detections of sperm whales are shown in Figure 7. Figure 8 displays automated acoustic detections from the RV Odyssey as kernel density plots in 15 nautical mile grid cells in the Perth Canyon area in the austral summer months and the Albany canyons (the area known for commercial whaling activity in Australia until 1978) and offshore in the New Holland historical whaling grounds in the autumn months. Research activities were biased towards obtaining sperm whale biopsy samples but this can serve as an indicator of presence of sperm whales in these areas.
Figure 7. The study area displayed with the track of the RV *Odyssey*, bathymetry, and all automated acoustic detections of sperm whales recorded by Rainbow Click.

Figure 8. Kernel density of number of automated acoustic detections of sperm whales during the voyage of the RV *Odyssey* off Western Australia. Data are shown in 15 nautical mile grid cells by season when the vessel was operating in the area.
Sixty biopsies of sperm whales were taken in the study area and source locations and sex of animals are indicated in Figure 9. Eleven animals sampled off the Albany Canyons were males and 12 were females. In the other areas where biopsies were collected, only females were recorded; 12 in the Perth Canyon, the rest offshore and in the old New Holland whaling grounds. Most of the samples were taken along the edge of the continental shelf but the four females sampled in deep waters (4000 m to >6000 m) were probably ‘travelling’ or migrating. Additionally, in the Perth Canyon the visual observations indicated that most of the sperm whales were ‘sub-adult’ with seven classified as ‘immature’.

Figure 9. The study area with the RV *Odyssey* track, bathymetry, location of the biopsy samples and gender of the sampled sperm whales displayed.
3.2 Historical data

3.2.1 Yankee whaling – Townsend charts (1735 – 1920)

Results of Yankee whaling sperm whale takes are displayed in point density maps in 15 nautical mile grid cells by austral season in Figure 10. Overall, 616 animals were killed in all seasons during this time period, primarily offshore in the historical New Holland whaling grounds during autumn, winter and spring. In the summer months, whaling activity occurred primarily offshore of the South-west coast though no activity occurred in the Perth Canyon.

Figure 10. Point density maps displaying seasonal distribution of sperm whales taken during Yankee whaling operations (Townsend, 1935) with shaded symbols indicating number of animals taken in 15 nautical mile grid cells.
3.2.2 IWC commercial whaling (1936-1978)

Overall, 16,080 sperm whales were killed in all seasons during this time period in the study area. Commercial whaling activity is displayed in kernel density maps (15 nautical mile grid cells) in Figure 13. Most of the commercial whaling occurred from the Cheynes Beach whaling station in Albany, WA with 91% of effort focused in the Albany canyons area. Other countries, including Japan (4%), USSR (5%) and USA (<1%) took sperm whales in the region though this activity occurred primarily offshore. Results from the IWC data include gender of the animals killed (17% females, 84% males) by season (Figures 11 and 12).

![Figure 11](image1.png)

**Figure 11.** Number of male and female sperm whales taken during commercial whaling operations off Western Australia between 1936-1978 by season (n=16,080) (Source: IWC).

![Figure 12](image2.png)

**Figure 12.** Number of sperm whales taken each year during commercial whaling operations off Western Australia with an indication of gender (n=16,080) (Source: IWC).
From 1953, whaling activity increased (Figure 12). And, although males were the primary targets of whaling activities until the 1970s, thereafter there was an increased take of females. In 1978, the Australian Commonwealth government banned commercial whaling and operations at the Cheynes Beaching whaling station ceased.

Figure 13. Kernel density maps of seasonal distribution of sperm whale ‘takes’ off Western Australia during the commercial whaling period (1936-1978). Data are shown by season in 15 nautical mile grid cells (Source: IWC).


Sperm whale sightings that occurred in summer and autumn seasons and sourced from OBIS-SEAMAP are displayed in Figure 16. Sightings are originally
sourced from the Australian National Sightings and Stranding database and demonstrate sperm whales presence off the continental shelf near the Perth Canyon.

![Map of Western Australia showing sperm whale sightings](image)

Figure 16. Point density plots of seasonal distribution of sperm whale sightings in 15 nautical mile grid cells from the OBIS-SEAMAP online portal Source: OBIS-SEAMAP.

### 3.4 Presence of sperm whales relative to bathymetry

The range and median depth of sperm whale presence was determined from the previously described data (Figure 17). The RV *Odyssey* primarily surveyed along the -2000 to -3000 m isobaths. Yankee whaling activity occurred further offshore in deeper water. Most of the commercial whaling activity occurred primarily from the Cheynes Beach whaling station in Albany, along the continental shelf at a median depth of -1000 m, mainly off the Albany canyon group.
Figure 17. Boxplots showing the median depth of each sperm whale dataset in the study area. The whisker length is equal to 1.5 interquartile range (IQR).

3.5 Sperm whale distribution model

3.5.1 Environmental variables influencing distribution

The results of the species distribution model included only the Odyssey, commercial whaling data and OBIS-SEAMAP presence data as this was statistically strong with a receiver operating curve (AUC) of 0.827 and standard deviation (SD) of 0.034 (Figure 18). The environmental variable with highest gain when used in isolation was distance from land (Dist shore). Key environmental and physical factors of this model were distance to -1000m, -200 m and -2000 m isobaths and SST. The model was tested with bias (pseudo-absence) and without, at a grid cell size of 15 nautical miles.
Figure 18. Distribution based on environmental suitability is on a scale of 0 to 1. Closer to 1, the more suitable the model is based on environmental factors. The mean AUC = 0.827.
Figure 19. Results from Jackknife tests showing most influential environmental variables in the model. A and B were used for model training, while C were from the final results. Values shown are averages over 25 replicate runs in Maxent. The results are highly correlated with the -1000 m, -200 m and -2000 m bathymetric contours. Based on environmental factors (>0.6), the model predicts that 19,442 km² of ocean offshore of South-west Australia is suitable habitat for sperm whales (Figure 20).
Figure 20. Sperm whale distribution model displayed in 15 nautical mile grid cells for summer/autumn seasons combined at 95% confidence level.

3.5.2 Distribution within South-west marine protected areas

Zoning is a fundamental planning tool in managing marine reserves and defines what activities can occur in which locations so as to protect the marine biodiversity and to provide for ecologically sustainable use (Australia. Director of Parks, 2013). An International Union for Conservation of Nature (IUCN) category has been ascribed to each marine protected area in the South-west Marine Reserves Network (Appendix 5), in accordance with the requirements of the EPBC Act (Australia. Director of Parks, 2013). Figure 21 displays the results from the sperm whale distribution model overlayed with the zones in the South-west marine bioregion plan.
Figure 21. The boundaries of the South-west marine bioregion protected areas shaded in black are displayed over the species distribution model of suitable sperm whale habitat.

Within the study area, predicted distribution occurs within Australia’s 200 nautical mile EEZ and the South-west marine bioregion. It also overlaps with some IUCN marine protected areas in the Perth Canyon and parts of the Albany Canyon group – areas of historical sperm whale distribution. The area of suitable habitat for sperm whales occurring within each marine protected area (with various levels of IUCN protection) is given in Table 3. Overall, 5.2% of suitable habitat offshore for sperm whales is within IUCN marine protected areas but only 1.8% of these areas are classified as a marine national park (IUCN II) which strictly regulates and limits most offshore activity including oil and gas exploration, mining, and commercial fishing.
Table 3. South-west marine bioregion protected areas cover 376,137 km² within the study area. Suitable habitat for sperm whale distribution (>0.6) is calculated within each marine protected area.

<table>
<thead>
<tr>
<th>South-west marine bioregion</th>
<th>Area of predicted occurrence &gt;0.6, within a marine protected area (km²)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanctuary, benthic sanctuary and marine national park zones (IUCN Ia and II)</td>
<td>6,852</td>
<td>1.8%</td>
</tr>
<tr>
<td>Habitat protection and conservation park zones (IUCN IV)</td>
<td>1,476</td>
<td>0.3%</td>
</tr>
<tr>
<td>Multiple use zones (IUCN VI)</td>
<td>9,545</td>
<td>2.9%</td>
</tr>
<tr>
<td>Special purpose zone (IUCN VI)</td>
<td>163</td>
<td>&gt;0.1%</td>
</tr>
<tr>
<td>Special purpose zone (oil and gas exclusion) (IUCN VI)</td>
<td>328</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>19,442</strong></td>
<td><strong>5.2%</strong></td>
</tr>
</tbody>
</table>

4. Discussion

4.1 Sperm whale distribution off Western Australia

Passive acoustic methods used in the RV *Odyssey* survey were an efficient and effective way to locate and track sperm whales in areas of historical abundance and regions of typical habitat, while working in difficult weather conditions. Critical habitat for cetaceans, such as sperm whales, are those parts of their range that are essential for day-to-day survival as well as maintaining a healthy population growth rate; these areas are regularly used for feeding, breeding, raising calves and, sometimes migrating (Hoyt, 2005). This study used three methods to identify critical habitat for sperm whales off WA, namely examination of historical distribution records, genetic results from biopsies and predictive species distribution modeling.

Although sperm whales spend a considerable time foraging at depth, they are highly social mammals (Connor *et al.*, 1998; Whitehead, 2003). Female sperm whales
are known to form concentrations a few hundred kilometres across, groups that move
together for days at aggregations over scales of 2-20 km, and form social units (long-
term companions) with bonds occurring over years (Watwood et al., 2006; Whitehead,
2003). This should be taken into account interpreting historical distribution records and
predicting future spatial distribution and movement patterns.

The Voyage of the *Odyssey* expedition found sperm whales in the Perth Canyon,
Albany Canyon group, and the historical New Holland whaling grounds. Previous aerial
surveys and passive acoustic studies have identified sperm whales in the Perth Canyon
region (Bannister, 1968, McCauley et al., 2004). However, the RV *Odyssey* results
provide the first detailed acoustic ‘presence’ data of sperm whales primarily distributed
along the continental shelf, submarine canyon and ridges. Of the 60 sperm whale
biopsies taken in the study area, results were consistent with historical commercial
whaling data demonstrating distribution of males and females using the Albany
canyons. However, in the other areas surveyed, only females were sampled; 12 in the
Perth Canyon, the rest offshore and in the old New Holland whaling grounds. The four
females that were biopsied in deep waters (-4000 m to >-6000 m) were most likely
‘travelling’ or moving between social groups (Whitehead, 2003). This is an indication
that female social units move between all three regions in the study area. Whitehead
(2003) described movements in a 24-hour period of female and immature animals to be
about 79 km when feeding conditions were poor, 25 km when they were good with an
estimated overall range for females and immature animals of about 1,450 km in any
direction.

Although only 16 data points were analysed from the OBIS-SEAMAP online
data portal, the results were consistent with the findings of the RV *Odyssey* of presence
of sperm whales along the western continental shelf. Interestingly, sperm whales were
found during both summer and autumn in the Perth canyon, a time when seasonal
feeding of pygmy blue whales occurs in the area (Rennie et al., 2009; Gavrilov et al., 2011).

In respect to the Townsend charts of historical Yankee whaling effort, there is known location bias in the presence points (T.D. Smith et al., 2012). Townsend and his cartographer plotted vessel locations as accurately as possible from logbook records but Bannister et al. (2008) noted that common criticisms of these charts were that the plots extended well beyond the areas where whaling actually took place. A ‘crowding effect’ of inaccurate point locations may be more of a problem with coastal species such as humpbacks than with offshore species such as sperm whales (Bannister et al., 2008). However, during this era, most animals were killed far offshore away from typical foraging habitat in very deep waters with a median depth ~ 5000 m. In addition, there was no presence in the Perth Canyon. This study concurs with T.D. Smith et al. (2012) and Torres et al. (2013) that these data may be better suited for studies on a global scale, rather than a regional scale.

IWC commercial whaling records reveal that more males (82%) were hunted than females (18%) in the study area and this was consistent with commercial efforts worldwide to target larger males (Whitehead, 2002). However, sperm whale groups are matriarchal, periodically visited by roving mature males (Whitehead, 1987; Whitehead, 2003). There was an increased take of females in the 1970s and this may have negatively impacted the population off the coast of Western Australia. Since the end of commercial whaling, there have been few regional studies, such as the RV Odyssey expedition, with a primary focus on sperm whales. So, the recovery and relative abundance of the species since is still unknown in the area.

The results demonstrate that sperm whales use the Albany canyons year-round. With 35% of all males taken during the spring (n=5,591), this season could have been important period for migrations of mature males moving south to Antarctica (or north
via WA), a productive time for feeding in submarine canyons, or important for mating with females in the region. Overall, while there may be some seasonal variation in sperm whale abundance in different areas, females do not seem to make pronounced seasonal migrations and their movements are best described by models of nomadic animals moving in response to changes in food abundance (Whitehead, 2003).

In general, mature males move to higher latitudes with age, with periodic migrations between lower-latitude feeding grounds and high-latitude feeding grounds beginning at about age 27 years (P.B. Best, 1979). With variable patterns of movement at high latitudes, animals stay resident in small areas for long periods. At low latitudes, there appears to be near continuous movement within a breeding area of a few hundred kilometres across, as mature males visit and re-visit resident groups of females (P.B. Best, 1979; Whitehead, 2003).

Bannister (1968) conducted aerial surveys during the commercial whaling era (1963-1965) and completed 24 monthly flights off Albany. He also incorporated additional sightings data from spotter planes that would regularly assist whaling ships off Carnarvon and the Cheynes Beach whaling station at Albany. Bannister (1968) hypothesised that there may be two distinct stocks of sperm whales off the west coast and speculated that their presence could be related to deep waters in the area adjacent to the steeply sloping continental shelf. He described the steep slope as favouring the production of food and recorded a very high proportion of whales (70-80% in 1964-66) off Albany that had recent remains of squid in their stomach contents (Bannister, 1968). Bannister (1968) found very little direct evidence for seasonal movements but indicated there was latitudinal rather than longitudinal movement off WA.

The RV *Odyssey* genetics data contained records of only the gender of the animals sampled, so Bannister’s hypothesis of two separate populations could not be tested. The RV *Odyssey* acoustic results showed that sperm whales use the continental
shelf off WA. Bannister (1968) spotted no animals on flights from Geraldton to Perth and Perth to Cape Leeuwin during the winter months (July-August 1964). This suggests that sperm whales use the Perth canyon region seasonally with animals undertaking latitudinal movement in the autumn to the New Holland grounds or back to the Albany canyons.

4.2 Environmental factors influencing distribution

Presence-only species distribution modeling using Maxent proved to be a useful method for synthesizing historical and modern ‘presence only’ data to predict critical habitat of sperm whales. Traditional methods of detecting and recording the presence/absence of sperm whales are done through visual methods including aerial surveys (Bannister, 1968; Levenson, 1974; Panigada et al., 2011) and shipboard surveys through both visual and acoustic methods (Barlow & Taylor, 2005; Lewis et al., 2007; Pirotta et al., 2011). In traditional line transect studies, animal abundance can be extrapolated to un-sampled parts of the survey area through examining the relationship between physical and environmental covariates (Evans & Hammond, 2004). Statistical modeling techniques such as generalised linear models (GLMs) and generalized additive models (GAMs) requiring both presence data and research survey effort, from which absence can be inferred, can be used to quantify cetacean distributions and the ecological processes determining these distributions (Buckland et al., 2001; Cañadas et al., 2002; Redferd et al., 2006; Pirotta et al. 2011).

The primary aim of the RV Odyssey acoustic effort was to obtain biopsy samples from sperm whale, so the research effort was biased towards this search. Traditional line-transect surveys estimating abundance would search across depth (Buckland et al., 2001; Mellinger & Barlow, 2003; Barlow & Taylor, 2005; Panigada et al., 2011; Pirotta et al., 2011). The RV Odyssey surveyed along the -2000 m to -3000 m isobaths to increase chances of acoustically detecting sperm whales. Therefore, the
absence data from the *Odyssey* was not suited to statistical habitat-modeling methods such as GLMs and GAMs (Redfern *et al.*, 2006) and was discarded in this study for the region.

Depth was correlated in the results, distance to -1000 m, -200 m and -2000 m isobaths along with SST. Past studies indicate that influencing environmental factors for sperm whale distribution are depth or slope (Hooker *et al.*, 1999; Pirotta *et al.*, 2011). Commercial whaling results had a median depth of over -1000 m and activity primarily occurred relative close to land off Albany along the continental shelf (approximately 25 nautical miles). However, the distance to the -2000 m and -1000 m isobaths were also strongly correlated, and this was indicated as suitable habitat for foraging for sperm whales in other regions (Hooker *et al.*, 1999; Pirotta *et al.*, 2011). In addition, the study area consisted of a large latitudinal area which accounts for SST being an important influence in the model. A grid cell size of 15 nautical miles was chosen due to the location bias in the Townsend Yankee whaling data and this influenced the model results being highly correlated to distance to land in earlier testing. The final model was chosen with Townsend data removed due to the sparse distribution offshore and inconsistent results of presence over depth (median depth ~ -5000 m). In addition, distance to land was tested and removed from the final model.

Each presence only dataset was spatially biased towards particular activities — biopsying by the *Odyssey*, hunting by Yankee and commercial whaling. To properly account for this bias and develop a more robust distribution model, it is necessary to incorporate a bias layer (pseudo-absence) as this improves model performance considerably by incorporating some of the original presence information (Phillips *et al.*, 2009; Edrén *et al.*, 2010; J.N. Smith *et al.*, 2012). A variety of bias layers were created and tested, ranging from randomly drawing from seasonal presence locations, to using the absence data from the RV *Odyssey* survey effort track-line. However, these bias
layers had mixed results and were not included in the final model. Although additional work is required to incorporate bias into a definitive model, our final model was statistically strong with a receiver operating curve (AUC) of 0.827.

4.3 Submarine canyons are critical habitat for sperm whales

Upwelling in canyons are known to cause productive feeding areas for cetaceans (Hooker et al., 1999; Rennie et al., 2009), and results indicate that submarine canyons are preferred habitat for sperm whales in South-west Australia, specifically in the Albany canyon group and the Perth Canyon. Commercial whaling results indicated that males and females were using the Albany canyon group year-round. Based on the numbers of animals killed during the commercial whaling era and that the RV *Odyssey* found animals using the areas, this region could be vital for foraging, breeding, social cohesion, mixing and mating with males moving to or from Antarctic waters. The species distribution model results demonstrate that this region contains critical habitat for sperm whales.

The RV *Odyssey* genetic results indicated that females were found in the Perth Canyon and north to the New Holland grounds. The RV *Odyssey* observational data indicated that seven of 11 whales in the Perth canyon were ‘immature’ (meaning they were juvenile females). Perth canyon could be both a critical feeding area and nursery for matriarchal family groups. In the summer months, pygmy blue whales feed in the Perth canyon (Rennie et al., 2009) and other species of cetaceans are present year-round, including true blue whales (*Balaenoptera musculus*) over the winter and migrating humpback (*Megaptera novaeangliae*) and southern right whales (*Eubalaena australis*) (McCauley et al., 2004).

4.4 Marine management and policy – South-west marine bioregion

Within the South-west marine bioregion plan, critical habitat is defined as scientifically important and critical to the survival of listed threatened species or listed
threatened ecological communities (Australia. SEWPaC, 2012a; 2012b; 2013). Cetaceans such as sperm whales occupy an extensive range, so there is a strong potential that by protecting their critical habitat, a wide variety of other species that regularly occur within the area and ecosystem processes, will be protected (Hoyt, 2005). Marine protected areas designed for cetaceans can provide protection, not only for the species for which it was designated, but also to several other marine mammal species (Hooker & Gerber, 2004; Hoyt, 2005).

Globally, many marine ecosystems have come under severe stress from increasing human impacts (Halpern et al., 2008). However, resources for conservation are limited (Halpern et al., 2006). In order to ensure that these limited resources are directed effectively, it is important to identify clear conservation objectives and to pinpoint priority areas that can meet these objectives most effectively, as protected areas are important for regional conservation strategies as they separate biodiversity from the factors that threaten its existence (Margules & Pressey, 2000). The study identifies critical areas for sperm whales as submarine canyons found offshore off Albany and Perth.

However, conservation planning outcomes relies on building human use data as a ‘cost’ to the conservation of biodiversity (Treblilco et al., 2011; Beckley & Lombard, 2012). The South-west marine bioregion plan identifies a number of pressures in one of the fastest growing economic regions in Australia (Australia. SEWPaC, 2012a). Anthropogenic threats to sperm whale populations in other regions include noise disturbance from increased offshore human activities such as seismic surveys for oil and gas exploration (Madsen et al., 2006; Miller et al., 2009); entanglement in fishing gear and increased ship traffic and chemical pollution (Wise et al., 2009; Savery et al., 2013a; 2013b).
There is a growing demand for predictive models of cetacean distribution to support conservation and management efforts (Redfern et al., 2006) and should be used to quantify this cost. This study demonstrated that approximately 5.2% of environmentally suitable habitat for sperm whales outlined in the distribution model (>0.6) was located within IUCN marine protected areas in the South-west marine bioregion. Internationally, it has been proposed that 20–50% of marine habitats be protected in restricted ‘no-take’ areas (Gell & Roberts 2003); i.e. sanctuary or marine parks that strictly limit activities that may negatively impact the marine ecosystem. Although sperm whales are protected within Australia’s 200 nautical mile EEZ as part of the Australian whale sanctuary, the activities allowed within these IUCN protected areas could impact the population. Further examination revealed that only 1.8% of the total suitable habitat for sperm whales is within a IUCN category II marine protected area suggesting that their critical habitat offshore may not be adequately addressed by the South-west marine bioregion plan. Therefore, expanding the boundaries of IUCN II protected areas to cover a larger percentage of offshore habitats used by sperm whales (~30-40%) could be beneficial for the species and to other marine fauna and ecosystem processes that occur in offshore areas.

Marine protected areas in the south-west currently regulate activity in parts of the Perth canyon and Albany canyon group (Appendix 5). Similar research of offshore submarine canyons off the coast of Nova Scotia, Canada, identified one, The Gully, as critical habitat, recommending a 10 km buffer zone around the marine sanctuary in order to reduce anthropogenic impacts and protect ecological processes suitable for prey (squid) of other deep diving odontocetes such as beaked whales (Hooker et al., 1999; Hooker et al., 2002).

Using ship-based methods to study and monitor species such as sperm whales is costly, as weather in regions such as WA is variable offshore. Because of this,
monitoring often does not occur with cetaceans in these areas (Donovan et al., 2004). However, it is essential to undertake systematic long-term monitoring of offshore species in order to inform conservation measures and evaluate their effectiveness (Panigada et al., 2011). The dive cycle and vocalisations produced by sperm whales make them a suitable species to use passive acoustic techniques to monitor their habitat use and can be used to understand their abundance, density and distribution in order to regulate potential impacts of anthropogenic activities.

Off WA, Gavrilov et al. (2011) used passive acoustic loggers including the CTBT hydroacoustic station (HA01) off Cape Leeuwin in WA from 2002 – 2007 and the Integrated Marine Observing System (IMOS) in the Perth Canyon from 2009-2010 to study pygmy blue whale vocalisations. From 2000-2006, McCauley & Jenner (2010) used passive noise loggers connected to hydrophones lying on the seabed floor of the north-west and south-west coasts to record pygmy blue whales vocalisations in order to estimate the abundance of the population off WA.

Similar techniques could be used to monitor sperm whales with adjustments to the sampling frequencies of acoustic data loggers used in these studies. New autonomous technologies such as ocean gliders may be the next step in providing a platform for passive acoustic monitoring of sperm whales as they operate over large distances for days at a time in any sea condition and have the potential to transmit data via satellite (Moore et al., 2008; Dassatti et al., 2011). In light of current technology, understanding of sperm whale bioacoustics, and their habitat preferences, there is the evidence for undertaking long-term passive acoustic studies to monitor the population within Commonwealth waters off WA in the Perth and Albany canyons based on historical data presented in the study in order to inform future management and policy decisions.
5. Conclusion

Sperm whales are found off Western Australia with year-round critical habitat offshore in the Albany canyons and seasonally in the Perth Canyon. Passive acoustic monitoring was an effective means to detect sperm whale presence working in variable weather conditions presented off the coast of WA during the Voyage of the *Odyssey* expedition in 2001-2002.

Using Maxent, presence only modeling of historical and modern species distribution can be used to fill the knowledge gaps of a region with little survey effort to predict species distribution based on environmental factors. Species distribution models can be used to assess current marine management policies, such as the South-west marine bioregion plan, and help inform systematic conservation planning efforts of offshore species such as sperm whales in the future. Based on the results of the study, it is recommended to incorporate a future passive acoustic monitoring program for sperm whales offshore in the Perth and Albany canyon area to measure and mitigate the effects of anthropogenic activities and their impacts.
6. References


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**Appendix 1.** A classification of social structure of nonbreeding, but sexually mature or maturing males, compared with those of females and immature sperm whales (Letteval et al., 2002; Whitehead, 2003).

<table>
<thead>
<tr>
<th><strong>Structure</strong></th>
<th><strong>Females and immatures</strong></th>
<th><strong>Nonbreeding males</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clans</td>
<td>~ 10,000’s of animals sharing coda dialect spread over large ocean area</td>
<td>No evidence</td>
</tr>
<tr>
<td>Concentrations</td>
<td>~1000’s of animals concentrated over an area. ~100’s of km across for months or more</td>
<td>Probably exist, but less pronounced than females</td>
</tr>
<tr>
<td>Aggregations</td>
<td>~10’s of animals aggregated over an area. ~10km across for a few hours</td>
<td>~20 males aggregated over an area. ~20 km across for days</td>
</tr>
<tr>
<td>Groups</td>
<td>~20 animals foraging in structured formations spanning ~1km for days</td>
<td>Little evidence for groups, except coordinated heading by aggregated males</td>
</tr>
<tr>
<td>Social units</td>
<td>~10 animals with long-term relationships over years to decades; may contain several matrilines</td>
<td>No evidence for long-term relationships</td>
</tr>
<tr>
<td>Clusters</td>
<td>~2 animals clustered at the surface over ~10min</td>
<td>Occasional clustering of 2 or more males</td>
</tr>
</tbody>
</table>
### Appendix 2. Key literature reviewed for this thesis.

<table>
<thead>
<tr>
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<tr>
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<tr>
<td>Dive, Foraging, Diet</td>
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<tr>
<td>Physiology</td>
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<tr>
<td>Anatomy</td>
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<tr>
<td>Environment</td>
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<tr>
<td>Chemical (SST / Chl a)</td>
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<tr>
<td>Physical (depth/slope/up-welling)</td>
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<tr>
<td>Policy / Management</td>
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<tr>
<td>Technology</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

#### Key literature reviewed for this thesis:

- Bannister (1997)
- Levenson (1974)
- Buckland et al. (2001)
- Whitehead (2002)
- Barlow & Taylor (2005)
- Panigada (2011)
- Gorden et al. (2000)
- Haste et al. (2003)
- Barlow & Taylor (2005)
- Whitehead (2009)
- Gedamke (2010)
- Pirotta et al. (2011)
- Barlow & Gisiner (2006)
- Redfern et al. (2006)
- Horrocks, Hamilton, & Whitehead (2011)
- Pirotta et al. (2011)
- Arribando (1987)
- Hammond (1996)
- Delfault & Whitehead (1995)
- Whitehead et al. (2008)
- Worthington & Schevill (1957)
- Norris & Harvey (1972)
- Gordon (1991)
- (Rendell & Whitehead, 2004a)
- Telouk et al. (2007)
- Pirotta et al. (2011)
- Watkins & Schevill, (1977a)
- Welgare & Whitehead (1993)
- Rendell & Whitehead (2004a)
- Marroux et al. (2006)
- Schulz et al. (2011)
- Gaskin (1964)
- Watkins et al. (1993)
- Watkins & Schevill, (1977b)
- Watkins et al. (1985)
- Thode et al. (2002)
- Wallberg (2002)
- Madsen et al. (2002b)
- Johnson & Tyack (2003)
- Watkins et al. (2006)
- Madsen et al. (2002b)
- Johnson & Tyack (2003)
- Madsen et al. (2002)
- Johnson & Tyack (2003)
- Madsen et al. (2009)
- Watkins & Schevill, (1997a)
- Watkins et al. (1997b)
- Watkins et al. (1998)
- Thode et al. (2002)
- Wallberg (2002)
- Madsen et al. (2002b)
- Johnson & Tyack (2003)
- Madsen et al. (2002)
- Johnson & Tyack (2003)
- Madsen et al. (2009)
- Clarke (1979)
- Beale (1839)
- Gill (1871)
- Jaquet & Whitehead (1996a)
- Jaquet et al. (2000)
- Rendell et al. (2004b)
- Pirotta et al. (2011)
- Jaquet et al. (1999)
- Hoyt (2005)
- Moore et al. (2008)
- Sánchez-García et al. (2010)
- Dassanti et al. (2011)
- (Holt, 1983)
- Bannister et al. (1996)
- Hooker et al. (1999)
- Hoyt (2005)
- Townsend (1935)
- Hjort (1937)
- Dakin (1947)
- Simon (1965)
- Ferrari (1985)
- Holt (1983)
Appendix 3. Literature on sperm whales in Western Australia.

<table>
<thead>
<tr>
<th>Author</th>
<th>Type of Study</th>
<th>Study Focus</th>
<th>Notes / Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Townsend (1938)</td>
<td>Whaling / Historical</td>
<td>Abundance. Examined sperm whale kills from Yankee whaling data.</td>
<td>The first visualization of the global distribution of sperm whales and shows populations off of Western Australia.</td>
</tr>
<tr>
<td>Chittleborough (1956)</td>
<td>Whaling / Historical</td>
<td>Population.</td>
<td>Notes increased take of sperm whales off the western coast impacting the population.</td>
</tr>
<tr>
<td>Bannister (1968)</td>
<td>Visual Survey</td>
<td>Aerial survey estimating distribution of sperm whales off the west coast of Australia.</td>
<td>Incorporated aerial survey data from whaling companies to fill knowledge gaps. No published survey of sperm whales in Western Australia since.</td>
</tr>
<tr>
<td>Holt (1983)</td>
<td>Whaling / Historical</td>
<td>Population. Establishment of the Indian Ocean Whale Sanctuary.</td>
<td>This is an international agreement that restricts whaling for scientific purposes in high-seas areas, including off of Western Australia.</td>
</tr>
<tr>
<td>Bannister et al. (1996)</td>
<td>Conservation</td>
<td>Policy. General action plan for cetaceans in Australia.</td>
<td>Mentions need to understand more about sperm whale habitat by undertaking further aerial surveys.</td>
</tr>
</tbody>
</table>
## Appendix 4. Literature relevant to sperm whales in Western Australia.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Type of Study</th>
<th>Study Focus</th>
<th>Notes / Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tynan (1998)</td>
<td>Conservation</td>
<td>Diet, Range. Sperm whales in the Southern Hemisphere migrate between highly productive Antarctic feeding grounds in summer and low-latitude breeding grounds in winter.</td>
<td>Most likely male sperm whales migrating to Western Australia are feeding in the Antarctic circumpolar current.</td>
</tr>
<tr>
<td>Hooker et al. (1999)</td>
<td>Visual Study; Conservation / Marine Protected Areas (MPAs)</td>
<td>Linear regression model used to explore use of depth and slope by cetaceans, and find 'critical habitat' in the Gully, Nova Scotia.</td>
<td>Study directly links submarine canyons to sperm whale use similar to Albany Canyon group and Perth Canyon. Uses habitat and spatial modeling for conservation purposes.</td>
</tr>
<tr>
<td>Gregr &amp; Trites (2001)</td>
<td>Modeling, Historical whaling</td>
<td>Used historical whaling and GLM to model species distribution</td>
<td>Using historical data with six environmental predictor variables to model sperm whale habitat off British Columbia, Canada.</td>
</tr>
<tr>
<td>Whitehead (2003)</td>
<td>Ecology, Life History</td>
<td>Distribution, Acoustics, Social Structure</td>
<td>This is the most comprehensive book written on sperm whales and their natural history</td>
</tr>
<tr>
<td>Evans &amp; Hindell (2004)</td>
<td>Conservation</td>
<td>Diet – The authors examined stomach contents of 36 sperm whales that stranded off the coast of western Tasmania.</td>
<td>Most likely, sperm whales in southwest Australia feed on similar prey (oceanic cephalopods).</td>
</tr>
<tr>
<td>Hoyt (2005)</td>
<td>Conservation / MPAs</td>
<td>Explores values of ecosystem based management and establishing MPAs for cetaceans.</td>
<td>Explores current protection and policy in Western Australia.</td>
</tr>
<tr>
<td>Rennie et al. (2009)</td>
<td>Acoustic Studies</td>
<td>Study of Pygmy blue whales in the Perth Canyon linking abundance to physical and chemical covariants.</td>
<td>Related study focused on how pygmy blue whales use submarine canyons in my study area. My MSc data will demonstrate that sperm whales use the Perth Canyon.</td>
</tr>
<tr>
<td>Pirotta et al. (2011)</td>
<td>Acoustic Studies</td>
<td>Review of habitat modeling. Examines abundance of sperm whales and maps critical habitat using acoustic methods.</td>
<td>Similar to the methods and type of acoustic data that I have in Western Australia. Can be applied to start a baseline in region of sperm whale abundance, density and distribution.</td>
</tr>
<tr>
<td>Clarke et al. (2012); De Vos et al. (2012)</td>
<td>Visual Study, Acoustic Study</td>
<td><strong>Voyage of the Odyssey</strong> research on sperm whales in the Maldives and Sri Lanka.</td>
<td>Explore techniques used by the RV Odyssey to gather visual and acoustic data.</td>
</tr>
</tbody>
</table>
Appendix 5. General guide to allowed (✓), allowable (A) and prohibited (X) activities in the South-west Commonwealth Marine Reserves Network (Australia. Director of National Parks, 2013).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Marine National Park Zone (IUCN II)</th>
<th>Habitat Protection Zone (IUCN IV)</th>
<th>Multiple Use Zone (IUCN VI)</th>
<th>Special Purpose Zone (Oil and Gas Exclusion) (IUCN VI)</th>
<th>Special Purpose Zone (IUCN VI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Use / Access</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Commercial shipping - transit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Commercial fishing</td>
<td>X</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>X</td>
<td>X</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Commercial tourism &amp; media</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Recreational fishing</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Mining</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
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<tr>
<td>Structures and works</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
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<tr>
<td>Research and monitoring</td>
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<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Defence and emergency response</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Activities not otherwise specified</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

✓ Activities are allowed in accordance with Plan prescriptions (without the need for a permit of class approval.
A Certain activities are allowable subject to Plan prescriptions.
X Activities are not allowed at all (i.e. totally prohibited).