Nest site selection by flatback sea turtles: Characterization of nesting beach topography with airborne LiDAR

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This thesis is presented as part of the requirement for the degree of Bachelor of Science (Honours) in Environmental Science, School of Veterinary and Life Sciences, of Murdoch University
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Declaration

I declare this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institute.

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Abstract

Protecting sea turtle nesting beaches is a commonly used management strategy for sea turtle conservation as gravid sea turtles are more vulnerable to predation and disturbance during oviposition. Therefore, understanding where sea turtles nest and the characteristics of their nesting sites is fundamental for their conservation. However, the process of nest site selection is not well understood. Beach topography is one factor that is believed to drive nest site selection, but considering that many nesting beaches, particularly in Australia, are large and remote, effectively acquiring beach topographic information is challenging. Airborne light detection and ranging (LiDAR) data can obtain accurate information on beach topography and can be used to understand how topography influences nest site selection. The aims of this study were to (i) characterize beach topography using LiDAR data of Eighty Mile Beach, a remote 220 km long beach in north-west Australia, and (ii) determine which features influenced nest site selection of the flatback sea turtle (*Natator depressus*) population nesting there. Metrics of beach features that were believed to be relevant for nest site selection were calculated from piecewise linear regression models fitted to beach profiles extracted from transects generated along Eighty Mile Beach. Aerial photographic survey data were used to quantify flatback sea turtle nesting and were converted to presence-absence and nesting density classes per photograph. Classification tree models were used to model the influence of beach topography on the density and presence-absence of nests. Nests were predicted to be present if the highest elevation in the profile was 9 to 12 m (overall accuracy = 60%, detection rate = 80%), though density could not be modelled successfully (overall accuracy = 18%, detection rate = 80%). These results agree with the hypothesis that the silhouette in front of a sea turtle influences nest placement, though moderate model performance suggests that nest site selection by flabtack sea turtles at Eighty Mile Beach are also influenced by other factors besides beach topography. The methods used in this study successfully characterized the beach topography of Eighty Mile Beach using LiDAR data and have the potential to be used on remote and large beaches in other parts of the world.
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1 INTRODUCTION

Sea turtles are a group of threatened charismatic megafauna with global distributions. With the exception of the Polar Regions, their foraging, nesting, and migratory range span all oceans of the world (Wallace et al. 2010). Seven species of sea turtle have been documented, all of which are listed on the International Union for the Conservation of Nature Red List of Threatened Species (Marine Turtle Specialist Group 1996; Red List Standards & Petitions Subcommittee 1996; Abreu-Grobois and Plotkin 2008; Mortimer and Donovan 2008; Seminoff 2004; Wallace et al. 2013; Casale and Tucker 2015). Though there are areas of the globe where sea turtle populations are secure (e.g. green sea turtles in Hawaii, Balazs and Chaloupka 2004; and the Great Barrier Reef, Hof et al. 2017; or Kemp’s ridley sea turtles in Florida, Shaver et al. 2016), sea turtles in other regions face significant threats to their persistence. These include loss of foraging and nesting habitats (e.g. Polidoro et al. 2017), poaching (Koch et al. 2006; Mancini and Koch 2009; Guebert et al. 2013; Nuno et al. 2018), unregulated exploitation (Tapilatu et al. 2017) and fisheries bycatch (Peckham et al. 2007; Riskas et al. 2018). These threats can expose sea turtles to greater cumulative impacts throughout their life as they are long-lived, wide-ranging animals with different life history stages occupying a variety of habitats (Bolten 2003; Bjorndal et al. 2005).

Breeding and reproduction can be a particularly vulnerable life history stage (e.g. Blamires et al. 2003; Sarahaizad et al. 2012) as females must emerge onto the beach to nest while the laid clutch does not receive parental care during the entire duration of incubation. Thus, successful nesting sites must maintain the safety of the nesting sea turtle during the processes of digging the body pit, nest chamber construction, egg laying, and camouflaging (Sarahaizad et al. 2012), as well as ensure the nest has the greatest chance of surviving heat stress, predation, and tidal inundation during the incubation period (Leighton et al. 2011). This means that the cues for nest placement are a conservation priority (Hamann et al. 2010) in order to protect current nesting beaches (Wallace et al. 2011) as well as predict where nesting may
occur as coastlines are altered by sea level rise or more violent and frequent storms (Poloczanska et al. 2010; Fuentes et al. 2011; Pike 2013). Protection of breeding grounds is a common conservation strategy for the population recovery of wide ranging, migratory animals (e.g. migratory birds, Wade and Hickey 2008; and nesting sea turtles, Nel et al. 2013). Indeed, management plans around the world ensure that the protection of nesting beaches are a priority for protected areas (e.g. flatback sea turtles, Department of Biodiversity, Conservation and Attractions 2017; or other marine turtle species, Asian Development Bank 2011).

1.1 SEA TURTLE NEST SITE SELECTION

At the local scale, vegetation, sand characteristics, and beach topography have been associated with nest site selection. Sea turtles appear to nest within or near vegetation (Kamel and Mrosovsky 2005; Leighton et al. 2011; da Silva et al. 2016), while the amount of moisture retained in the sand may aid in nest chamber construction (Bustard and Greenham 1968; Garmestani et al. 2000; Chen et al. 2007). However, sand that is too moist can impede gas exchange (Ackerman 1977) and could be an indicator the sea turtle is below the high tide line. Beach topography might be a strong driver for nest site selection, as cues indicating the nesting sea turtle is above the high tide line means the nest clutch would not be inundated by the tide during incubation (Whitmore and Dutton 1985; Miller et al. 2003). Beach elevation may be an important factor for this reason; studies at resolutions of the nesting site (Kikukawa et al. 1999; Katselidis et al. 2013) and at the scale of beaches (Yamamoto et al. 2012; Dunkin et al. 2016) have found beach elevation to be an important predictor of nest site selection. Another study postulates that landward silhouettes in front of the sea turtle are an important cue for nest placement (Salmon et al. 1995; Witherington et al. 2011a, 2011b), whether it is a dune (Witherington et al. 2011b), a cliff-face (Mazor et al. 2013), clumps of vegetation (Hays and Speakman 1993), an unused building (Salmon et al. 1995), or a temporarily erected barrier (Witherington et al. 2011a). Topographic heterogeneity was also found to be an important driver for nest site selection. For example, leatherback sea turtles in Florida, USA, nested in areas of the beach that were higher than the surrounding area (Yamamoto et al. 2012), while loggerhead
sea turtles on the Sunshine Coast, Australia nested on areas of the dune where there was greater concavity at the dune toe and were not highly rugged (Kelly et al. 2017).

Although considerable research has investigated sea turtle nest site selection, uncertainties still remain. There are also gaps in the distribution of research effort by species and by nesting region. Of the 34 studies reviewed from the literature (see Appendix I: Literature Review), 19 of these studies were conducted on loggerhead sea turtles, of which 13 came from the United States. In contrast, flatback sea turtles, a species of sea turtle that can only be found in Australia, was investigated by only 4 studies (Limpus 1971; Blamires et al. 2003; Koch and Guinea 2006; Bannister et al. 2016).

1.2 FLATBACK SEA TURTLES

Flatback sea turtles (Natator depressus) are the only species of sea turtle without an oceanic post-hatchling or juvenile phase (Walker and Parmenter 1990), resulting in their endemism to the continental shelf waters of Australia (Limpus 2007). The IUCN lists them as data deficient (Red List Standards & Petitions Subcommittee 1996) but they are listed as vulnerable throughout Australia (Department of Environment and Energy 2018). There have been several recent studies on the flatback sea turtle populations in Western Australia (see Appendix I: Literature Review), but few studies investigated nest site selection for this species throughout Australia. These have generally supported the role of beach topography: initial observations by Limpus (1971) found that flatback sea turtles in southern Queensland selected nesting sites on the top of dunes. Another study found the steepness of the dunes in Fog Bay, Northern Territory, confined the flatback sea turtles to nest at the dune base (Blamires et al. 2003). Two studies at Bare Island, Northern Territory, found flatback sea turtles nested on beaches with gently sloping dunes (Bannister et al. 2016; Koch and Guinea 2006).

These studies were carried out on beaches that were relatively short (between 1 and 30 km), but other flatback sea turtle nesting beaches can be expansive and remote, such as Cape Domett (Whiting et al. 2008), Barrow Island (Pendoley et al. 2014), or the 220 km long Eighty Mile Beach (Department of Parks and Wildlife 2014) in Western Australia. Long and remote
beaches used for other sea turtle species can also be found around Australia. For example, the closest settlement to loggerhead, green, and possibly hawksbill sea turtle nesting sites at Gnaraloo Bay and Cape Farquhar (Riskas 2014; Thomson et al. 2016) is Carnarvon at 120 km. Obtaining data relevant for nest site selection from such remote and long beaches can be logistically challenging.

1.3 APPLICATIONS OF ESTIMATING TOPOGRAPHY WITH LIGHT DETECTION AND RANGING (LiDAR)

Advances in technology that remotely obtain information on beach topography can be useful for studies investigating nest site selection by sea turtles. Traditional methods for measuring beach topography are generally restricted in the number of observations that can be made and are generally limited to the nest site itself (Wood and Bjorndal 2000; Mazaris et al. 2006; Zavaleta-Lizarra and Morales-Mavil 2013), and are less able to comprehensively characterize the entire beach. Such techniques may be more difficult to conduct at remote and expansive beaches, such as many nesting beaches in Australia. Existing global elevation datasets have resolutions that are too coarse to capture the subtle nuances of the beach profile that may be relevant for a sea turtle in its selection of a nesting site. For example, the Shuttle Radar Topography Mission as a resolution of 30 m and does not have data for intertidal habitats (NASA Jet Propulsion Laboratory (JPL) 2013).

Light detection and ranging (LiDAR), which captures detailed 3D measurements of the Earth’s surface may be ideal for these purposes. LiDAR technology is an active sensor that fires pulses of light to measure the distance of objects. Distance to objects are determined by the time it takes for the pulse of light to return to the sensor. When attached to an aircraft, elevation can be determined with geo-referenced points where the lasers contact the ground. These can be used to obtain data that captures fine-scale topographic variability. This detailed information on landscape topography has been used to model suitable habitats. This has been particularly useful when the distribution of an organism is reliant on the topography of the landscape, such as predicting the distribution of plants (Sellars and Jolls 2007; Andrew and Ustin 2009; Questad et
LiDAR was also the preferred method of obtaining topographic information of coastlines because of its high vertical accuracy and ease at which large areas can be mapped quickly (Mason et al. 2000). For these dynamic landscapes, LiDAR scans taken over time (Woolard and Colby 2002; Shrestha et al. 2005; Kerfoot et al. 2012) or before and after storms (Zhang et al. 2005; Stockdon et al. 2009) can accurately quantify changes in the beach topography. These studies were able to rapidly obtain data on topography across large areas of beach, which highlights the potential for the use of airborne laser scans of expansive and remote beaches in Australia. Further, given that many of these beaches are nesting sites for endemic flatback sea turtles, there is also an opportunity to determine the influences of topography on their nest site selection.

The overall aim of the current study was to determine how beach topography affects flatback sea turtle nest site selection. Specifically the study objectives were to (i) characterize the topography of the extensive and remote beach with airborne LiDAR data; and (ii) to determine the topographic feature(s) that influence nest site selection by flatback sea turtles.

2 METHODS

2.1 STUDY SITE

This study investigated sea turtle nest site selection at Eighty Mile Beach, a 220 km long beach situated in northwest Western Australia within the Eighty Mile Beach Marine Park (Figure 1). It is considered to be a non-continuous, tide-dominated, ultra-dissipative beach broken by bluffs and tidal and river inlets (Short 2006a) with high wave energy in the southwest (Cape Keraudren) but lower wave energy in the north (Cape Mississiy) (Piersma et al. 1999). The tidal range along Eighty Mile Beach varies from 4 to 10 m, resulting in wide intertidal areas
that can reach 4 km (Short 2006a, 2006b), such as those found at the Anna Plains Sanctuary Zone in the north. These shallow and wide intertidal zones are thought to attenuate wave energy (Piersma et al. 1999), allowing for the deposition of marine-derived carbonate mud in the middle and upper intertidal environments (Semeniuk 2008). On the other hand, the high-energy south-western region of Eighty Mile Beach has much of its sand derived from Mesozoic-tertiary bedrock or reworked quaternary desert dunes (Semeniuk 2008). A majority of the Eighty Mile Beach coastal areas are backed by an expansive fore dune system (Short 2006b) formed from sedimentation deposited into the Canning Basin (Department of Parks and Wildlife 2014; Semeniuk 2008). The exception to this is an area south of the Anna Plains Sanctuary Zone, where a mangrove meets the ocean and has no dune development (Short, 2006b).

Climate in north-west Australia is characterized by hot and wet summers and dry winters (Bureau of Meteorology 2015; O’Donnell et al. 2015). Precipitation in the region has been increasing in the last two centuries (Smith 2004; Feng et al. 2013; O’Donnell et al. 2015; Ren and Leslie 2015) and mainly occurs during the austral summer-autumn period (December – March) with average annual rainfall exceeding 310 mm (O’Donnell et al. 2015; Bureau of Meterology 2018). Tropical cyclones are common during this period and are the greatest contributor to rainfall in north-western Australia (Ng et al. 2015). This period also experiences the highest average monthly maximum air temperatures, reaching up to 40℃ Celsius (O’Donnell et al. 2015). The dry season (April – October) has less rainfall and cooler temperatures, with average monthly maximum air temperatures reaching a minimum of 25℃ and an average monthly rainfall not exceeding 10 mm (Bureau of Meteorology 2015; O’Donnell et al. 2015).

Flatback sea turtles nest across Eighty Mile Beach (Pendoley Environmental 2017) during the austral summer (Department of Parks and Wildlife 2014). The highest density of nests occurs within the Wallal Recreation Zone adjacent to Eighty Mile Beach Caravan Park and within the Anna Plains Sanctuary Zone (Figure 1; Department of Parks and Wildlife 2014).
Figure 1. Boundary of Eighty Mile Beach Marine Park and its major management zones. PSZ = Pardoo Sanctuary Zone, CKSZ = Cape Keraudren Sanctuary Zone, PwSPZ = Paruwuturr Special Purpose Zone, WRZ = Wallal Recreational Zone, WSPZ = Waru Special Purpose Zone, PSPZ = Pilyarlkarra Special Purpose Zone, ASPZ = Anna Plains Sanctuary Zone, JSPZ = Jangyjartiny Special Purpose Zone.
2.2 QUANTIFYING FLATBACK TURTLE NESTING

An aerial survey conducted by Pendoley Pty. Ltd. was flown along the shoreline from Broome to Port Hedland at low altitude (200 m) during the flatback sea turtle nesting season on 7th January 2014 to document nesting activity on the beach. Three areas with a cumulative total distance of about 25 km (or 11%) of Eighty Mile Beach were not surveyed during the flight mission as these were characterized as tidal or river inlets, which are not normal nesting areas for sea turtles (Figure 2; Weishampel et al. 2003; Yalçın-Özdilek et al. 2007) and to conserve battery power. Geotagged photographs (sampling units) were taken with a Sony SLT-A99V digital SLR camera at a frequency of 40 photos/minute with ~60 m spacing between photograph centroids and approximately 10 – 20% overlap between photographs. Only nesting pits (herein known as “pits”) within each photograph were manually counted to determine the distribution of pits across Eighty Mile Beach. A pit was counted when a stark depression in the sand was seen within the photograph and were considered proxies for ideal nesting habitat (as pits could be abandoned nesting attempts). The pits within the overlapped regions between two photographs were managed by assigning the pit to the count of the north-eastern photograph in order to maintain consistency of sampling units (approximately 60 m) and avoid double counting (Figure 3).
Figure 2. Regions of Eighty Mile Beach sampled during the aerial survey for flatback sea turtle pits by Pendoley Pty. Ltd. on the 7th of January, 2014.
Figure 3. Example photos illustrating how overlaps between aerial survey photographs were managed. Yellow circle highlights a pit, and yellow box highlights sea turtle tracks. The size of the sampling unit equals the size of the photo minus the region of overlap on the north-eastern side. The pit depicted in the photo is assigned to the count for photo 2.

2.3 CHARACTERIZING BEACH TOPOGRAPHY

2.3.1 Airborne LiDAR Survey

The airborne LiDAR flight mission was flown between Port Hedland and Broome by Airborne Research Australia (www.airborneresearch.org.au) on 24th and 25th September, 2015 using a light aircraft equipped with the LiDAR RIEGL Q680i-S scanner. The flight path was centred above the dune crest to ensure the swath (approximately 450 m) included the upper intertidal zone, beach, primary dune, and some landward dunes. Point clouds were returned at approximately 10 points/m² with a nominal vertical precision of 0.1 m (2 standard deviations) and vertical accuracy of 0.25 m (1 standard deviation). These point clouds were then used to generate digital elevation models (0.5 m horizontal resolution), which were provided by the contractor. Though the time between the aerial photographic survey of turtle nesting and the
LiDAR flight mission was 20 months, there was no cyclone activity at Eighty Mile Beach in between these times (Bureau of Meterology 2018), so the coastline is expected to have undergone little change.

2.3.2 Extraction of Beach Profiles

The digital elevation models were used to obtain beach profiles along the entire length of Eighty Mile Beach. A contour line was first generated from the digital elevation model to delineate the general direction of the beach. Contour line elevations were specific to 10 km stretches of beach as continuous contour lines of on 10-km section were different from the continuous contour line of another section. Transects were then established perpendicular to the contour line at a 10-m spacing, a distance argued to be wide enough before variability between transects would increase. The elevation and coordinates of the digital elevation model were extracted from each pixel along each transect to represent vertical profiles of the beach. Contour lines and transects were made in ArcMap 10.3.1 (ESRI, Redlands CA) while the extraction of beach profiles was carried out using the Region of Interest tool within ENVI 5.3.1 (Exelis Visual Information Solutions, Venice). As Eighty Mile Beach Marine Park is within two UTM zones, digital elevation models were split and processed into their respective coordinate systems: WGS 84 UTM50S and UTM51S. A UTM projected coordinate system was used over a geographic coordinate system as UTM minimized visual distortion within a localized area.

2.3.3 Characterization of Beach Topography

Beach profiles can have complex shapes that may provide relevant cues to nesting sea turtles. For example, the beach profile from sea to land will change in angle and elevation between the beach face, the primary dune toe, and the peak of the primary dune. Piecewise linear regression models were used to characterize the complexity of the beach profile as this method is able to distinguish several regression models within a dataset without being prompted where specific breaks between regression models may lie (Muggeo, 2003). Using a beach profile as an example (Figure 4a), a linear piece would be generated along the beach face. As the beach profile changes from the beach face to the primary dune face, the model can no longer
maintain the best linear fit, and a breakpoint is generated at the dune toe. This is followed by the
generation of another linear segment to be fitted on the primary dune face. This process
continues piecewise along the entire beach profile, resulting in several linear segments
connected at breakpoints. The segmented package (Muggeo, 2003, 2008) in R version 3.4.3 (R
Core Team 2017) was used to carry out the piecewise linear regression modelling.

For each profile, a series of models were generated with sequentially increasing numbers
of breakpoints up to a maximum of 15 breakpoints; among these, the model providing the best
fit of the beach profile was selected using the Akaike Information Criterion. Preliminary results
revealed that, for many profiles, the majority of the allowed breakpoints were used to
characterize the complex terrain on the landward side of the primary dune, resulting in poor
model fit on the seaward side (Figure 4b). As a result, two rounds of piecewise linear
regression models were conducted. The first round identified the peak of the primary dune,
which allowed for the landward side of the profile to be removed. The second round of
piecewise linear regression modelling was then carried out on the seaward side of the primary
dune, allowing all breakpoints to be used to effectively characterize subtle changes in the beach
profile (Figure 4c). The breakpoints and slopes of different parts of the beach profile derived
from the piecewise linear regression models were used to quantify beach topographic
characteristics expected to be relevant for sea turtle nest site selection, such as the angle of the
primary dune and the elevation of the primary dune peak (Figure 4d; Table 1). The only
information retained from the landward side of the primary dune was the highest peak in the
profile.
Figure 4. Diagram to explain metrics used in the analysis of beach topography. (a) Areas of the seaward side of a profile that would be characterized in a piecewise linear regression (grey line). (b) Piecewise linear regression segments fitted on the entire beach profile (black line), resulting in the seaward side of the primary dune being poorly fitted. (c) Identification of the peak of the primary dune (yellow circle) with the removal of the landward side of the primary dune and retention of the seaward side of the primary dune. (d) Beach metrics derived from the piecewise linear regression.
Table 1. Topographic metrics used to characterize beach topography with descriptions and justification of the metrics and references for their importance in nest site selection.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Justification</th>
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<tr>
<td><strong>Angle of beach face before primary dune</strong></td>
<td>A smaller angle at the beach face followed by a steeper angle at the primary dune would be an indicator to a sea turtle that it has reached an area above the high tide line</td>
<td>Wood and Bjorndal 2000; Katselidis et al. 2013; Roe et al. 2013</td>
</tr>
<tr>
<td><strong>Angle of primary dune</strong></td>
<td>A steeper angle may be an indicator the sea turtle transitioned to an area of beach above the high tide line</td>
<td>Horrocks and Scott 1991; Wood and Bjorndal 2000; Cuevas et al. 2010; Spainer 2010; Zare et al. 2012; Katselidis et al. 2014</td>
</tr>
<tr>
<td><strong>Length of primary dune face</strong></td>
<td>The space on the primary dune on which the sea turtle would be able to nest in</td>
<td>Limpus 1971; Salmon and Witherington 1995; Blamires et al. 2003</td>
</tr>
<tr>
<td><strong>Elevation of primary dune peak</strong></td>
<td>Tall landward objects in front of a sea turtle have been found to be an important factor in nest site selection in other studies</td>
<td>Kikukawa et al. 1999; Yamamoto et al. 2012; Dunkin et al. 2016</td>
</tr>
<tr>
<td><strong>Highest elevation in profile</strong></td>
<td>Silhouettes in front of the sea turtle are hypothesized to be an environmental cue for nest placement</td>
<td>Salmon et al. 1995; Witherington et al. 2011b, 2011a; Mazor et al. 2013</td>
</tr>
<tr>
<td><strong>Number of breaks before primary dune</strong></td>
<td>An index for the complexity that indicates beach morphology</td>
<td>Whitmore and Dutton 1985; Hays et al. 1995; Rizkalla and Savage 2011; Yamamoto et al. 2012; Kelly et al. 2017</td>
</tr>
</tbody>
</table>

2.4 MODELLING NEST SITE SELECTION

As 25 km of Eighty Mile Beach was not surveyed during the 2014 aerial survey, 195 km (88%) of Eighty Mile Beach was used in the analysis. Pits found within each photograph were visually interpreted as nesting pits of flatback sea turtles. Counts of pits within each photograph ranged from 0 to 8 (Figure 5) with the majority showing no pits. These counts were converted to the presence or absence of a pit or the density class of pits in a photograph, using the Jenks natural breaks optimization in ArcMap 10.3.1 to divide nesting density into low (1 pit) or high (2 – 8 pits) density classes (Jenks 1967). Nest presence/absence and density classes were modelled against characteristics of beach topography using classification tree analyses.
Figure 5. The number of photographs relative to the number of pits in each photograph taken in the aerial survey along Eighty Mile Beach.

Classification tree modelling is a non-parametric machine learning technique that can be used in predictive modelling (Breiman et al. 1983). This modelling technique has been found to perform well in species distribution models (Seguaro and Araujo 2004; Elith and Graham 2009; Elith et al. 2006; Andrew and Ustin 2009) and has shown good predictive power in determining sea turtle nest site selection under current climate conditions (Mazaris et al. 2006), after anthropogenic impacts (Rizkalla and Savage 2011), and in future climate-change conditions (Mazaris et al. 2015). Classification trees recursively split a dataset at nodes along the explanatory variable that groups the data into as homogenous groups as possible. The process continues iteratively until the data can no longer be partitioned into homogenous groups, ending at a terminal node with a predicted value (Franklin, 2009; Loh, 2011; Strobl et al., 2009; Therneau and Atkinson, 2018a). In this study, classification trees were used to determine how beach topography influences nest site selection by flatback sea turtles using the rpart package (Therneau and Atkinson 2018b) in R version 3.4.3 (R Core Team 2017). The
analysis units for these models were the beach lengths sampled by individual photographs in the flatback sea turtle aerial nesting surveys; henceforth, analysis units will be referred to as “photographs” for brevity.

Classification trees are sensitive to imbalances within the dataset (Chawla 2003; Menardi and Torelli 2014), which were prevalent in this study as photographs with no pits were substantially more frequent than photographs with pits (Figure 5). Imbalance can be corrected by weighting rare classes to give them equal influence to the model as common classes. Weights used in presence/absence and density class models were calculated from the frequency of each class in the photographs and are provided in Table 2.

The data was geographically sub-sampled into training and testing sets. Spatial autocorrelation between photograph centroids was accounted for by grouping photographs into 10 km segments, followed by subsampling every fourth segment as testing data. This method has shown to reduce spatial autocorrelation between testing and training data (Boria et al. 2014; Radosavljevic and Anderson 2014; Jiménez-Alfaro et al. 2018). The same training and test subsets were used when modelling for both the presence or absence of pits and the pit densities. Model performance was evaluated by calculating the overall error, omission error, and commission error. For the presence/absence model in the current study, omission error is the proportion of photographs with pits observed but were predicted to be absent, while the commission error is the proportion of photographs predicted to have pits but were not observed to have pits. For the density model, omission error is the proportion of photographs with high pit density that were predicted to be other classes, while the commission error is the proportion of photographs that were predicted to have high density but were observed to be other classes.

Variables were jack-knifed to determine their importance in the classification tree models. This technique creates alternative models with subsets of the variables, and assesses changes in model performance when leaving out a focal variable, and when creating univariate models with only the focal variable. Variable importance was evaluated with the overall error, commission error, and omission error of jack-knifed models applied to testing data relative to
the full model, though focus was given to omission error, which was judged to be the most important type of prediction error in this context. For the density class models, focus was given to the high-density class as it was of interest to predict where areas of high nesting density was occurring across Eighty Mile Beach.

Table 2 Assigned category of each photograph relative to the number of pits present, their frequency within the dataset, the proportion of the dataset each category constitutes, and the weighting applied.

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of pits</th>
<th>Category</th>
<th>Frequency</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presence/absence</td>
<td>0</td>
<td>Absent</td>
<td>1890</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1 or more</td>
<td>Present</td>
<td>586</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>None</td>
<td>1890</td>
<td>1.00</td>
</tr>
<tr>
<td>Nest density/photograph</td>
<td>1</td>
<td>Low</td>
<td>343</td>
<td>5.51</td>
</tr>
<tr>
<td></td>
<td>2 - 8</td>
<td>High</td>
<td>243</td>
<td>7.78</td>
</tr>
</tbody>
</table>
3 RESULTS

3.1 FLATBACK SEA TURTLE NESTING ALONG EIGHTY MILE BEACH

The photographic aerial survey yielded 2,476 photographs of Eighty Mile Beach. Of these photographs, 1,890 had no evidence of any pits and 586 with visible pits. Within each photograph that had pits visible, the number of pits ranged from 1 ($n = 343$) to 8 ($n = 1$), with a total of 972 pits recorded. Figure 6 shows the number of pits within each photograph along Eighty Mile Beach relative to their distance from Cape Keraudren, the southern-most landmark in the study extent. Several of the photographs with high pit densities were found within the Wallal Recreation Zone and Anna Plains Sanctuary Zone. Figure 7 shows the spatial running mean of photographs with pits across Eighty Mile Beach.

![Figure 6](image-url)  
**Figure 6.** Number of pits in each photograph along Eighty Mile Beach, relative to distance from Cape Keraudren in the southwest. Each point in the graph represents the number of pits in each photograph, with darker shades of grey indicating greater density of pits. The pink shaded area is the Wallal Recreation Zone, while the blue shaded region is the Anna Plains Sanctuary Zone.
Figure 7. Spatial running mean of pits present and the observed presence-absence of nests in two sites at Eighty Mile Beach. Photographs were assigned a value between 0 and 1 based on the proportion of photographs that had a pit present within a 2.5 km radius of a given photograph (a). Insets map the presence/absence of pits within photographs for the Wallal Recreational Zone (b) and the south-eastern region of Anna Plains Sanctuary Zone (c).
3.2 EIGHTY MILE BEACH TOPOGRAPHIC CHARACTERISTICS

Using the LiDAR data, six beach metrics were calculated for 20,105 cross-shore transects along Eighty Mile Beach. Examples of beach profiles and the piecewise linear regression models fitted to them are given in Figure 8, which show how well the model fits to the beach profile. The root mean square error (RMSE) of the piecewise linear regression models along transects ranged from 0.00 to 2.27 m (mean ± s.d. = 0.30 ± 0.24 m), indicating they successfully characterized the shape of the profiles.

Figure 8. Examples of beach profiles (grey lines) along Eighty Mile Beach with fitted piecewise linear regression models (dashed red lines) segmented at breakpoints (yellow circles). RMSE for the

- **a** RMSE = 0.15 m
  - Length of primary dune face = 34 m
  - Angle of primary dune = 12°

- **b** RMSE = 0.29 m
  - Length of primary dune face = 128 m
  - Angle of primary dune = 5°

- **c** RMSE = 0.13 m
  - Length of primary dune face = 34 m
  - Angle of primary dune = 11°

- **d** RMSE = 0.07 m
  - Length of primary dune face = 136 m
  - Angle of primary dune = 1°
fitted piecewise linear regression model is also provided. \( a = 0 \) km from Cape Keraudren, \( b = 75 \) km, \( c = 121 \) km, \( d = 157 \) km.

Figure 9 shows how the measures of the beach metrics vary with position along the beach, measured as the distance from the start of the beach at Cape Keraudren. Overall, there is large variability in the measurements of the beach metrics across Eighty Mile Beach except for the regions in Anna Plains Sanctuary Zone and about 130 to 150 km from Cape Keraudren. The area 130 to 150 km from Cape Keraudren is characterized by a long section of marsh and salt flats that extend directly onto the intertidal zone, and hence has very little dune development. The angle of the beach face was steepest between 60 and 110 km from Cape Keraudren, with a decline in the beach angle between 120 km and Anna Plain Sanctuary Zone (Figure 9a). This was followed by an increase within the sanctuary zone until Cape Missiessy in the north. Some beach faces had negative angles, or angles of depression, which generally occurred in areas of river and tidal inlets near the Waru Special Purpose Zone (Figure 9a). The steepest primary dunes were found between 60 and 100 km from Cape Keraudren, near Pardoo Station, while primary dunes with the smallest angles were found between 130 and 160 km (Figure 9b). Primary dune faces were longer the farther they were from Cape Keraudren, with the longest primary dune face (270 m) occurring in Anna Plains Sanctuary Zone 191 km from Cape Keraudren (Figure 9c). The tallest primary dunes were between 60 and 100 km from Cape Keraudren in the western region of the beach, followed by the primary dunes in Anna Plains Sanctuary Zone in the north. The shortest primary dunes were found between 130 and 150 km from Cape Keraudren (Figure 9d). Profiles had higher peaks between 60 and 80 km from Cape Keraudren, followed by a decrease between 130 and 150 km (Figure 9e). Beach profiles appeared to be more complex, with a greater number of breakpoints used in the piecewise regression models, between 90 and 130 km from Cape Keraudren, followed by lower complexity at 180 km and a slight increase number of breaks from 200 km to Cape Missiessy (Figure 9f).
Figure 9. Beach metric measures relative to their distance from Cape Keraudren. Greater opacity indicates greater density of points. Pink shaded region is the Wallal Recreation Zone, while the blue shaded area is the Anna Plains Sanctuary Zone. (a) Angle of beach face before primary dune. (b) Angle of primary dune. (c) Length of primary dune.
Figure 9 (cont.). Beach metric measures relative to their distance from Cape Keraudren. Greater opacity indicates greater density of points. Pink shaded region is the Wallal Recreation Zone, while the blue shaded area is the Anna Plains Sanctuary Zone. (d) Elevation of primary dune. (e) Highest elevation in profile. (f) Number of breaks in beach profile before primary dune.
Table 3 shows the summary statistics for each beach metric. These metrics were not highly correlated with each other; the minimum correlation was –0.55 (primary dune length and breaks in beach profile) and the maximum correlation was 0.41 (elevation of primary dune peak and primary dune length).

Table 3. Range and mean (± standard deviation) of the beach metrics along Eighty Mile Beach derived from LiDAR data.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Range</th>
<th>Mean ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of beach face before primary dune</td>
<td>-19° – 28°</td>
<td>2° ± 2°</td>
</tr>
<tr>
<td>Angle of primary dune</td>
<td>0° – 74°</td>
<td>10° ± 9°</td>
</tr>
<tr>
<td>Length of primary dune</td>
<td>1 – 270 m</td>
<td>51 ± 47 m</td>
</tr>
<tr>
<td>Elevation of primary dune peak</td>
<td>0 – 25 m</td>
<td>8 ± 3 m</td>
</tr>
<tr>
<td>Highest elevation in profile</td>
<td>2 – 26 m</td>
<td>11 ± 4 m</td>
</tr>
<tr>
<td>No. breaks before primary dune</td>
<td>1 – 15</td>
<td>5 ± 3</td>
</tr>
</tbody>
</table>
3.3 MODELLING NEST SITE SELECTION BY FLATBACK SEA TURTLES

3.3.1 Presence and Absence of Flatback Sea Turtle Nesting Pits

The distribution model performed moderately with an overall error (when applied to the test dataset) of about 40%, while the omission error (20%) was substantially lower than its commission error (66%, Table 4). When applying the jack-knifed one-variable models to the testing data, the angle of the primary dune, the highest elevation in the profile, and the number of breaks before the primary dune were the most important variables in predicting the presence of pits, as their use resulted in a low omission error comparable to that of the full model (Figure 10). Removed-variable models (when evaluated against the testing data) indicated the most important variable was the highest elevation in the profile as its removal resulted in the greatest gain in omission error relative to the full model.

Table 4. Confusion matrix for the predicted and observed presence/absence of pits in a given photograph when evaluated on the testing data. Values indicate number of photographs.

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Presence</td>
<td>Absence</td>
<td>Row total</td>
<td>Commission Error</td>
</tr>
<tr>
<td>Presence</td>
<td>118</td>
<td>230</td>
<td>348</td>
<td>66.1%</td>
</tr>
<tr>
<td>Absence</td>
<td>29</td>
<td>258</td>
<td>287</td>
<td>10.1%</td>
</tr>
<tr>
<td>Column Total</td>
<td>147</td>
<td>488</td>
<td>635</td>
<td></td>
</tr>
<tr>
<td>Omission Error</td>
<td>19.7%</td>
<td>47.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>59.2%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 10. Variable importance for jack-knifed models with photographs predicted to have pits. Overall error (left), commission error (middle), and omission error (right) are provided for models that only use one variable (top row) and models that remove one variable (bottom row). Each variable (blue bars) is displayed along the x-axis and compared to the full models (orange bar).
Consistent with the variable importance results, the full model only included the highest elevation in the beach profile term, despite being supplied with all six variables to use in constructing the model. The model predicted that profiles with intermediate heights (9 – 12 m) would have pits present; beach profiles less than or greater than this were predicted to not have any pits (Figure 11). When mapping the model results across Eighty Mile Beach, profiles were predicted to have suitable nest sites around the Wallal Recreation Zone, the Waru Special Purpose Zone, and the Anna Plains Sanctuary Zone. A small region with several photographs predicted to have pits was found south-west of the Paruwuturr Special Purpose Zone in the south-eastern region of Eighty Mile Beach (Figure 12).

Figure 11. Classification tree modelling the presence or absence of a pit within a given photograph. Terminal nodes identify the predicted response and the number of photographs classified into each node. For these photographs, pie charts show the proportion with pits observed to be present (black) and absent (white).
Photographs are assigned a value between 0 and 1 based on the proportion of photographs that are predicted to have a pit present within a 2.5 km radius of a given photograph (a). Insets show photographs with the predicted presence/absence of pits at Wallal Recreational Zone (b) and the south-eastern region of Anna Plains Sanctuary Zone (c).
3.3.2 Density of Flatback Sea Turtle Nesting Pits

The density model for flatback sea turtle nesting performed poorly, with an overall error of 82% when applied to the testing data (Table 5). The omission error for high pit density (20%) was substantially lower than the commission error (85%), while both error metrics were considerably worse when modelling low pit density (omission error = 69%, commission error = 90%). The high omission error associated to modelling low densities is due to the model not being able to distinguish between areas of low pit densities with areas of high pit densities, while the high commission errors are driven by the model predicting there are areas of high and low pit density where none were observed. Jack-knifed one-variable models show that the most important variable was the number of breaks in the profile before the primary dune as it resulted in the lowest omission error for the high-density class when it was the only variable used in the model (Figure 13). The most important variables in jack-knifed removed-variable tests for high pit densities were the length of the primary dune face, the elevation of the primary dune peak, and the number of breaks in the profile before the primary dune. The removal of these variables resulted in greater omission errors when compared to the full model.

Table 5. Confusion matrix for the predicted and observed density of pits in a given photograph when evaluated on the testing data. Values indicate number of photographs.

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Observed</th>
<th>High</th>
<th>Low</th>
<th>None</th>
<th>Row total</th>
<th>Commission Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td></td>
<td>49</td>
<td>54</td>
<td>231</td>
<td>334</td>
<td>85.33</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>10</td>
<td>27</td>
<td>218</td>
<td>255</td>
<td>89.4%</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>2</td>
<td>5</td>
<td>39</td>
<td>46</td>
<td>15.2%</td>
</tr>
<tr>
<td>Column Total</td>
<td></td>
<td>61</td>
<td>86</td>
<td>488</td>
<td>635</td>
<td></td>
</tr>
</tbody>
</table>

Omission Error & 19.7% & 68.6% & 92.0%

Accuracy & 18.1%
Figure 13. Variable importance for jack-knifed models with photographs predicted to have high pit density. Overall error (left), commission error (middle), and omission error (right) are provided for models that only use one variable (top row) and models that remove one variable (bottom row). Each variable (blue bars) is listed along the x-axis and compared to the full model (orange bar).
The full model of nest density classes made use of two variables: highest elevation in the beach profile and the elevation of the primary dune. This discrepancy from the variable importance results likely arose because the assessment of variable importance emphasized omission error rates of the high density class, while model construction attempted to minimize confusion between all density classes. Photographs were predicted to have lower nesting densities when profiles had higher peak elevations (greater than 9 m) and lower primary dune peak elevations (< 1 m). In cases where the primary dunes were higher (≥ 1 m), photographs were predicted to have high nesting densities when the highest elevation in the profile was less than 12 m. Profiles with a peak elevation lower than 9 m or greater than 12 m did not have any nests predicted in their photographs (Figure 14), similar to the distribution model (Figure 11).

Mapping the model predictions across Eighty Mile Beach reveals that areas predicted to have high pit densities were within the Anna Plains Sanctuary Zone, the north-eastern part of the Wallal Recreation Zone, and south-east of the Paruwuturr Special Purpose Zone (Figure 15).

![Classification tree modelling](image)

Figure 14. Classification tree modelling of the pit density categories within a given photograph. Terminal nodes contain the predicted response and the number of observations classified into each node. For these photographs, pie charts show the proportion with pits observed to be in high density (black), low density (grey), and where none were observed (white).
Figure 15. Mapped predictions for classification tree model of different densities. Photographs are assigned a value between 0 and 1 based on the proportion of photographs that are predicted to have a high density of pits within a 2.5 km radius of a given photograph (top panel). Insets show areas where photographs would be predicted to have high pit density at Wallal Recreational Zone (a) and the south-eastern region of Anna Plains Sanctuary Zone (b).
4 DISCUSSION

The aims of this study were to develop a method to characterize the topography of a remote and expansive beach and determine which features of its topography influenced sea turtle nest site selection. The use of airborne LiDAR addressed the challenge of efficiently obtaining beach topography data from the 220-km long coastline of Eighty Mile Beach at resolutions high enough to capture fine-scale variations. Piecewise linear regression models were then used to quickly calculate ecologically relevant metrics that were tailored to the needs of modelling flatback sea turtle nest site selection. This study highlights the ease at which beaches of this type can be swiftly characterized.

4.1 CHARACTERIZATION OF BEACH TOPOGRAPHY

This study demonstrates that the use of airborne LiDAR can be useful in obtaining information that is relevant for ecological research, especially for studies of this type. Such LiDAR data sources are becoming readily available; for example, more than 700 km of the south-west coast of Australia has been mapped with airborne LiDAR (Department of Planning, Lands and Heritage 2017), while United States coastlines are periodically surveyed by LiDAR, and the data made publicly available (NOAA 2018). However, to effectively extract information from LiDAR-derived digital elevation models in a manner that characterizes different features of the beach can be challenging. Moving window analyses are commonly performed across rasterized digital elevation models and can estimate topographic features such as slope or relative elevation (e.g. Sellars and Jolls 2007). However, beaches have distinct, intuitively recognizable features, such as beach slopes and dunes, which are organized in a way that is consistent with other beach features in the profile. These would not easily be captured by a moving window approach because it ignores the essentially linear nature of beach systems. The extraction of profiles along the beach and fitting piecewise linear segments to these profiles allows these distinct beach features to be identified and measured. Quantitative information on
each feature can then be quickly calculated from the fitted linear segments, which can be customized to the requirements of coastal or conservation managers (Mason et al. 2000).

Here, six beach metrics were calculated from fitted piecewise linear regression models of 20,105 coastal profiles at a spacing of 10 m across the 220-km coastline of Eighty Mile Beach. These metrics were tailored to capture features hypothesised to be relevant for nest site selection: the angle of the beach face before the primary dune, the angle of the primary dune, the elevation of the primary dune peak, length of the primary dune, the highest elevation in the profile, and the number of breaks in the profile before the primary dune. The good fit of the piecewise linear regression models (mean RMSE ± s.d. = 0.30 ± 0.24 m) suggests that the measurements calculated from the fitted linear segments are a reasonable reflection of the LiDAR scans of Eighty Mile Beach topography. These can then be corroborated by comparison of these results to previous site visits and descriptions of Eighty Mile Beach (Short 2006a, 2006b). For example, in the current study, the angle of the beach face before the primary dune was consistently low (mean ± s.d. = 2° ± 2°), which agrees with previous work describing Eighty Mile Beach as an ultra-dissipative beach (Short 2006a, 2006b). Another detail captured by the LiDAR data was an area lacking dunes approximately 130 to 150 km from Cape Keraudren, which was described previously as a 16 km stretch of coastline characterized by mangroves and several small drainage creeks where dunes are absent (Short 2006b). This method thus shows the use of piecewise linear regressions to extract several metrics has the potential to be useful in several areas of ecological research, such as sea turtle habitat use.

4.2 FLATBACK SEA TURTLE NEST SITE SELECTION

The current study found the flatback sea turtle population at Eighty Mile Beach nested in areas where the highest elevation in the profile was between 9 and 12 m. Other studies indicate flatback sea turtles preferentially nested on the dune face above the high tide line, such as those in Mon Repos, Queensland (Limpus 1971), Crab Island, Queensland (Limpus et al. 1983), Mundabullangana, Western Australia (Blamires et al. 2003), and Bare Sand Island, Northern Territory (Bannister et al. 2016). The selection of a particular site on the dune may be dependent
on the ease at which the flatback sea turtle is able to scale the dunes (Koch and Guinea 2006; Bannister et al. 2016). Flatback sea turtles in Fog Bay, Northern Territory, were confined to the dune base as they could not scale the steep gradient of the dune (Blamires et al. 2003), while those at Bare Island, Northern Territory, nested on the top of the dune because of the low dune gradient (Koch and Guinea 2006; Bannister et al. 2016). Though the flatback sea turtles at Curtis Island, south-east Queensland were found to scale the steep dunes to nest at the dune peak, this is not a usual occurrence (Limpus 1971).

However, the results of these other studies are not directly comparable with the current study as they described the exact nesting site relative to the cross-section of the beach. In contrast, the current study considered nest site selection in the perpendicular direction, determining how variation between beach profiles influences nest placement of flatback sea turtles in Eighty Mile Beach. By considering the metrics of the entire beach profile, the current study obtained results that are consistent with the conclusions of other studies that the silhouette in front of the sea turtle is an important environmental cue for nest site selection (Mazaris et al. 2006; Witherington et al. 2011a, 2011b). Witherington et al. (2011a) erected barriers in front of loggerhead sea turtles as they were emerging onto the beach found that the sea turtles began nest construction about 3 m away from the barrier, making no attempt to move around or climb over the barrier (e.g. as leatherbacks did with an escarpment, Roe et al. 2013). They concluded that the silhouette of a landward feature in front of the sea turtle was the cue for nesting (Witherington et al. 2011a). These results may explain why the highest elevation in the profile may be the most important factor in the presence or high density of flatback sea turtle nests at Eighty Mile Beach. Differences between the present findings and previous investigations of flatback turtle nesting behaviour may also be due to population-specific characteristics. The flatback sea turtle population at Eighty Mile Beach is its own genetic stock (Tucker et al. 2015), and thus the influences that drive nest site selection by the flatback sea turtles at Eighty Mile Beach may be unique to this population. Population-specific nesting behaviour has also been seen in hawksbill sea turtles, for example, where those in French West Indies preferred nesting
in low-lying vegetation or on sand adjacent to the forest edge (Kamel and Delcroix 2009), while those in El Salvador preferred to nest amongst the dense woody vegetation (Liles et al. 2015).

Two other studies have utilized LiDAR-derived beach measurements to determine the influence of beach topography on nest site selection on other sea turtle species. Both these studies were conducted on the east coast of Florida (Yamamoto et al. 2012: approximately 85 km; Dunkin et al. 2016: 200 km), but obtained different results to the present study. Yamamoto et al. (2012) found that higher beach elevations were the strongest predictor for loggerhead sea turtle nesting, that green sea turtle nesting was correlated with deeper offshore approaches, and that leatherback sea turtles nested on areas of beach with a higher topographic positional index. The second study (Dunkin et al. 2016) found that a beach elevation of 5 m was the optimal elevation for nesting by loggerhead sea turtles, which also yielded the lowest omission error (11%). Both these studies appear to mirror other findings that found beach elevation was important for nest placement by sea turtles, as this may be a cue the sea turtle is above the high tide line (Horrocks and Scott 1991; Kikukawa et al. 1999; Katselidis et al. 2013).

However, direct comparisons between the two Florida studies and the current study are difficult. It should be noted that the current study did not use beach elevation as an explanatory variable as it was collinear with other beach metrics of the model. In addition to using different suites of explanatory variables than the current study, the previous studies also used different scales of analyses and modelled different response variables. Both studies in Florida predicted density of nests in 20 km segments of beach, while explanatory variables were summarized statistics at the same sampling unit. This was due to the fact that information on sea turtle nesting was only available at beach level. In contrast, sea turtle nesting data used in the current study was available at a resolution of 60 m. These differences in resolution can yield different results. Models developed from coarser resolutions can perform poorly because the factors that influence species distributions at larger scales may not be the same processes at work with smaller resolutions (Nyström Sandman et al. 2013). In other words, the predicted distribution of sea turtle nesting pits modelled from summarized elevations across 20 km might not be
ecologically relevant for a sea turtle that is selecting a suitable nesting site at a scale of 5 m (but see below for discussion on modelling distribution vs. density). Modelling nest site selection at larger resolutions may be appropriate for coarse-scale biogeographical studies (see Austin and Van Niel 2011), but not for the purpose of predicting suitable habitat (e.g. Nezer et al. 2017). Species distribution models that are developed on data available at finer resolutions can reveal the processes that drive nest site selection at these smaller scales.

### 4.3 MODEL PERFORMANCE

The presence/absence model for flatback sea turtle nest site selection performed moderately (overall error = 40%), but the density model performed poorly (overall error = 80%). The difference in performance between the two models may be based on the resolution of the response variable; distribution models have a tendency to perform better than models that attempt to predict abundance (Pearce and Ferrier 2001). Such examples can be found when predicting the abundance and occurrence of red kites across the Iberian Peninsula (Seoane et al. 2003), breeding aggregations of raptors (Estrada and Arroyo 2012), seabirds in marine protected areas (Oppel et al. 2012), or moose in Canada (Michaud et al. 2014). The better performance of distribution models may be attributed to the fact that the presence, rather than abundance, of an organism can be driven by less complex multivariate relationships between environmental variables at a given place or time (Pearce and Ferrier 2001). On the other hand, attempting to predict abundance can prove difficult as varying abundances may be driven by complex combinations between environmental parameters (Michaud et al. 2014) or because confounding variables not accounted for can result in models that are oversimplified (Merow et al. 2014). In such cases, predicting the occurrence of an organism would allow for lower overall error, as in the current study.

There are several types of errors in classification analyses, which have different implications to the useability of the results. In the current study, omission error was given greater emphasis in evaluating model performance as it was determined to be more important to ensure that areas where nests were observed were correctly predicted by the model (Franklin
If the purpose was to ensure that the majority of nesting areas were correctly predicted by the model, both the distribution and density model can be useful in predicting the presence or the high density of pits (omission error = 20%). Though commission error was not given as much importance as omission error, the high commission errors in both the distribution and density models in predicting presence or high density of pits indicate the models over-estimated where pits may occur across Eighty Mile Beach. This could be due to areas with nesting pits were similar to other possibly suitable beaches that did not have any pits observed, and hence predicting those areas to have nests when none were observed. However, the nest survey data used for the current study was a single day within an entire nesting season. Thus, recorded absences in this dataset may not reflect a true absence of pits, and hence a truly unsuitable site for nesting (MacKenzie et al. 2002). The addition of nesting data evenly distributed in time across the season could improve the performance of the model.

The moderate performance of the presence/absence model in this study, however, may be an indicator that other variables besides beach topography may influence nest site selection. At coarser scales, it has been hypothesized that offshore bathymetry was an important driver for nesting beach selection (Mortimer 1982; Yamamoto et al. 2012). At the scale of the nesting site itself, vegetation appears to play an important role in nest site selection, as sea turtles may nest within or near vegetation (Kamel and Mrosovsky 2005; Leighton et al. 2011; da Silva et al. 2016) as this may be an indicator to the sea turtle that it is above the high tide line. Sea turtles may also nest within the vicinity of vegetation due to the sand being more stabilized by vegetation roots (Bustard and Greenham 1968; Chen et al. 2007), making construction of the nest chamber easier as it would not continuously collapse during construction. In this regard, sand moisture might also play an important role in easing nest construction, as drier sand tends to be looser (Garmestani et al. 2000; Wood and Bjorndal 2000; Chen et al. 2007). Sand moisture might be helpful to a certain threshold (Chen et al. 2007); sand that is too moist can impede gas exchange (Ackerman 1977) or be an indicator to the sea turtle that it is below the high tide line. Nesting density also appeared to decrease in closer proximity to river inlets (Weishampel et al. 2003; Yalçın-Özdilek et al. 2007). Vegetation and river inlets can be detected by LiDAR, so
even if the current project only focused on the influence of topography on nest site selection, including vegetation and river inlets in the presence/absence and density models might improve their performance.

5 CONCLUSION

The approach developed in this study allowed the topography of a remote and long beach to be characterized and models to be developed that predicted the presence/absence and density of flatback turtle nests along Eighty Mile Beach. The presence/absence of nests was found to be associated with the highest elevation in a profile between 9 and 12 m. These findings agree with the conclusion of other studies that the silhouette of a landward feature in front of a sea turtle is an important environmental cue for nest placement. The presence/absence model performed only moderately, while the density of nests could not be successfully modelled. This restricts the usefulness of the density model to managers as identifying areas of high density may be of greater conservation interest. The poor and moderate performance of the density and presence/absence models may be attributed to the study using sea turtle nesting data that was from a single day in an entire nesting season or that nest site selection is driven by environmental cues other than topography. The inclusion of nesting data from more days in the nesting season as well as other variables that can be estimated from the LiDAR data – such as the presence of vegetation or river inlets – may improve the performance of both models. The current study demonstrates that characterizing long and remote beaches is possible, and that the methods used here can be applied to similar beaches in other parts of the world. Given the importance of coastal environments, such as habitat for the threatened charismatic megafauna like sea turtles, other studies such as these can be invaluable to informing management for their conservation.
6 REFERENCES


INTRODUCTION

The conservation of sea turtles is an objective shared amongst scientists, indigenous peoples, and the general public alike (Campbell and Smith 2006; Smith-Marder 2006; Morgan 2007; Wallace et al. 2011). Conservation programs around the world are underway to ensure the continued persistence of sea turtles, though becoming increasingly difficult with limited monetary resources. Obtaining information to make informed decisions is critical to ensure that conservation outcomes are maximized (Wallace et al. 2011). One such conservation strategy is the protection of coastal areas as several sea turtle life-history processes, such as breeding and nesting, can be protected within a single area (Wallace et al. 2011; Nel et al. 2013). New technologies such as airborne laser scanning are tools used in ecological and coastal research to characterize forest structure and beach topography (Mason et al. 2000; Lefsky et al. 2002; Zhang et al. 2005; Simonson et al. 2014), and has already been extended to understand the importance of beach topography for the nest site selection by sea turtles (Long et al. 2011; Yamamoto et al. 2012, 2015).

The use of airborne laser scanning has the greatest benefits in expansive landscapes, such as Australian beaches, some of which are also nesting beaches to endemic flatback sea turtles. This species of sea turtle nest in several important rookeries on the continent, one of which is Eighty Mile Beach (Limpus 2007; Department of Parks and Wildlife 2014). This literature review focuses on nest site selection by flatback sea turtles and the use of airborne laser scanning in characterizing topography of nesting beaches in Eighty Mile Beach Marine Park. This review will cover the anthropogenic threats facing the seven species of sea turtles first, followed by a focus on flatback sea turtles, including their biology, distribution, and the specific threats they face in Western Australia. A review of the literature covering what is known about sea turtle nest site selection will also be discussed, with a particular focus on topography and a brief discussion on other factors of nest site selection. Airborne laser scanning will then be
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introduced, with a brief explanation on how the technology works, followed by the applications of airborne laser scanning in ecology. The review then transitions into the brief evolution of Eighty Mile Beach, followed by the ecological, cultural, and recreational values of the marine park itself. The review is concluded with the aims of the current project, which are focused on determining how beach topography is used by flatback sea turtles as a factor for nest site selection.

SEA TURTLES AND ANTHROPOGENIC THREATS

The seven extant species of sea turtles are faced with the threat of extinction. Each of these species of sea turtles has undergone rapid and large population declines (Table 1), resulting in being listed as either vulnerable, endangered, critically endangered, or data deficient under the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (Marine Turtle Specialist Group 1996; Red List Standards & Petitions Subcommittee 1996; Seminoff 2004; Abreu-Grobois & Plotkin 2008; Mortimer & Donnelly 2008; Wallace et al. 2013; Casale & Tucker 2015). Green sea turtles, for example, have seen 50% declines of nesting populations in three generations (Seminoff 2004), while it is estimated that the Kemp’s ridley sea turtles have lost 80% of their nesting population within three generations (Marine Turtle Specialist Group 1996). Future population losses are also predicted to be substantial, with hawksbill and green sea turtles predicted to lose an additional 80% of their nesting populations within three generations (Meylan and Donnelly 1999; Seminoff 2004; Mortimer and Donnelly 2008).

This is not true for other sea turtle populations around the world. For example, the green sea turtle nester abundance in Hawaii has increased from less than 100 individuals to more than 500 over thirty years, faster than what was predicted since their harvesting was made illegal in the 1970s (Balazs and Chaloupka 2004). Intensive protection of nesting beaches in the Caribbean has seen an increase in leatherback sea turtle nester abundance over 20 years, with a predicted annual increase in population abundance of 13% (Dutton et al. 2005). Hawksbill sea turtles, which are listed as Critically Endangered by the IUCN, have seen an increase in their
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nesting abundance over 15 years in Barbados, West Indies, which was a testament to the local and regional protection of this species (Beggs et al. 2007). Intensive captive-rear and release programs conducted on the Kemp’s ridley sea turtle in the United States has even seen the return of a reproductive female to nest (Shaver et al. 2016).

Australian sea turtle populations are protected under federal and several state laws, which have allowed their populations to persist. Green sea turtles in Edgecumbe Bay, Queensland, have seen an annual increase of 8.3%/year, which was testament to the involvement of the indigenous community in sea turtle conservation (Hof et al. 2017). An earlier study in the southern Great Barrier Reefs have seen green sea turtle population abundances increase by 11%/year (Chaloupka and Limpus 2001), but was not necessarily true for the loggerhead sea turtles, which saw population declines of possibly 3% (Chaloupka and Limpus 2001). The authors attributed these declines to recruitment failure due to fox predation of nests and the mortality of juveniles during their pelagic phase to incidental long line fishing (Chaloupka and Limpus 2001). This study highlights that though there are increases in population abundance of some sea turtle populations, but this increase is dependent on the successful execution of conservation programs and protection of foraging and breeding sites (Wallace et al. 2011; Wallace et al. 2013; Nel et al. 2013;). Without the successful execution of such conservation programs, sea turtle populations may continue to decline.

The conservation of sea turtles is complicated by the geographically expansive nature of their life cycle. For example, sea turtle nesting beaches can occur several thousands of kilometres from their foraging grounds, and sea turtles must undertake long-distance migrations between these sites approximately every two years (Limpus et al. 1992; Bowen et al. 1995; Hughes et al. 1998; Miller et al. 1998; Luschi et al. 2003). This means that the protection of both foraging grounds, nesting beaches, and migratory corridors used by sea turtles are necessary to ensure the continued viability of the species (Wallace et al. 2011; Nel et al. 2013; Pendoley et al. 2014b). Further, very little is known about where and how hatchling sea turtles disperse once they enter offshore oceanic currents, or how long they remain within them (Carr
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1954; Bolten 2003; McClellan et al. 2010; Mansfield et al. 2014; Scott et al. 2014). The inability to identify important oceanic habitats for these pelagic “lost years” and potentially providing insufficient protection for these habitats can jeopardize the viability of sea turtle species (Hamann et al. 2010; Wallace et al. 2011).

Table 1 The seven species of sea turtles (taxonomic and common names), occurrence and nesting regions, IUCN status, and estimated percent-population decline over three generations.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
<th>Nesting Regions</th>
<th>IUCN Status</th>
<th>Estimated percent-population decline</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Dermochelys coriacea</em></td>
<td>Leatherback turtle</td>
<td>Tropical</td>
<td>Vulnerable</td>
<td>40.1%</td>
<td>Wallace et al. (2013)</td>
</tr>
<tr>
<td><em>Chelonia mydas</em></td>
<td>Green turtle</td>
<td>Tropical</td>
<td>Endangered</td>
<td>48% to 67%</td>
<td>Seminoff (2004)</td>
</tr>
<tr>
<td><em>Natator depressus</em></td>
<td>Flatback turtle</td>
<td>Australian Tropical</td>
<td>Data deficient (requires updating)</td>
<td>Needs updating</td>
<td>Red List Standards &amp; Petitions Subcommittee (1996)</td>
</tr>
<tr>
<td><em>Eretmochelys imbricata</em></td>
<td>Hawksbill turtle</td>
<td>Tropical</td>
<td>Critically endangered</td>
<td>84% to 87%</td>
<td>Mortimer &amp; Donnelly (2008)</td>
</tr>
<tr>
<td><em>Caretta caretta</em></td>
<td>Loggerhead turtle</td>
<td>Sub-tropical and Temperate</td>
<td>Vulnerable</td>
<td>47%</td>
<td>Casale &amp; Tucker (2015)</td>
</tr>
<tr>
<td><em>Lepidochelys olivacea</em></td>
<td>Olive ridley turtle</td>
<td>India and west coast of Mexico</td>
<td>Vulnerable</td>
<td>63% to 83%</td>
<td>Abreu-Grobois &amp; Plotkin (2008)</td>
</tr>
<tr>
<td><em>Lepidochelys kempii</em></td>
<td>Kemp’s ridley turtle</td>
<td>Gulf of Mexico, United States</td>
<td>Critically Endangered</td>
<td>80%</td>
<td>Marine Turtle Specialist Group (1996)</td>
</tr>
</tbody>
</table>

The seven species of sea turtles share very similar life histories and many of the anthropogenic threats are associated to the different life-history stages (Fig 1). Anthropogenic lighting from onshore coastal estates can deter gravid sea turtles from nesting on a beach (Salmon, Reiners, et al. 1995; Mazor et al. 2013). Egg clutches laid on beaches are vulnerable to being illegally or legally harvested by people (Marcovaldi and Chaloupka 2007; Valverde et al. 2012; Stringell et al. 2013; Humber et al. 2014), damage by tourists as well as beach users (Katselidis et al. 2013), or feral animal predation (Brown and MacDonald 1995; Blamires et al.
Tyre ruts and pedestrian tracks left behind by off-road vehicles and beach visitors on beaches can prolong the time taken by newly-emerged hatchlings to reach the water (Hosier et al. 1981; van de Merwe et al. 2012), increasing the time they are vulnerable to predation. Anthropogenic lights on the landward side of the beach can cause sea hatchlings to move towards the light inland rather than towards the ocean (Salmon and Witherington 1995; Salmon, Tolbert, et al. 1995; Tuxbury and Salmon 2005; Berry et al. 2013), while offshore lights (such as those on oilrigs) can cause sea turtles to swim towards them instead of swimming out to open ocean (Thums et al. 2016). Hatchlings, neonates, juveniles, and sub-adults in their pelagic phase are vulnerable to becoming victims of by-catch (Polovina et al. 2003; Wallace et al. 2008; Levy et al. 2015) and may also ingest marine debris (Bjorndal et al. 1994; Bugoni et al. 2001; Lazar and Gracan 2011; Schuyler et al. 2012). Sub-adults and adults that recruit into neritic habitats are also at risk of poaching (Garcia-Martinez and Nicols 2000; Mancini and Koch 2009), legal harvesting (Humber et al. 2014), or being injured and killed by boat strikes (Davenport and Davenport 2006). Coastal development can also impact sea turtles, especially during breeding. The building of seawalls can cause beaches to passively erode, reducing nesting success while increasing the likelihood that clutches are washed out when these beaches completely erode (Rizkalla and Savage 2011). Continued development of coastlines can reduce the length of available beaches to nest on, which can result in sea turtles “squeezing” nests onto available beaches (Mazaris et al. 2009) or remove these beaches entirely (Lai et al. 2015). These impacts are only the direct impacts that humans have on sea turtles, as climate change poses a different suite of impacts that also threaten sea turtles.
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Fig 1 The life cycle of a sea turtle with various threats faced in different life history stages. Their life cycle begins with a clutch of eggs in the sand incubated between 45 – 65 days (a). Emergence of hatchlings (b) is followed by a dash into the surf and a swimming frenzy (c). They live their pelagic stage (d) until they are large enough to recruit into neritic environments (e). After developing sufficient energy stores, they migrate back to their natal site to nest (f).

The human-induced climate change of recent times also has far reaching effects on sea turtles in all stages of their life cycle. For example, sea turtle egg clutches can only develop within a range of temperatures, with warmer temperatures generating more females and cooler temperatures creating more males (Mrosovsky and Provancha 1992; Mrosovsky et al. 1992; Godfrey et al. 1999; Broderick et al. 2000; Tomillo et al. 2014). Rising temperatures as a result of climate change can result in 100% mortality within egg clutches (Segura and Cajade 2010; Howard et al. 2014), entirely female-biased clutches (Broderick et al. 2000), or hatchlings that do not perform adequately while swimming to offshore currents (swimming frenzy) (Burgess et al. 2006; Sim et al. 2014). Rising temperatures from global warming can also affect offshore
carbonate producers and reef-forming communities, causing changes in sediment accretion of mainland and island beaches used by nesting sea turtles (Fuentes et al. 2010). Stronger storms and rising sea levels can also wash out and drown entire clutches of eggs (Milton et al. 1994; Fuentes et al. 2011; Dewald and Pike 2014; Patino-Martinez et al. 2014) or erode current and potential nesting beaches (Mazaris et al. 2009; Rizkalla and Savage 2011). Foraging habitats, such as seagrass communities, can also be degraded or lost (Short and Neckles 1999; Koch et al. 2013). This can lead to an abundance of sea turtles with poor body condition and increased mortality of reproductive adults (Poloczanska et al. 2010), which can result in reduced breeding and lower reproductive output. These threats are not unique to any one species of sea turtle, and even sea turtles that do no display an oceanic phase, such as the flatback sea turtle of Australia, are vulnerable.

**FLATBACK SEA TURTLES**

Flatback sea turtles (*Natator depressus*) are endemic to tropical Australia (Fig 2) and are markedly different from other species of sea turtles. They are flatter than other sea turtle species (Bustard and Limpus 1969; Limpus 2007) and lay clutches with fewer eggs (Bustard and Limpus 1969; Pendoley et al. 2014a), while the eggs and hatchlings themselves are considerably larger (Bustard and Limpus 1969; Limpus et al. 1984; Hewavisenthi and Parmenter 2002; Limpus 2007; Pendoley et al. 2014a). Flatback sea turtles also have no oceanic post-hatchling or juvenile phase (Limpus et al. 1983; Walker and Parmenter 1990), a trait that is shared in the other species of sea turtles. Indeed, the colouration and size of flatback sea turtle hatchlings and neonates would allow them to quickly evade predators while living in their turbid neritic habitat of Australian continental waters (Salmon et al. 2009, 2010).
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Western Australia is home to Southeast Indian Ocean Management Unit of flatback sea turtles, one of the four management units within Australia (Table 2) (Dutton et al. 2002; Limpus 2007; Whittock et al. 2016). Initially, very little was known about the flatback sea turtles of this management unit (Limpus 2007), but many publications in recent years have addressed several of these knowledge gaps (Sperling et al. 2010; Pendoley et al. 2014a; Pendoley et al. 2014b; Whittock et al. 2014; Pendoley and Kamrowski 2015; Whittock et al. 2016; Pendoley et al. 2016; Pendoley and Kamrowski 2016). For example, flatback sea turtle nesting has been found to be evenly distributed throughout different subregions of the Pilbara (Fig 3) (Pendoley et al. 2016), while the ranges of female flatback sea turtles between nesting events (inter-nesting period) has been shown to be fairly consistent (Sperling et al. 2010; Whittock et al. 2014). Migration corridors between foraging and feeding grounds were identified along the northwest shelf for individuals from the Pilbara (Pendoley et al. 2014b), with their foraging grounds found near Eighty Mile Beach, offshore from Quondong Point, and in the Lynher and Holothuria Banks (Whittock et al. 2016). Addressing these knowledge gaps
was important, particularly for the flatback sea turtle population in the Pilbara, as this population often interacts with the oil and gas industry of the region.

Table 2: Management units of flatback sea turtles throughout Australia.

<table>
<thead>
<tr>
<th>Management Unit</th>
<th>Major rookeries</th>
<th>Breeding migration</th>
<th>Peak nesting</th>
<th>Post-hatchling migration</th>
<th>Location of foraging adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Australian Management Unit</td>
<td>Peak Island, Wild Duck Island</td>
<td>Up to 1,300 km</td>
<td>Late Nov to Early Dec</td>
<td>Neritic waters within Great Barrier Reef lagoon</td>
<td>Captured in trawl fisheries over soft-bottom waters</td>
</tr>
<tr>
<td>Gulf of Carpentaria and Torres Strait Management Unit</td>
<td>Crab Island, Deliverance Island, Kerr Island</td>
<td>Out of Gulf to Arafura Sea and northern Great Barrier Reef</td>
<td>July</td>
<td>Gulf of Carpentaria &amp; Southern Arafura Sea</td>
<td>Open water soft-bottom habitats of the Arafura Sea, Gulf of Papua, and Great Barrier Reef</td>
</tr>
<tr>
<td>Western Northern Territory Breeding Unit</td>
<td>Coburg Peninsula /adjacent islands, Cape Domett</td>
<td>Unknown</td>
<td>July</td>
<td>Recorded in coastal waters</td>
<td>Occur at low densities within coastal waters such as Darwin Harbour</td>
</tr>
<tr>
<td>Southeast Indian Ocean Management Unit</td>
<td>Barrow Island, Thevenard Island, Dampier Archipelago, Mundabullagana</td>
<td>Utilize a 1,200 km corridor in NW Australia</td>
<td>Jan</td>
<td>Unknown</td>
<td>Eighty Mile Beach, Lacepede Islands, Lynher Banks</td>
</tr>
</tbody>
</table>

Data obtained from Pendoley et al. (2014a, 2014b, 2016) and Limpus (2007)
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Many of the threats faced by the flatback sea turtles of the Pilbara come from their interactions with the urban and oil and gas activities of the region. Hatchlings emerging from their nests have shown to be misoriented in the presence of offshore lights (Thums et al. 2016). The inter-nesting ranges of flatback turtles within the Pilbara were found to be in close proximity of several major resource developments and within offshore lease title areas, suggesting that flatback sea turtles were potentially exposed to multiple risks during their inter-nesting period (Whittock et al. 2014). This is of concern as the inter-nesting period is used for rest while female flatback sea turtles undergo ovulation, which may be sensitive to disturbance (Sperling et al. 2010). Almost half (48%) of the migratory corridor used by flatback sea turtles between their foraging and nesting grounds are in unprotected waters, potentially leaving them...
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vulnerable to the impacts by industrial activities (Pendoley et al. 2014b). Though adult flatback sea turtles displayed foraging behaviour that make them robust against offshore developments, their very nature of being endemic can reduce their ability to adapt should developments expand (Bonn et al. 2002; Whittock et al. 2016).

Managing these threats must be prioritized to ensure that conservation outcomes are maximized with limited financial resources. As mentioned before, protecting a species with a wide geographic distribution can be difficult (Wallace et al. 2011). As suggested by Pendoley et al. (2014b), protecting migratory corridors can ensure the safe migration of flatback sea turtles between their foraging grounds and breeding sites (Pendoley et al. 2014b). The development of additional protected coastal areas provide habitat that will assist in their protection (though other factors can influence population decline), especially if nesting beaches are protected (Nel et al. 2013).

NEST SITE SELECTION

The protection of high-density nesting beaches can increase the reproductive output of sea turtles by ensuring they have a safe habitat for nesting, clutch incubation, hatching, and hatchling emergence (Mortimer et al. 2011; Nel et al. 2013). Therefore, to protect or mitigate human impacts upon sea turtles, it is necessary to understand which beaches are used by sea turtles as nesting habitats (Hamann et al. 2010; Wallace et al. 2011). This can be difficult as how a sea turtle selects one nest site over another is not well understood, and has been identified as a priority for research to determine which beaches require protection (Hamann et al. 2010).

Nest site selection between species and between different populations of the same species appear to have some similarities, particularly with respect to beach topography (Mortimer 1982; Wood and Bjorndal 2000; Katselidis et al. 2013; Roe et al. 2013; Dunkin et al. 2016). Elevation of the nesting site above sea level appeared to be important, but the profile of the beach may also be a determining factor, while interactions between topographic variables may also exist (Horrocks and Scott 1991; Roe et al. 2013; Katselidis et al. 2014). For example, loggerhead sea
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Turtles in Sanibel and Captiva in Florida, United States, always above the most recent high tide line (Hays et al. 1995). An experimental study in the Archie Carr National Wildlife Refuge in Florida extended this finding and found the loggerhead sea turtles began nest construction when a temporary barrier was erected in front of a loggerhead sea turtle (Witherington et al. 2011). Loggerhead sea turtle populations on the Sunshine Coast, Queensland, however, were found to preferentially nest on areas of beach where there was greater concavity at the dune toe (Kelly et al. 2017). In comparison, hawksbill sea turtles in Barbados appeared to prefer sites 1 m above the high tide line (Horrocks and Scott 1991). The distance travelled inland by these hawksbill sea turtles was dependent on the slope of the beach; steeper slopes meant shorter distances travelled across the beach, while beaches with lower slopes meant the sea turtle needed to travel greater distances across the beach in order to reach an elevation of 1 m (Horrocks and Scott 1991). In contrast, hawksbill sea turtles in El Salvador preferred to nest within dense vegetation (Liles et al. 2015). A separate study in Greece modelled the importance of beach orientation, width, length, elevation, and slope for where loggerhead sea turtles would place their nests (Katselidis et al. 2013). Though an elevation of 1 m above the mean sea level was the most reliable indicator for where a sea turtle would nest, the authors also found that the loggerhead sea turtles had a preference for steeper slopes (Katselidis et al. 2013).

Studies that modelled nest site selection over larger areas detected single variables such as elevation as important factors for nest site selection (Yamamoto et al. 2012; Dunkin et al. 2016). A study in Florida using airborne laser scanning on 87 km of beach showed that minimum elevation on the beach dune was the most important factor in nest site selection (Yamamoto et al. 2012). A separate study conducted in Florida across 200 km of coast using a multi-criteria decision support model showed that the model was sensitive to the removal of elevation, but not to other morphological characteristics, indicating that elevation was an important factor for nest site selection by sea turtles (Dunkin et al. 2016).

Topography may be an important factor for where a sea turtle may decide to nest on a beach, but other factors appear to be important to varying spatial extents. The region which sea
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turtles nest in is driven by natal homing, where males and females use geomagnetic cues to return to regions they hatched from (Allard et al. 1994; Lohmann et al. 2008; Lohmann et al. 2013; Brothers and Lohmann 2015). Beach selection appears to be driven by where the paths of storms and cyclones cross the coast. Beach selection has been suggested to be driven by the location of storms and tropical cyclone pathways crossing the coast; important nesting sites between Brisbane and Prosepine in Queensland appeared to be just south of areas that had higher storm frequencies (Fuentes et al. 2011). This may be attributed to the selection of beaches that were not undergoing erosion (Koch et al. 2007) or sudden changes in beach volume (Long et al. 2011; Yamamoto et al. 2015). Offshore approaches that are open and have fewer rocks are also preferred as sea turtles may sustain fewer injuries when approaching the beach to nest and returning to the ocean after depositing its eggs (Mortimer 1982). This preference is also apparent with flatback sea turtles in eastern Australia, where many rookeries are fronted by mudflats rather than coral reef flats (Limpus 2007). Green turtles on Ascension Island (Mortimer 1982) and leatherback turtles nesting in the Pacific coast of Costa Rica (Roe et al. 2013) appear to prefer deeper offshore approaches, which may be due to deeper offshore approaches correlating with steeper beach slopes (Roe et al. 2013). Within the nesting site itself, the moisture of the sand is important during the construction the egg chamber as nests in drier sand collapse more often than moister sand (Mortimer 1990; Chen et al. 2007). Plant roots also stabilize sand, which may explain why green sea turtles in Taiwan (Chen et al. 2007) or hawksbill sea turtles in Nicaragua (Liles et al. 2015) show a preference for nesting at the edge of vegetation. However, other authors noted that highly dense vegetation will have higher root density and impede nest digging (Hays et al. 1995).

How a sea turtle may decide to nest in one site on the beach over another is further complicated by the dynamic nature of beach systems. Beaches can vary between dissipative, reflective, or various intermediate beach types (Woodroffe 2002). Dissipative beaches experience high wave energy that is initially broken by an offshore bar and is continually lost along a wide surf zone (Bird 2008). Because wave energy is dissipated across the wide surf zone, these beaches are usually flat with a wide intertidal zone (Woodroffe 2002). Reflective
beaches are on the opposite end of the spectrum, where waves surge onto the beach and wave energy is reflected off the beach face itself (Bird 2008). Such beaches are steep and occur in protected regions (e.g. embayments) and often have a deeper offshore bathymetry than dissipative beaches. Wave periods also tend to be longer on reflective with lower wave energy (Woodroffe 2002). Intermediate beach types occur in between these two extremes, with an unstable beach shifting through intermediate types and acquiring dissipative and reflective beach characteristics at any single time. For example, an intermediate beach can have an upper portion that is reflective while the lower portion is dissipative (Woodroffe 2002). Such beaches are also characterised by offshore bars (Woodroffe 2002), which can build or erode over time, shifting to become more dissipative or reflective. The response of the beach, and the beach front behind the beach, would be to erode, accrete, or stabilize (Woodroffe 2002).

The response of gravid sea turtles to a highly dynamic environment would be to move where erosion occurs the least over generational time (Spanier 2010; Fuentes et al. 2011). Green, flatback, hawksbill, and loggerhead sea turtles from eastern Queensland nest in areas with low occurrence of tropical cyclones to nest on beaches that have a lower potential to erode (Fuentes et al. 2011). Indeed, it has been demonstrated that sea turtles nesting several times during a season in different locations is a legacy of natural selection as a response to beaches that are more dynamic than others (Hart et al. 2013). If one area of beach is washed out and entire clutches are lost, a single sea turtle would have egg clutches in other areas of beach that would not have eroded (Hart et al. 2013). Loggerhead sea turtles in the Gulf of Mexico, for example, have been shown to travel great distances during their inter-nesting periods to nest in sites separated by hundreds of kilometres (Hart et al. 2013). This has implications for conservation, as the availability of beaches does not necessarily indicate the availability of preferred beaches to nest on (Fuentes et al. 2011).

Of the various conditions for nest site selection, beach topography appears to be important in determining where a sea turtle will initiate digging. It is then important to predict where a sea turtle may initiate pit construction in order to protect and mitigate impacts from

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human development on current and potential nesting beaches (Salmon, Reiners, et al. 1995; Mazaris et al. 2009; Rizkalla and Savage 2011; Mazor et al. 2013;). However, sea turtle nesting can occur over large ranges, whether a single sea turtle travels expansive distances to nest several times in a single season (Hart et al. 2013) or if a breeding population nests along a vast stretch of beach (Dunkin et al. 2016). Attempting to collect detailed information on beach topography over large scales can be nearly impossible with traditional, ground-based methods. Airborne laser scanning can resolve this, as described below.

LIGHT DETECTION AND RANGING (LiDAR)

Airborne laser scanning is an excellent source of consistent, detailed topographic data over large extents. Light detection and ranging (LiDAR) technology uses light pulses to measure distance (Fig 4). When attached to a plane with a global positioning system (GPS) and side-to-side scanner, it is able to obtain elevation data of the ground as well as the heights of objects on the surface of the earth (Lefsky et al. 2002; Woolard and Colby 2002; Beraldin et al. 2010). The combined result of geo-referenced laser points over an expanse of land generates a point-cloud, where each individual point on the ground represents where a laser has struck the ground (Fig 5). Because the accuracy of point-clouds can be within centimeters (Beraldin et al. 2010), they can be converted into detailed digital surface models (DSMs) or digital elevation models (DEMs) (Xiaoye 2008; Lindenbergh and Pietrzyk 2015) that capture fine-scale topographic variation (Andrew and Ustin 2009; Long et al. 2011; Montaghi et al. 2013), an attribute that has great appeal to coastal managers and researchers (Mason et al. 2000).
**Fig 4** Schematic of airborne laser scanning over a landscape. Landscape (right) being scanned by a LiDAR scanner attached to the plane, with the point-cloud data forming behind the plane (left) (Rogalski and Chrzanowski 2014).

**Fig 5** An example of a point-cloud obtained from the flight mission during this study. Each point in the image represents where the laser struck the Earth’s surface. Warmer colours are higher elevations (red is highest), while cooler colours are lower elevations (green in this image is the lowest).
Airborne laser scanning has been useful in several applications to coastal management and research. Out of various techniques to quantify beach topography, airborne LiDAR met the needs of the various groups of people (e.g. coastal defence, economic exploitation, etc.) based on cost efficiency and vertical accuracy (Mason et al. 2000). This made LiDAR appealing to coastal managers and researchers who wished to determine the rate or extent of coastal erosion over time or after cyclonic events. For example, airborne LiDAR can detect small-scale changes to beach volume after hurricane events (Zhang et al. 2005) or changes to beach volume over various time scales (e.g. weeks or years) (Shrestha et al. 2005). Airborne LiDAR-derived DEMs can also be coupled with multispectral imaging and aerial photography to successfully detect erosion on coasts with greater accuracy, accurately classify substrate types (Kerfoot et al. 2012), and correctly characterize scours along the beach landscape (Sherman et al. 2013).

The ability of LiDAR to capture fine-scale variation in the landscape has seen its applications extended to investigating habitat suitability and species diversity. In terrestrial habitats, forest structure and its relation to species assemblages has often been investigated as LiDAR is able to detect attributes of vertical forest structure (Vierling et al. 2008; Bergen et al. 2009; Simonson et al. 2014). For example, different forest attributes such as the presence of dead trees and openness of canopies can be detected by LiDAR (Martinuzzi et al. 2009). This data can be used to generate or improve habitat suitability models for birds (Martinuzzi et al. 2009; Tattoni et al. 2012). Airborne laser scanning-derived topographic data of coastal habitats can also be used to model habitat suitability, such as the case for a species of flowering plant on the Atlantic barrier islands (Sellars and Jolls 2007) or to determine important measures of beach topography used by sea turtles to select nesting sites (Yamamoto et al. 2012; Dunkin et al. 2016). The ability to capture fine-scale changes in coastal habitats has also been used to determine the response of sea turtles to changes in beach volume over time (Yamamoto et al. 2015) or after storm events (Long et al. 2011). Airborne laser scanning-derived benthic rugosity can also be used to assess fish species assemblages in coral reefs (Wedding et al. 2008) as coral reef rugosity is positively correlated to fish species assemblages (McCormick 1994; Knudby and LeDrew 2007).
It is worth mentioning that although airborne LiDAR may be a panacea in determining the importance of different topographic variables for nest site selection, the scale at which the data is analysed needs to be considered (Woolard and Colby 2002). For example, a study in Florida investigated how nest site selection of loggerhead sea turtles changed before and after a hurricane event, but averaged the slopes of 25 m sections of beach (Long et al. 2011). Another study further south of the previous study used 5 m resolution to investigate nest site selection of loggerhead sea turtles (Yamamoto et al. 2012). Though the studies investigated different questions and were in different locations, the information obtained based on the scales used would be significantly different, even if they were investigating the same topic (Woolard and Colby 2002). Focused on nest site selection, it may be interesting to determine if important variables or interactions between variables for nest site selection change as the scale used during analysis changed as well.

Nevertheless, the benefits of using LiDAR in ecosystem studies are two-fold. First, data can be obtained over large extents, such as 200 km of coastline in the study of nest site selection of loggerhead sea turtles in Florida (Dunkin et al. 2016). Second, LiDAR can detect fine-scale variations within the landscape, which can be used to create DEMs that reflect the real-life topography of the study site (Andrew and Ustin 2009). Such benefits have been highlighted when used to understand how topography is important for sea turtle nest site selection (Long et al. 2011; Yamamoto et al. 2015, 2012; Dunkin et al. 2016). The application of LiDAR to Australian landscapes is ideal, where many long beaches on this continent are remote as well as inaccessible and cannot be characterized effectively with ground-based methods.

**EIGHTY MILE BEACH MARINE PARK**

Eighty Mile Beach is a 220-km continuous beach located in the northwest region of Western Australia at the Canning Basin. The Canning Basin is a sedimentary basin of marine sediment that began forming 500 million years before present (BP) (Short 2006a). Eighty Mile
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Beach only developed when the glaciers began to form at 7,500 years BP (Semeniuk 2008).
Offshore sand barriers developed 7,500 – 5,000 years BP along areas of coast that were open to high energy waves (Semeniuk 2008). The coast continued to expand seawards as the glaciers formed and sea levels dropped (Semeniuk 2008). Being open to high energy waves, much of the sedimentation of Eighty Mile Beach today is primarily tidally-reeved carbonate and Mesozoic-Tertiary bedrock (Short 2006b; Semeniuk 2008). The continued formation of offshore sandbars has made Eighty Mile Beach an ultra-dissipative beach with a low gradient and a wide intertidal zone (Short 2006a). This has provided a suite of habitats for several animal species (Wilson 2013).

The intertidal and high tide beach areas of Eighty Mile Beach are recognized as important habitats for benthic invertebrates and vertebrate animals alike (Short 2006a; Wilson 2013). The benthic invertebrate species richness found within the Eighty Mile Beach intertidal zones have a much higher density per square metre than intertidal zones found in other parts of the globe (Honkoop et al. 2006; Compton et al. 2008). These high-diversity benthic invertebrate communities sustain a population of 3.5 million migratory shorebirds that travel along the East-Asian Australasian Flyway (Rogers et al. 2011; Minton et al. 2013). Flatback sea turtle nesting sites have also been identified along the coast of Eighty Mile Beach (Department of Parks and Wildlife 2014). This incredible array of biodiversity, amongst other key values, was significant enough to warrant Eighty Mile Beach to be gazetted as a marine park (Department of Parks and Wildlife 2014).

Eighty Mile Beach Marine Park was gazetted as the 13th marine park in Western Australia in 2013. The key ecological values mentioned above can be found in several areas along the beach, such as the three sanctuary zones: Anna Plains, Kurtamparanya, and the Pananykarra Sanctuary Zones (Fig 6). Other zones are of cultural significance, such as the four special purpose zones designated for their importance to the people of the region. The Paruwuturr, Waru, and Pilyarlkarra Special Purpose Zones are found in Nyangumarta country, while Jangyjartiny is jointly held by traditional owners of the Nyangumarta and Karajarri people.
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(Department of Parks and Wildlife 2014). The Wallal Recreation Zone has been designated for recreational purposes and is adjacent to the Eighty Mile Beach Caravan Park. This site is a popular tourist area that experiences high visitation during the dry winter months and provides easy access onto the beach for vehicles and pedestrians (Short 2006a; Department of Parks and Wildlife 2014; Beckley et al. 2015). The Wallal Recreation Zone is also an important nesting site for endemic flatback sea turtles (Department of Parks and Wildlife 2014). Conflict between flatback sea turtle nesting and recreation is alleviated by the nature of how the area is used; flatback sea turtles nest from November to December during the hot summer months, while visitors tend to visit the beach during the cooler winter months (Department of Parks and Wildlife 2014; Beckley et al. 2015).

Eighty Mile Beach Marine Park is an important nesting site for flatback sea turtles, but very little information about the nesting population in this area is available. Initial satellite tagging of sea turtles has been conducted by the Department of Parks and Wildlife (Tucker et al. 2015), but no studies on nest site selection by the flatback sea turtles has been undertaken for this population so far. Because of the extensive expanse of beach (220 km), it provides the ideal case study to obtain topographic data over a broad extent with airborne LiDAR scanning, which can be processed into DEMs. These DEMs can be analysed to determine the importance of beach topography for flatback sea turtles in selecting nesting sites, which was obtained from aerial flight surveys by Pendoley Environmental Pty. Ltd.

AIM AND RESEARCH QUESTIONS

The overall aim of this project is to determine the importance of topographical variables for nest site selection by flatback sea turtles at Eighty Mile Beach Marine Park. The specific research questions derived from this aim are:

1. To characterize the topography of a remote and expansive beach
2. To determine the influences of different features of beach topography on nest site selection.
Fig 6 Location of Eighty-Mile Beach Marine Park (blue) in the Kimberley Region of north-west Australia indicating the various sanctuary and special purpose zones. Figure adapted from Eighty Mile Beach Marine Park Management Plan (Department of Parks and Wildlife 2014, p.18). PSZ = Pardoo Sanctuary Zone, CKSZ = Cape Keraudren Sanctuary Zone, PwSPZ = Paruwuturr Special Purpose Zone, WRZ = Wallal Recreational Zone, WSPZ = Waru Special Purpose Zone, PSPZ = Pilyarlkarra Special Purpose Zone, ASPZ = Anna Plains Sanctuary Zone, JSPZ = Jangyjartiny Special Purpose Zone.
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