INVESTIGATING FOREDUNE MORPHODYNAMICS AND ECOLOGY USING AIRBORNE LIDAR IN SE AUSTRALIA.

Thomas B. Doyle and Colin D. Woodroffe

Abstract

LiDAR (Light Detection and Ranging) has been used to investigate coastal landform morphology, evolution and change for almost a decade. Repeat LiDAR surveys can provide the scientific community with significant observations of how our shorelines have evolved, which may then enable forecasts of future patterns of change. There has been little research however, that has considered the application of this new technology to the study of foredunes, their vegetation and vulnerability. There have been several studies in the USA that have shown the importance vegetation plays in the mitigation of flood risk, or influence on foredune height, but neither were using LiDAR. This study aims to demonstrate how airborne LiDAR can be incorporated into eco-morphologic research, and used for the collection of useful data in a time-efficient manner. A method for attaining vegetation height, density and extent, as well as foredune height and volume, on a single beach compartment in South-east Australia is described; showing the application of a protocol that not only incorporates morphological studies, but also key vegetation parameters too. This will benefit both coastal managers and researchers, as it will demonstrate a method to conduct widespread eco-morphologic studies along coasts for which there is LiDAR data.

1. Introduction

LiDAR has certainly advanced in the past decade, and is becoming a well-used and trusted technology that enables the acquisition of rapid, precise and high-resolution elevation data for many areas of physical science (Schmid et al. 2011). It is a remote sensing technique that uses laser pulses to obtain elevation data of the Earth's surface. There are two main types of LiDAR, Terrestrial Laser Scanning (TLS) which are laser surveys conducted from the ground, and Airborne Laser Scanning (ALS), which records laser pulses from a scanner mounted on an aircraft. ALS topographic elevation is determined by measuring the round trip time the laser pulse takes from being released from the aircraft, to reflection off a surface and back to the scanner (Olsen et al. 2012). LiDAR is even more useful for coastal environments, with the applications of various algorithms, it is now possible to distinguish between bare-earth (ground) topography, canopy top, mid-vegetation, and lower vegetation returns, using different waveforms or laser energy returns (Nayegandhi et al. 2009). This has the potential to open up many more capabilities and developments for coastal research. The ability to rapidly survey large swathes of our coast for example, is extremely valuable, not only because going out and doing it manually (and to the same detail and accuracy) requires excessive financial and human resources, but having the ability to investigate synoptically areas of the coast that were once isolated or inaccessible, will be extremely beneficial. The capability of capturing three- dimensional (3D) records of entire sections of coast is another feature of LiDAR, which will allow for a more in-depth and holistic understanding of how entire systems work.

Foredunes, the first vegetated dune behind a beach, are important aspects of the coastal environment, as they are buffer zones, or one of the first lines of defence, against oceanic hazards and extreme events (James 2000; Kandrot 2012; Lin & Liou 2013; Arkema et al. 2013).They protect the coastline in both the short and long term (Bindoff et al. 2007; Durán & Moore 2013), play an important part in coastal ecology, visual beach amenity, and protect hind areas from sand and salt spray.

LiDAR techniques have the potential to capture highly accurate 3D surfaces of coastal environments (Hugenholtz & Barchyn 2010); this study therefore aims to demonstrate a general protocol for coastal managers to use, when investigating foredune ecology and morphodynamics, using airborne LiDAR data. This will include assessment of foredune volumes, morphology and ecology both along and across, Werri Beach, an embayed/ exposed beach compartment in SE Australia (Woodroffe 2003). This was done in order to demonstrate what parameters can be collected from ALS. The extracted profiles were then compared to RTK GPS (Real Time Kinematic Global Positioning System) profiles, to ground truth the LiDAR and confirm it is showing 'real world' surfaces.

2. Background

The have been a number of studies that have used LiDAR to investigate morphological or volumetric change detection in coastal dunes (Woolard & Colby 2002; Saye et al. 2005; Houser et al. 2008; Richter et al. 2013; Seabloom et al. 2013; Keijsers et al. 2014; Houser 2013), but very few have used this type of technology to study foredune vegetation (Table 1). Table 1 highlights the many options available for coastal dune research when LiDAR is run along a coastal strip and made available for researchers to interpret.

Table 1: Studies that have incorporated LiDAR into foredune research, and how that LiDAR was used.

Authors	Location	Period	Use of LiDAR
Woolard, Colby (2002)	Nth Carolina, USA	1996-1997	Calculated dune volume changes & determined the best resolution for LiDAR to be at when studying coastal dune environments.
Saye et al., (2005)	England/ Wales, UK	1998-1999	Calculation of foredune volumetric changes associated with erosion & accretion events.
Houser et al., (2008)	Florida, USA	2004	Foredune morphology change/impact from storm activity.
Kandrot (2012)	Cork, Ireland	2011	Compared RTK GPS with LiDAR data to determine LiDAR accuracy, & generate 3D morphological surfaces.
Richter et al., (2013)	Sylt, Germany	1999-2008	Documented changes & evolution of Sylt coast (inc. foredunes).
Seabloom et al., (2013)	NW USA	2006-2009	LiDAR derived elevation transects/profiles to distinguish morphological characteristics of foredunes (i.e. height of crest, slope angle…).
Keijsers et al., (2014)	Netherlands	1995-2013	Spatial-temporal investigation of erosion & accretion on foredunes.

The Topographic Compartment Analysis Tool (TopCAT) is a new GIS extension for ESRI's ArcGIS that also uses this morphological data to quantitatively and statistically assess and display sea cliff and beach change in 3D (Olsen et al. 2012). Part of TopCAT's "toolkit" is the "compartment", and "subdivide compartment" tools, that allow users to create defined 'Areas of Interest' (AoI), and split those AoI into smaller parts if the users desires more in-depth analyses. Olsen et al. (2012) have recommended this approach to the study of coastal dunes also, but this has yet to be tested. This study has further applied the 3D methodologies mentioned in TopCAT, to the study of coastal foredune morphodynamics and ecology.

There have been many studies that have used LiDAR to determine vegetation parameters, such as tree height, canopy structure, Leaf Area Index (LAI) and biomass (Drake et al. 2002; Harding et al. 2001; Kempeneers et al. 2009); however, most of these applications of LiDAR are aimed at forestry research. Kempeneers et al. (2009) and Schmid et al. (2011) seem to be the main studies that have applied LIDAR to coastal vegetation research. Kempeneers et al. (2009) in particular have assessed the combination of LiDAR and aerial digital camera data to classify dune vegetation along the Belgian coastline. The study found that LiDAR improved vegetation classifications by almost 20% when it was fused with multi-spectral imagery. This type of work, however, has yet to occur along the Australian coastline. Understanding foredune morphological patterns and their associated vegetation structure can infer the relative strength of the foredune belt. With alongshore variations in these factors along the NSW coast, this knowledge is critical in terms of the vulnerability of coastal residents, foredune stability, and erosion status to present and future storm impacts, as well as the projected impacts of climate change (Kempeneers et al. 2009).

3. Methodology

Overall Procedure

The foredune protocol runs primarily through ESRI's ArcGIS 10.2, and will make use of several tools within that program. LiDAR data needs to be in LAS (LASer file) format, and processed to either level 3 or 4 LiDAR point cloud classification level (ICSM 2010). The foredune protocol includes the following steps:

1. Create study area boundary (i.e. the foredune), using a polygon shapefile or feature class (Figure 1.1).
2. Determine the corresponding LAS files that are found in the defined “area of interest”, using the “tile index” provided by the data supplier.
3. Create LAS Dataset (LasD) files from the raw LAS files within ArcMap, to get a beach-wide overview of the foredunes and ecology (i.e. Create LAS Dataset – Data management tool).
4. Using the LasD data, and the “LAS Dataset Profile Viewer”, test the most effective transect width to implement on the study beach (Figure 1.4).
5. Segment the beach – dune area into smaller compartments along the length of the beach. Similar to the “subdivide compartments tool” used in TopCAT (Olsen et al. 2012) (Figure 1.5).
6. Perform volumetric calculations (i.e. Polygon Volume – 3D Analyst tool) on each segment, using the ‘ideal’ transect width found in step 4 (Figure 1.6).
7. Perform ecological calculations on each segment along the length of the beach (i.e. vegetation structure, height, density and extent) (Figure 1.7 and 1.8) (see Section 3.3).
8. Compare segments along the beach – dune compartment (i.e. north to south or vice versa) and discern any patterns.

Calculating Foredune/Beach Volume

To calculate foredune/beach volume, the user needs to convert the LasD files of the beach/dune into a Triangulated Irregular Network (TIN), have a designated area of interest (AOI) confined within an ESRI polygon shapefile or feature class (Figure 1.1), a baseline (either a line feature class or shapefile) defined behind the AOI, and set an end and start point along that baseline (i.e. using “Feature vertices to points” tool). In the case of this study, the baseline will be set behind the established foredune of the beach system. The baseline needs to be split into equal segments all along the beach, so an alongshore investigation can take place (the “construct points” option in the editor toolbar was used, with a spacing of 50m). Perpendicular transects were then drawn from these points along the baseline, across the dune or beach until they reach the opposing AOI boundary (see Figure 1.5). Once transects have been drawn, ESRI’s “buffer” tool was used to generate the desired width of each dune or beach segment. This width is important as it will be used in the volume calculations of those segments, meaning they need to be wide enough to capture enough surface information (morphology and vegetation) to do the calculations, but not include too much alongshore variability of the environment (Figure 2). Finally, to produce volumes for each segment, the “Polygon Volume” tool (in the 3D Analyst toolbox) is run, using the TIN layer as the ‘input surface’, and the buffer zones (Figure 1.4) as the ‘input feature class’ (with the layer’s height set to 0 meters). Volumes will be added to the “Attributes table” of the buffer zone layer, where they can be exported to excel for further analysis. The entire foredune, beach, and total system volumes are also calculated, using the same procedure above, but instead of the buffer layer being the input feature class, the AOI feature classes are used.

Producing Ecological Metrics

The ecological metrics were derived from two separate procedures. The vegetation cover was completed by following a similar method to ESRI’s “Estimating forest canopy density” procedure, but applied to the coastal foredune setting. This involves using the previously generated LAS datasets, and converting them into two “raster” layers, one representing just bare ground elevations and the other representing vegetation (which included low, medium and high vegetation classifications). By doing this, the AOI is split into small equal-sized units so that a comparison can be made between the number of vegetation points and the total number of points (bare ground and vegetation added together) (Geoprocessing tools; “plus” and “divide”, ArcMap).

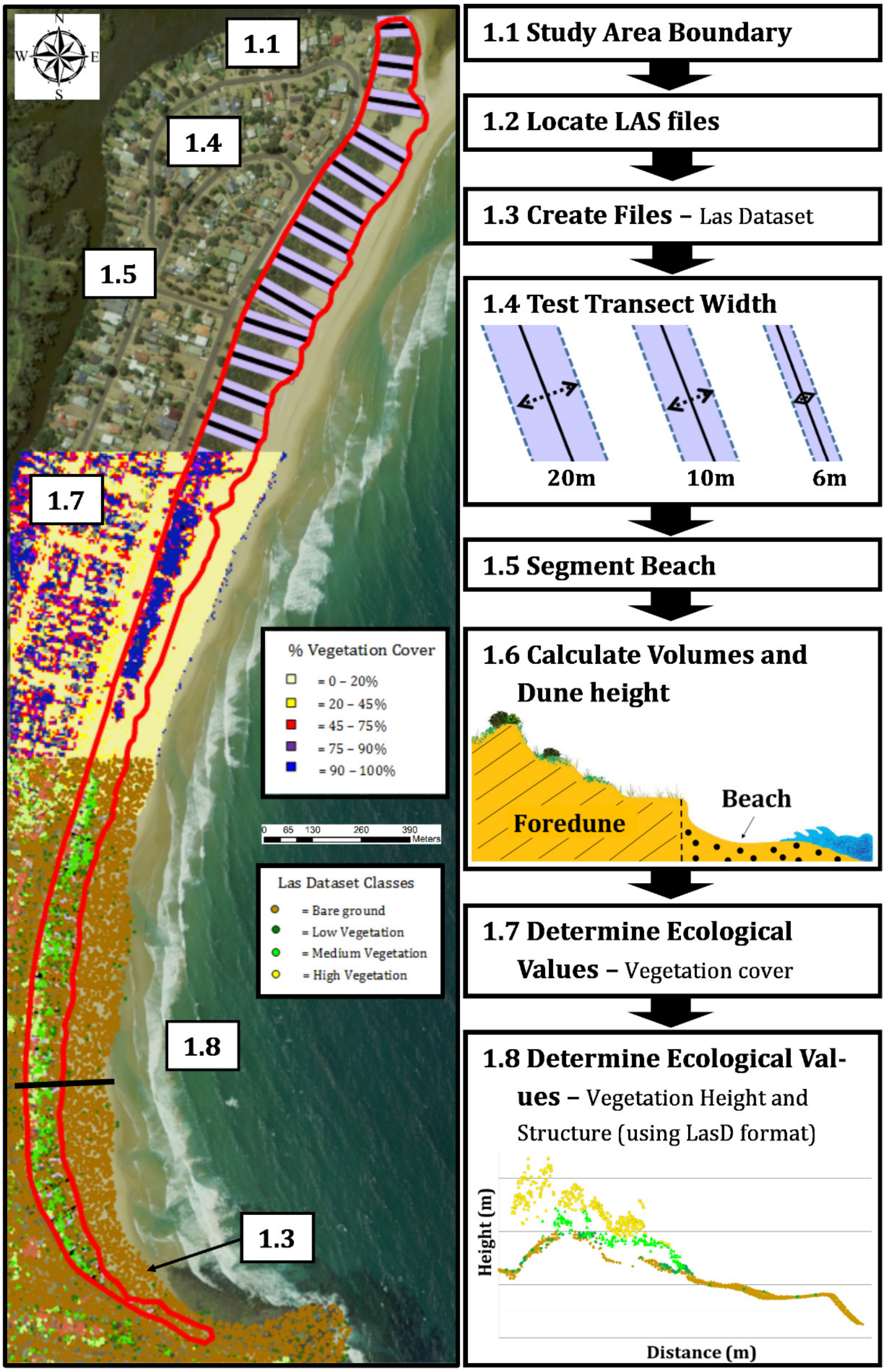

Figure 1. Summary of the Foredune procedure, illustrating the foredune area of Interest polygon (1.1), transect width used in this study (1.4), way in which the beach-dune is segmented (1.5), volume calculation parameters (1.6), and the ecological values discerned, i.e. percent vegetation cover (1.7), and vegetation structure and extent from transect and LasD data (1.8).

Vegetation height and structure were both discerned from the LasD layer, using the "LAS Dataset Profile Viewer" tool, available in the "LAS Dataset" toolbar. Each transect (Figure 1.5) was traced using this profile viewer tool and the output (see Figure 2) was analysed for vegetation height and structure trends. Note, in Figure 2, the Profile Viewer output, how LAS points are classified into bare ground, low, medium and high vegetation classes, making it possible to query vegetation structure.

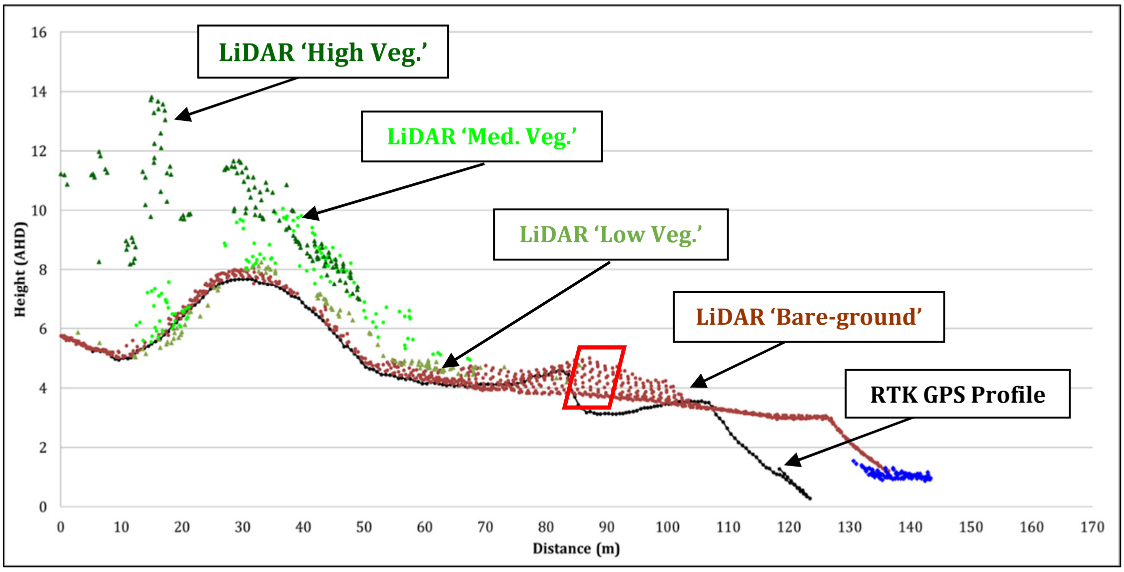

Figure 2. LAS Dataset point cloud ("Profile Viewer") output. Note the RTK GPS profile (24.06.13), the LiDAR 'bare-ground' profile (Black), and the vegetation structure. The vegetation is sorted into assigned classifications; Brown: bare-ground elevation, Olive green: low vegetation, Fluro Green: medium vegetation, and Dark Green: high vegetation. The red inset shows alongshore beach variability, which highlights the importance of getting an 'ideal' transect width to split the beach or foredune into, this width was 15m (Data source: © Land and Property Information (LPI) [2011]).

4. Regional Setting

To demonstrate the applicability of this protocol to the study of foredune eco-morphodynamics, Werri Beach on the southeast coast of Australia was analysed using the proposed protocol. The case study site is located within the Illawarra region and the Kiama Local Government Area (LGA), which comprises a tectonically-stable, compartmentalised section of the NSW coast (Figure 3). The Sydney Basin geology played an important role in producing the range of coastal features and beach types found in this area. As a result, these beaches range in size and aspect (predominantly east).

The coastal environments of the Illawarra are dominated by the energetic south - south easterly swells, with a mean H_o of 1.6 m (T = 10 s), a microtidal spring tide of 1.2m and a neap tide of 0.8m. Intermediate wave-dominated embayed beaches predominate (Figure 3) (Short 1993). The beaches are highly dynamic, with nearshore bars, frequent rip currents and prone to frequent change. The foredunes are not so dynamic, but major storms reach the dune base and cause substantial scarping.

Human settlement and subsequent spread has been affecting the Kiama coastal environments for over a century, which has only increased with time. The beach-dune history at Werri Beach reflects this impact. Werri Beach underwent a complete dune reconstruction and re-vegetation in 1992 as part of a Bitou bush removal management plan, which completely altered the dune environment with the entire backshore being replaced with *Banksia integrifolia*, *Leptospermum laevigatum* (coastal tea tree), *Acacia longifolia* var. *sophorae* and *Spinifex sericeus* (Figure 3, c). Locations that have an anthropogenic history like this are likely to further complicate beach-dune responses and reemphasise the need for local studies in order to inform beach-dune management.

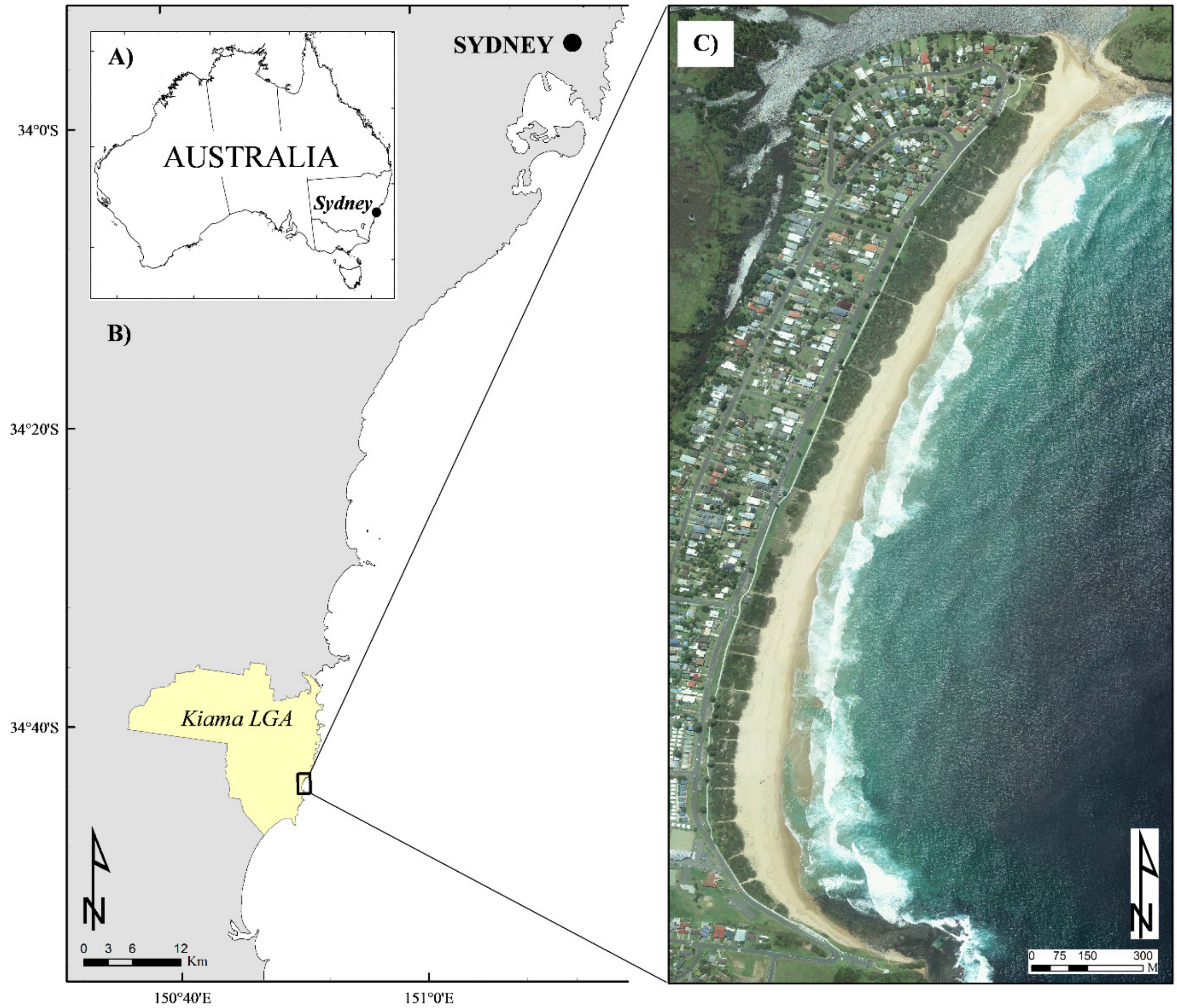

Figure 3. A) Map of Australia, highlighting Sydney's location. B) The location of the case study site with respect to the Sydney coastline and the NSW state. C) Aerial view of Werri Beach, which is found within the Kiama LGA (Data Source: LPI [2012]).

5. Case Study results and discussion

Topographic Data Information

The topographic data used in this study was acquired from an airborne LiDAR survey of the entire Kiama LGA between 8th – 23rd March 2011, by the NSW State Government Department, Land and Property Information (LPI). The data was supplied in raw LAS files, classified to C3, Level 3 point cloud classification (ICSM 2010) and manipulated, as section 3 stipulates, to test the proposed foredune protocol proposed in this study. The Level 3 point cloud classification, not only splits the point cloud into the 31 various layers (i.e. Ground, low vegetation, high vegetation etc.) but it does this to an industry standard accuracy, particularly ground classified points. This involves highly supervised (often manual or semi-automated algorithms) to correctly classify at least 99% of the ground points (ICSM 2010).

Case Study – Werri Beach

Werri Beach is the second largest beach-dune system found within the Kiama LGA, which has a single dominant foredune along the entire length of the embayment. The foredune has a maximum height of 9.4m, and minimum value of 0.5m (Figure 4, B). Figure 4 summaries some of the key output parameters of the foredune protocol, to note is the Digital Elevation Model (DEM) or foredune morphology (dune height) layer (Fig 4, B), the Digital Surface Model (DSM) or vegetation height layer (Fig 4, C) and the vegetation cover layer (Fig 4, D).

These layers display higher foredunes at the northern end of Werri, which are accompanied by much higher, wider and denser vegetation. The vegetation height ranges from 27m to 5m, and cover values range from 45 – 75% to 90 – 100%.

Figure 5 summarises how the foredune vegetation structure and volume changes along the system (from north to south). Vegetation structure remains constant all along the system, having a low, medium and high vegetation zonation across the beach and foredune, with the exception of transect D (Fig 5, b). This zonation seems to be wider in the northern end of the embayment, as seen in Figure 4, C and D) too. The extent of the vegetation also is constant all the way down the system, with it extending well onto the beach zone (Fig 5, a, b). Alternatively, there is a clear variation in dune volume and height along the beach. The maximum volume is found in the northern end of the system (570m^3/m), which then decreases to the south, with a minimum of approximately 30m^3/m (Fig 5, c).

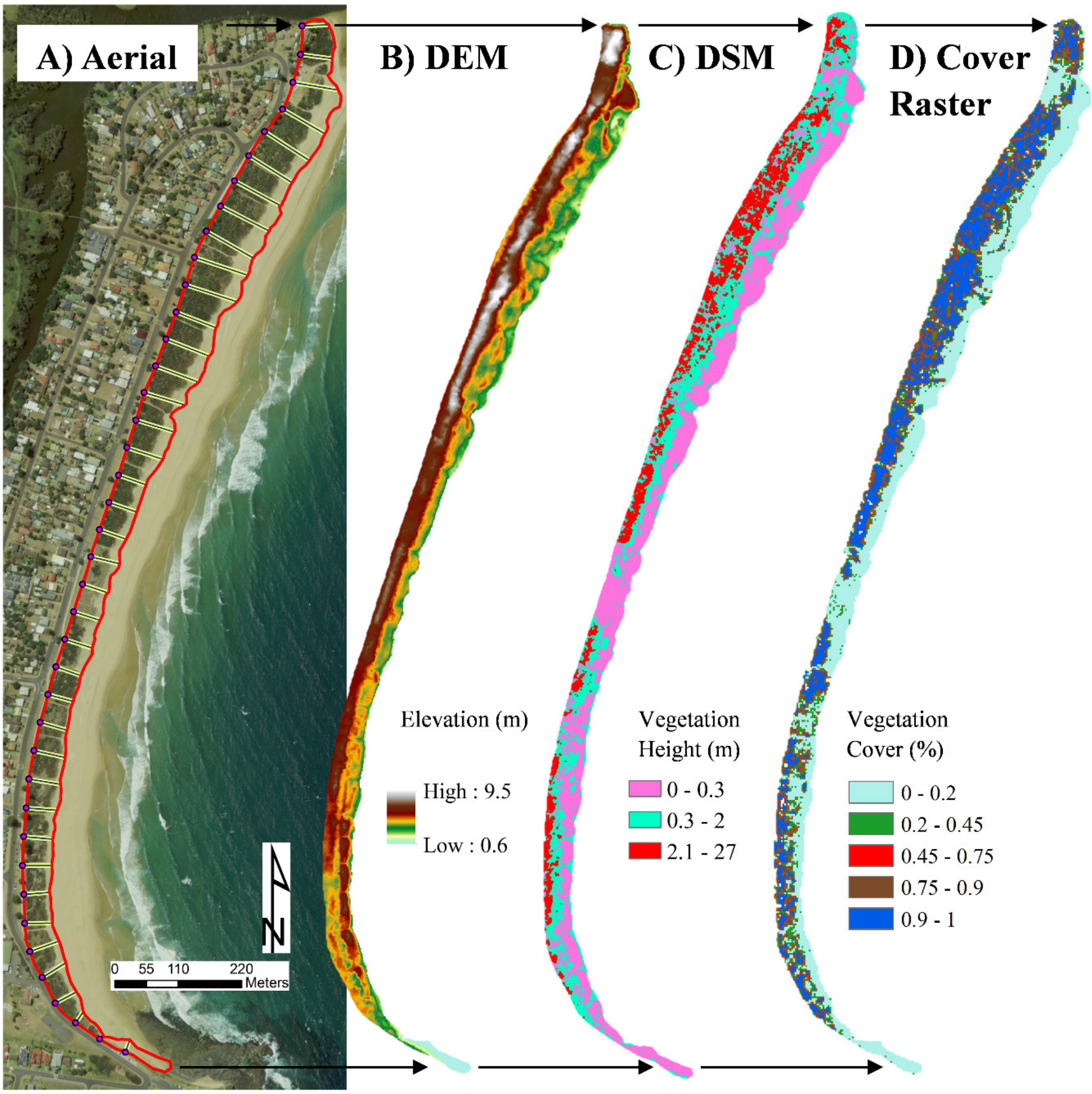

Figure 4. Several key output parameters generated from the foredune protocol; A) the foredune AoI (red boundary), transects (black lines), transect width (yellow bars) and spacing used to calculate volumes. B) Digital Elevation Model (DEM) of the foredune AoI, showing the bare-ground morphology of the dune (using a transect width of 8m). C) Digital Surface Model (DSM) of the foredune vegetation, which shows the true height of the vegetation. D) Raster layer of the AoI, showing the percent vegetation cover along the system (Data Source: LPI [2009, 2011]).

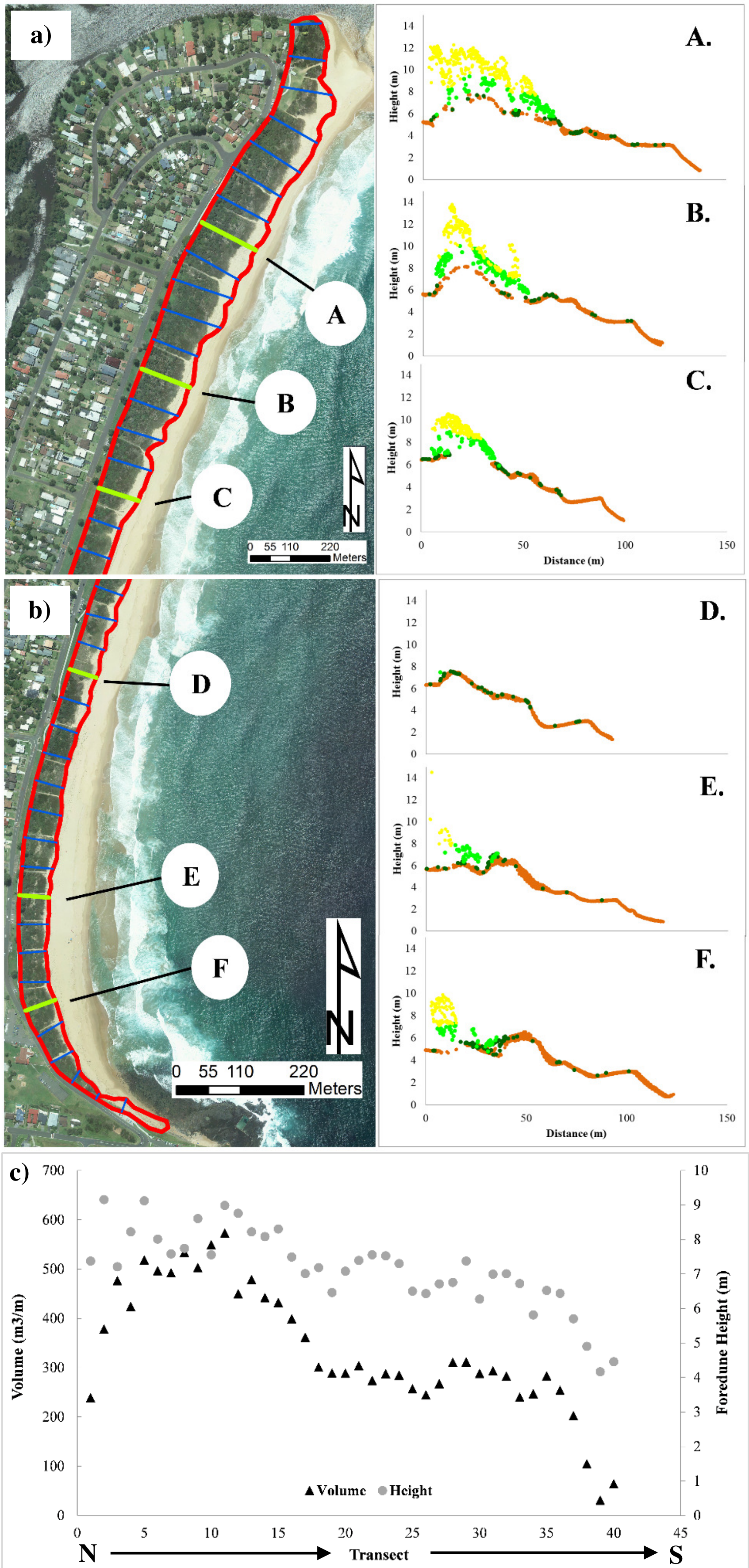

Figure 5. a) North Werri, illustrating the application of step 7 (Fig 1.8) of the foredune protocol; producing vegetation height and structure information. (Left inset) shows aerial photo, Foredune AoI (red outline), transects of entire beach (blue) and selected transects used to generate vegetation parameters (green lines). b) South Werri, similarly showing the vegetation height and structure profiles. c) Graphical display of step 6 of protocol; calculating foredune volume (m^3/m) and height (m) (Data Source: LPI [2011, 2012]).

Error Assessment

The airborne LiDAR used in this protocol seems to provide useful data for foredune morphodynamic research, however this needs to be confirmed, to ensure that "real world" surfaces of both dune morphology and vegetation are being produced and analysed. On site surveying, of both dune surfaces (i.e. ground morphology and vegetation layers), was used to do this. A Trimble R8 Real Time Kinematic (RTK) Global positioning System (GPS), with sub-centimetre accuracy, was used to plot dune 'bare-ground' morphology. These profiles were then compared to LiDAR derived profiles to begin the error assessment. Figure 6 summaries the results of this test, and as the figure reveals, the LiDAR and RTK profiles align well (Figure 2 and 6, b). The variation in beach berm morphology was due to the difference in dates each survey was conducted, and storm activity after 2011; the LiDAR was flown in 2011, where the on-site survey was done in 2013. The vegetation surveys also show similar results, vegetation height corresponded well, and the zonation of the vegetation in the LiDAR (i.e. high – medium – low vegetation layers) did resemble different plant heights and individuals, not just lower branches of the same plant (see Figure 6).

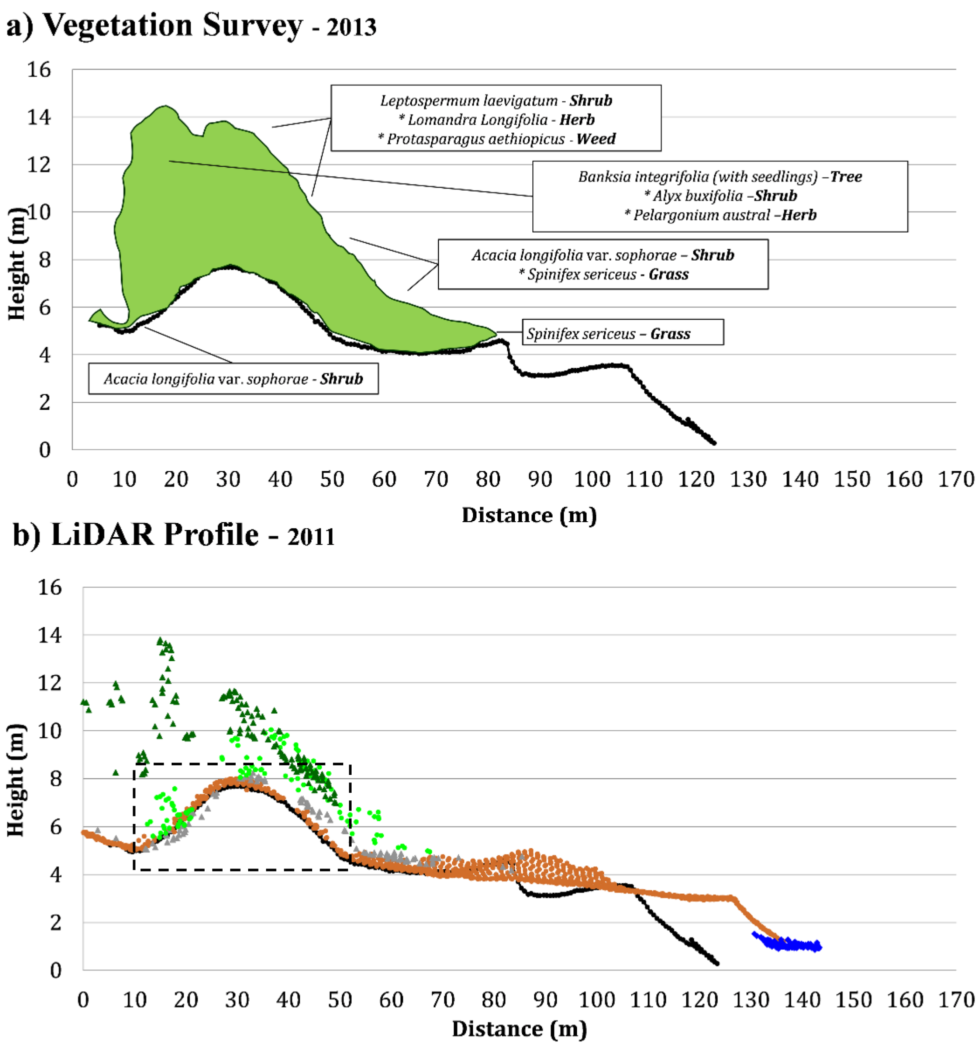

Figure 6. a) On-site vegetation survey of Werri foredune, noting vegetation height, structure and dominant species present. b) The same profile geographically, but generated using the airborne LiDAR. Note the similarity in vegetation height, structure and extent, as well as the foredune morphology between the LiDAR profile and RTK GPS (black inset) (Data Source: LPI [2011]).

Discussion

By applying this foredune protocol along Werri Beach, this study has shown an embayment that has larger foredunes, and therefore volumes, in the north. The foredunes are then shown to decrease towards the south, both in terms of size and volume (Figure 5, c). These observations support previous studies, as several other Australian researchers have also noted this increased foredune height (and volume) at the northern sections of NSW embayments (Hesp 1988b; Wright 1970). It was noted that this was especially the case for beaches that are flat, wide and are considered a 'higher energy' beach type. Hesp (1988) believed that this was, and is, a function of increasing exposure to wind and wave energy (or morphodynamic beach type), as well as beach width, and to a lesser extent sediment supply. Werri experiences a predominant south to south-easterly swell all year round, which would make the northern end the more 'active' area for sediment movement, and wave energy (Short 1993); however the beach width is similar if not narrower than the south. These types of patterns still seem to be an area of uncertainty, however with more widespread and rigorous experimentation, it may be possible to help understand them.

Vegetation height, width, structure, density and percent cover also seemed to accompany this alongshore morphological variation (Fig 4 and 5). Higher and wider vegetated areas, which are zoned, and more densely covered with vegetation have been found on the higher foredune locations. Again, this is something that has been questioned within coastal literature, where it was found that increased density of foredune vegetation, particularly on the incipient foredunes of the Fens Embayment region, made narrower but higher dunes (Hesp, 1988). Additionally, Hesp found in central NSW that percent vegetation cover on a foredune directly affected the morphology or type of foredune formed. Those with a higher vegetation cover, were generally more stable and uniform in shape, than those with lower vegetation coverage (which also formed more 'hummocky' or non-uniform appearances) (Hesp 1988a; Hesp 2002). It was also found for the Younghusband Peninsula, (South Australia), that the alongshore foredune vegetation patterns were due to two main variables; sand supply and salt aerosol levels. This created foredune environments where wider ecological zones (and therefore wider vegetation extents) were found on the higher energy areas of the embayment, and narrower vegetation zones on the more protected areas (Hesp 1988b). This occurrence is due to the ability of vegetation to deal with the constant sediment delivery; pioneering species deal most effectively with this type of environment, which may explain the wider pioneer zone in north of Werri, and less so in the south (Hesp 1988b). Vegetation is also influenced by the amount of salt spray delivered to the foredunes, higher energy surfzones deliver more to the dunes, explaining why there is a tendency to find a low species richness in more dissipative areas of a beach-dune and therefore increased richness in the protected areas. This cannot be discerned from this protocol yet, but Werri Beach was re-vegetated in 1992, so it is not representative of a strictly natural system.

Werri Beach underwent a complete foredune remodelling and re-vegetation in 1992, in response to a weed removal management program. Essentially the entire dune system was bulldozed (along with the weed; Biotu Bush) into a dug trench in front of the foredune belt, which was covered and then using the dugout sands, the dunes were rebuilt and replanted with natural vegetation, according to the NSW coastal dune management handbook (NSW-Government. & DLWC 2001; Kesby & Druett 1992).

There was only one outlying transect along Werri Beach, and it was displayed in Figure 5 (b); Transect 4 (T4). During the replanting stage of the management plan, this one area remained devoid of native shrubs and trees, despite them being planted. It is unusual that this site has retained only grass-like vegetation since this management plan, however having bare foredunes at Werri is not an uncommon desire amongst the local community, especially beach front owners. Despite not knowing exactly what has caused this vegetation phenomenon, it demonstrates why the protocol needs to be extended to other beaches, both similarly managed and those that are fully natural, to see how they have responded to other management initiatives or natural processes respectively.

These results of this foredune protocol have been observed for only a selected study environment along the NSW coastline. Having procedures like this one available, and the capability of collecting or utilizing existing LiDAR data, the entire length of any one coastline (i.e. NSW) can be conducted. This may lead to the discovery of more robust patterns of foredune morphology and vegetation in south-east Australia, as well as elucidating possible causes of these patterns.

6. Conclusions

LiDAR is a remarkably powerful tool for geomorphological research, particularly for the coastal zone. It can be used to investigate coastal evolution and change, erosion, or the impact of storm events on beaches and dunes (Table 1). With the implementation of the protocol developed in this study, coastal managers and researchers can now examine the ecological and morphological characteristics of entire beach compartments or sections of coast, at an efficient rate, using acquired LiDAR data. Application of this technique is described along one beach- foredune region of the southern NSW coastline, in order to investigate the variation in foredune morphology and vegetation characteristics. It is intended that this research will help establish more efficient and effective foredune management plans, ultimately assisting in, decreasing the vulnerability, and increasing the sustainability of the NSW coastal environment.

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