

Analysis of beach and foredune changes by aerial photography and topographic profiles, Tasmania, Australia

Abstract

Beach foredunes following introduction of *Ammophila arenaria* have been shown to promote accretion and progradation, but after a few decades, large steep-faced foredunes develop that subsequently erode. Beach profile measurement combined with spatial change techniques have not been applied to investigation of *A. arenaria* foredune change before. This study investigated two adjacent beaches in Tasmania along 3.4km of coastline, one infested by *A. arenaria* and the other retaining native vegetation. Dune profile surveys were derived from topographic measurement and LiDAR data, and recent aerial imagery was analysed using the Digital Shoreline Analysis System to quantify net shoreline movement and rates of change. Results showed lack of progradation on the *A. arenaria* infested beach, with tall, steep-faced, concave foredunes that retreated up to 15m in 10 years. By contrast, the native vegetated beach showed continued progradation, with smaller convex-faced foredunes. The *A. arenaria* foredunes retreated particularly where the dune toe was lower in elevation. Sediment supply is likely reduced by the tall foredunes with dense vegetation-holding sand, causing storm erosion not to be replaced, hence a lowering beach and dune toe. Future erosion is likely to be a greater risk with sand supply locked into high volume *A. arenaria*-infested dunes, relative to native vegetated dunes.

Keywords: beach profile, invasive species, spatial analysis, progradation, erosion, *Ammophila arenaria*, Tasmania

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Introduction

Countries with long shorelines, such as Australia, with a coastal length of 29,900km comprising 49% of sandy beach systems,¹ are expected to experience the greatest loss of coastal land and the largest costs associated with sea-level rise.² Tasmania has the largest ratio of coastal length to land area of all Australian States and Territories, with 2,237km of coastal length of the main island, of which 39% is sandy beaches and dunes.¹ More than 8 in 10 Australians within 50km of the coast,³ and this trend has accelerated.⁴ Tasmania's population centres and major industries are mostly located within one kilometre of the State's coastline.⁵ Beaches are the most popular recreational destination for Australian people,⁶ which brings additional pressures on erodible landforms. On the east coast of Australia, slowly rising sea level in the last century has resulted in permanent coastal changes, breaching of coastal dunes and loss of sand spits.⁷ Increased storminess caused by climate change⁸ will likely result in dune erosion, accelerated beach erosion, and coastal recession.⁹⁻¹¹ Where the invasive marram grass (*Ammophila arenaria*) has been introduced, problems may be exacerbated by locking sediment into over-steepened foredunes.

Coastal foredunes form where sand is transported off the beach to above high tide, and vary in their height and slope.¹² Vegetation establishes, and growth of the foredune over time is controlled by the interaction of nearshore and aeolian processes that control the amount of sand supplied from the beach and the amount eroded or carried inland.¹³ The common European dune species *Ammophila arenaria* (L.) Link (marram grass) was successfully used for dune rehabilitation in Europe following storm and human-induced dune erosion.^{14,15} Problems with mobile dunes early last century in Australia and New Zealand led to the deliberate introduction of *A. arenaria*, including

to Tasmania.^{16,17} Dune form was subsequently greatly changed,¹⁸ with the trapping of aeolian sand to cause large steep faced foredunes, in contrast to the lower angled foredunes associated with native vegetation.^{16,19,20} *A. arenaria* invasion results in the formation of a tall, steep foredune (Hilton, 2006) that forms a barrier to the backdune environment.¹⁷ For dune erosion, a steeper slope causes greater erosion than a lower gradient slope,²¹ hence a steepened foredune owing to *A. arenaria* infestation may lead to its eventual erosion during storms. These negative impacts documented following *A. arenaria* infestation may have confounded the objectives of its introduction, which were to stabilise and build coastal dunes.

Using two adjacent beaches of similar aspect at Beechford in North Tasmania, one with dunes infested by *A. arenaria* and the other with native vegetation,²² low-resolution spatial analysis 1950-2016 showed considerable differences in rates of spatial change and foredune evolution.²³ (Figure 1) The native vegetated beach showed steady and consistent progradation, while the *A. arenaria* infested beach showed rapid progradation for a few decades, which then halted. Foredune steepening under *A. arenaria* has been previously described,^{16,24} and has been indicated for the Beechford infested beach by historical community photographs.²³ The present study combines quantitative elevation determination using beach profiles, and more intense spatial analysis to investigate shoreline changes over the past decade, to determine recent rates of change both spatially and topographically and properties can provide insight into beach accretion and processes,^{25,26} and differences across the beaches and dunes were assessed to contribute to beach profile and spatial change analysis. The combination of spatial analysis with beach profile measurement techniques has not previously been applied to investigation of *A. arenaria* dune foredune change.

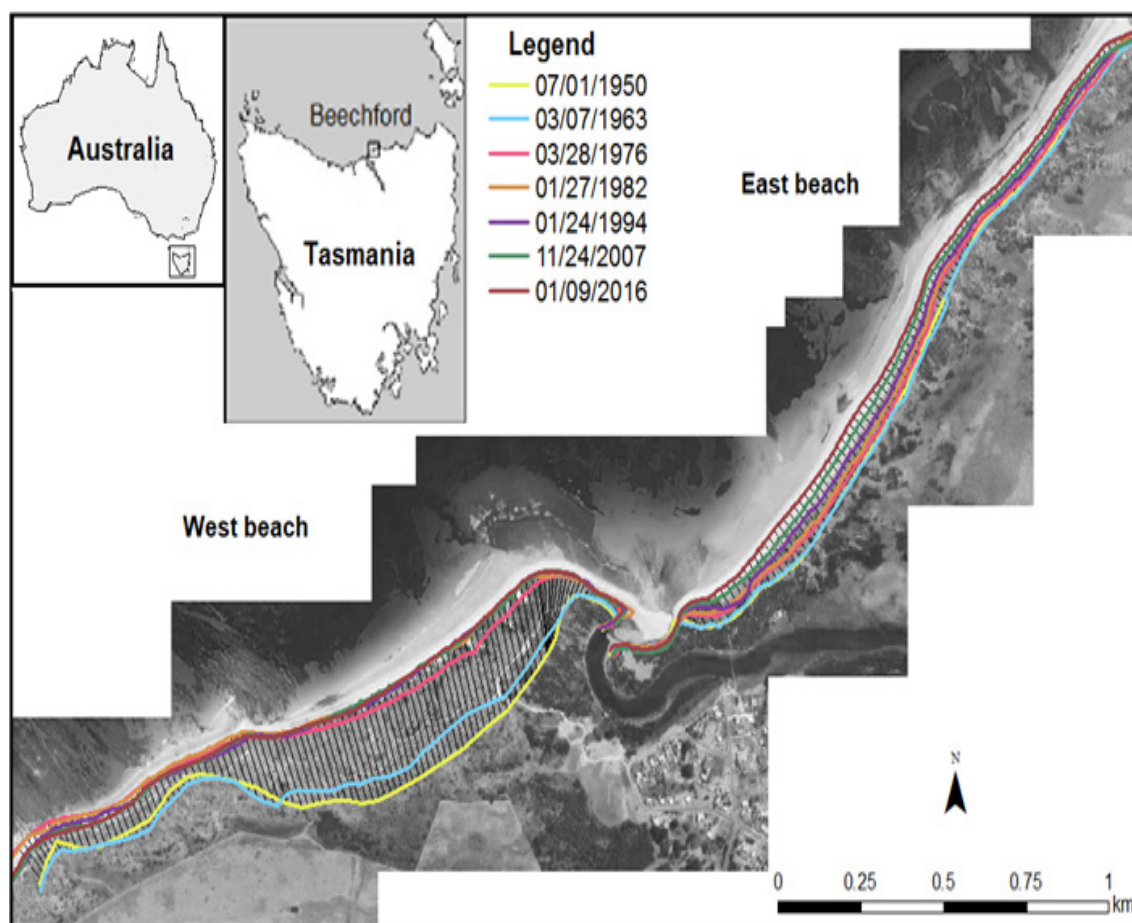


Figure 1 Historical shorelines of Beechford, Tasmania mapped from aerial imagery and transects cast by Digital Shoreline Analysis System 1950-2016. Adapted from Masterman and Ellison.²³

Methodology

Study area

Beechford (41° 01'30"S; 146° 56'42"E) is located on Tasmania's north coast, in the central inflection where there is little longshore drift^{27,28} (Figure 1). There are weak tidal currents in this central section, and long resident times adjacent to the Beechford coastline.²⁹ Wave energy is low to moderate with wave heights of 1.3–1.4m and a semi-diurnal micro-tidal range¹ of 2.4m. Beechford is at the mouth of Curries River, with a small low gradient catchment area of 81.4km². The study area has two beaches both of north-westerly aspect, west beach extends west of the Curries River mouth for 1.6 km (Figure 1), and east beach extends from the Curries River mouth to the east for 1.8km. The dune vegetation history 1950-2005, showed that following introduction in 1958, *A. arenaria* infestation of west beach dunes had occurred by 2005 with 68% coverage, while native vegetation remained predominant on east beach,²² with *A. arenaria* coverage of only 11-15%.

Spatial analysis

Three large scale aerial photographs (Table 1) underwent polynomial rectification to correct for geometric distortions in the images using a combination of ERDAS ER Mapper 2014 and Global Mapper 17.0 software packages using ground control points of recommended density.²³ They were then analysed using

Digital Shoreline Analysis System (DSAS),³⁰ to determine rate of change statistics. Shore-perpendicular transects were spaced at 20m intervals, and statistics were generated at a 95% confidence interval. The seaward dune vegetation line was used as the shoreline proxy, being a reliable indicator of shoreline change on aerial photographs.³¹ Measurements included the Net Shoreline Movement (NSM), and the Weighted Linear Regression (WLR) which fits a least-squares regression line to all shoreline points along a transect, with the slope of the line being the rate of change.

Beach profiles

Beach profile survey is an established technique used quantify beach morphology change over time.^{32–34} Three transects were previously established on the west beach in 2006 by the Tasmanian Shoreline Monitoring and Archiving project (TASMARC),³⁵ and were measured in 2006, 2007, 2012, 2013 and 2016 (Table 2). On the east beach three beach profile transects were established in April 2016 by the authors. All transect start points were located by GPS, and marked with a fixed metallised post. Locations of all transects used in this study are shown in Figure 2.

A Topcon Total Station GTS-603 was used for beach and dune topographic survey. Surveying involved placing the reflector pole at each change in gradient along the transects, on top of a thin, flat piece of metal to ensure it did not sink into the sand so as to accurately record dune surface elevation.

Table 1 Details of aerial imagery used

Date	Scale	Height (ft)	Total positional error (\pm m)	Source
27/11/2006	1:12,500	6,250	2.88	DPIPWE
09/1/2010	1:12,500	6,300	2.88	DPIPWE
09/1/2016	1:12,500	-	3.33	Google Earth

Table 2 Details and dates of transects surveyed. *Italic dates are those undertaken before this research and sourced from TASMARC (2018)*

Transect	Reference mark coordinates	Survey dates used in analysis
W1	-41.02805699 S, 146.93150787 E	<i>16/2/2006, 19/09/2007, 26/11/2013</i> , 18/6/2016
W2	-41.02672355 S, 146.93591691 E	<i>16/2/2006, 19/9/2007, 26/11/2013</i> , 18/6/2016
W3	-41.02617538 S, 146.93788037 E	<i>16/2/2006, 19/9/2007, 25/4/2012, 26/11/2013</i> , 18/6/2016
E1	-41.02448 S, 146.95119 E	7/3/2014, 29/4/2016, 20/6/2016
E2	-41.02416 S, 146.95168 E	7/3/2014, 29/4/2016, 20/6/2016
E3	-41.023878 S, 146.952176 E	7/3/2014, 29/4/2016, 20/6/2016

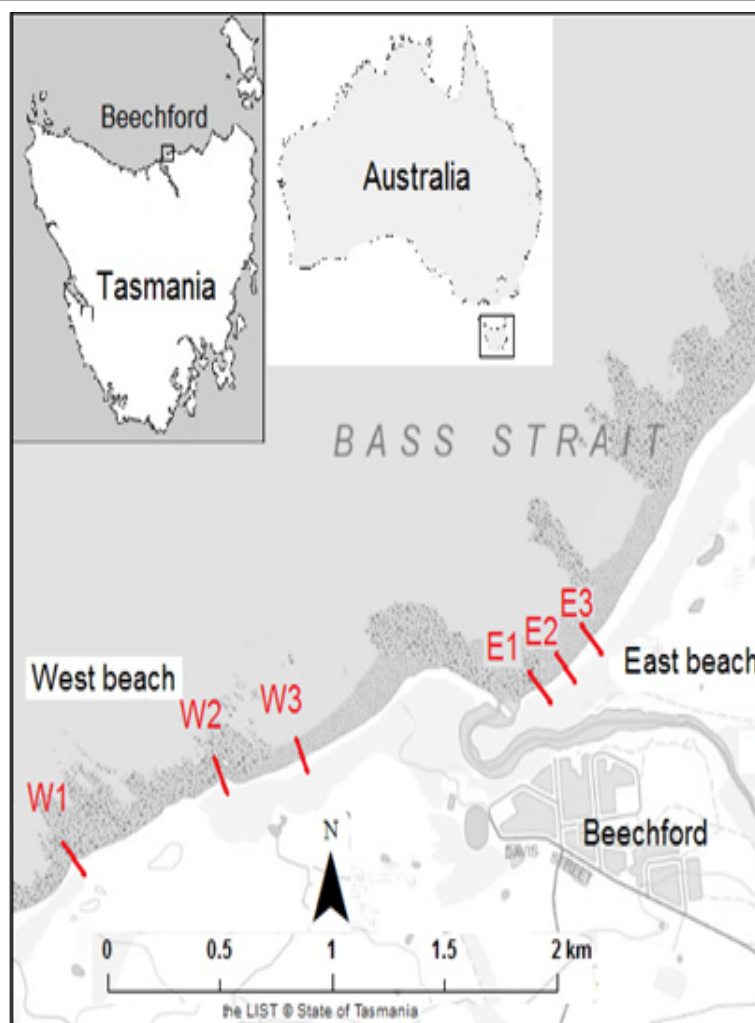


Figure 2 Locations of dune and beach topographic survey transects at Beechford.

LiDAR extraction

Light Detection and Ranging (LiDAR) data has emerged this century as a technique of vast potential in coastal elevation determination and topographic survey.³⁶ LiDAR has been used to show dune topography in recent studies^{36,37,38} and data availability was searched for the Beechford area. Some was available from 2014 for a 2.61km² area at Beechford that encompassed the eastern transects that lacked historical topographic surveys³⁹ (Figure 3), and this was analysed to gain profile data from before the measured period (Table 2).

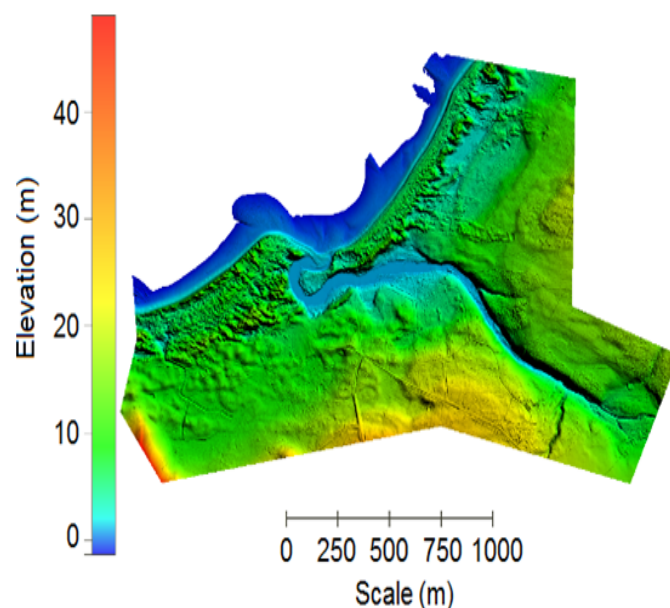


Figure 3 Digital Elevation Model with hill shading of Beechford showing LiDAR data for the study area, sourced from Land Tasmania.³⁹

Data analysis

The beach profile data were divided into two groups, West (W) group which included the three re-surveyed TASMARC transects, and East (E) group which included the more recent profile transects setup by authors (Table 2). The elevation data were corrected to the Australian Height Datum (AHD), which was set to MSL in 1979.⁴⁰ The west transects were adjusted to AHD using on the elevation of the TASMARC survey marks which was established using differential GPS, while the east transects were adjusted using the LiDAR data datum. Gradients were calculated using trigonometry of the profile vertical and horizontal measurements. The excel add-on Profiler XL 3.2⁴² was used to calculate beach profile volume changes.

Sediment analysis

Sand surface samples of 500g were collected along each profile from the back dune, fore dune and foreshore of the beach for comparative analysis of properties. Samples were oven dried at 60°C for 4 days and analysed using standard sieve cascade techniques for grain size,⁴⁴ and roundness.⁴⁵ Results were analysed using GRADISTAT⁴⁶ for mean, sorting, skewness and kurtosis using standard graphical methods.⁴⁷ Sorting shows the similarity or difference in grain sizes found in a sample⁴⁴ such as caused by wave action, and skewness is a measure of asymmetry grain size distribution, with positive skewness indicating excess of fine sediment and negative skewness indicating excess of coarse sediment. Carbonate proportion was determined by chemical analysis using HCl⁴⁸ and calculated from loss of mass.

The obtained LiDAR data had a vertical accuracy of $\pm 0.30\text{m}$ (95% CI) and a horizontal accuracy of $\pm 0.80\text{m}$ (95% CI), this resolution being high enough⁴⁰ for use in creating a 2014 beach profile to compare to the theodolite surveyed profiles (Table 2). Once acquired, the LiDAR ASCII file was loaded into Global Mapper and the '3D Path Profile' tool was used to place a line beginning at the survey mark coordinates and following the orientation of the profile, thus generating a new vertical profile along the transects from the LiDAR point data. XYZ distance and slope values for each profile were exported in a CSV file.

Results

Figure 4A shows the NSM results at 20m interval transects calculated using DSAS for 2006-2016. The east beach showed progradation along most of the beach of up to 15m apart from the edge margins, and consistent progradation of at least 6m. The WLR results (Figure 4B) showed rates of progradation of between 1 - 2 ma^{-1} . By contrast the west beach showed little change, with sections of small progradation and small regression shown by the NSM results, with rates of change of mostly less than 0.5 ma^{-1} (Figure 4B).

Beach profile results

The analysis of changes in morphology and volume over the past decade showed variability between the beach systems. Beach profiles from the west beach with elevation corrected to the AHD are shown in Figure 5, where AHD was set to MSL in 1979.⁴¹ Transect locations are shown in Figure 2.

Transect W1 showed an overall loss in beach volume across the period (Figure 5), combined with a dune crest retreat. Minor dune erosion occurred between 2006–2007 with a volume loss of 9.9 m^3 . Between 2007–2013 a similar volume was lost, this loss occurred mainly on the foredune thus decreasing dune height by approximately 0.7m, while the dune crest advanced. From 2013–2016 the profile shows a loss of 22.2 m^3 of sand, which was mostly from the in the foredune which receded inland by 16m and reduced in height by 0.5m, and the dune toe also lowered by 1m.

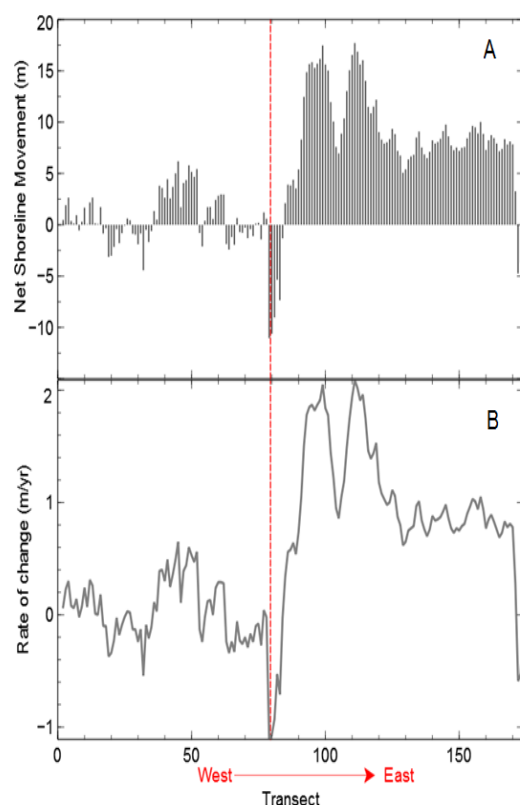


Figure 4 Shoreline change at Beechford 2006-2016. Transects are at 20m intervals and ascend from west to east, and the dotted line indicates the creek mouth between the beaches. (A) Net Shoreline Movement in meters along the 20m transect intervals. (B) Weighted Linear Regression (meters per year).

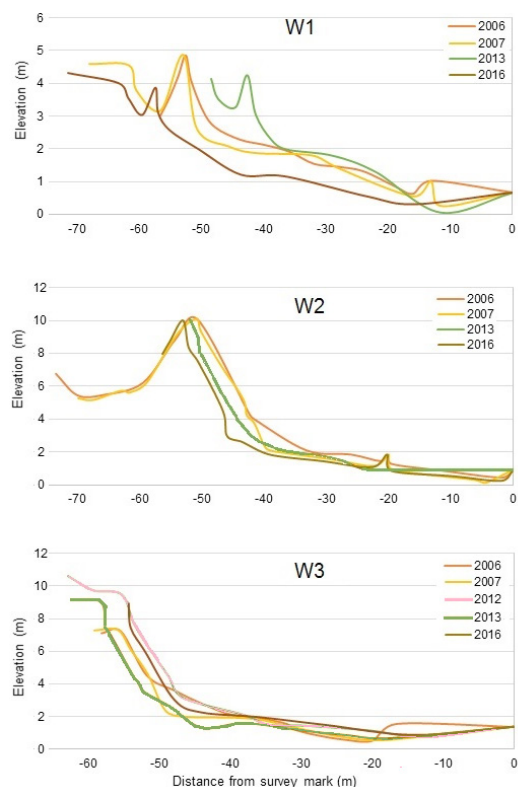


Figure 5 Foredune profiles 2007-2016 of Beechford west beach. Profile data 2006-2013 is sourced from Tasmarc.³⁵

Transect W2 showed a foredune height of 10m above AHD, and consistent gradual retreat over the decade (Figure 5). Between 2006–2007 there was a sand loss of 18.7m³ primarily from the dune base. For 2007–2013 volume loss was 7.7m³, causing recession in the foredune position. The dune front face became steeper to the steepest concave profile of the decade of 45°, and the dune toe lowered by 0.5m.

Transect W3 showed a varying foredune height of 7-10m and a retreat of the foredune face, of gradient 41°, of 5m 2012-2016 (Figure 5). From 2006–2007 there was a 19.9m³ loss of sand that was mainly from the lower section of the foredune face. Between 2007–2012 there was moderate dune increase both horizontally and vertically, and in addition a depression in the upper beach surface was also filled in. In the following year, a loss of 4.0 m³ occurred across the profile, and 2013–2016 a further 29.3m³ was lost from the transect mostly from the foredune face. The foredune toe elevation decreased by 0.5m 2012-2016, to about 1m above AHD.

Beach profiles from the east beach with elevation corrected to the AHD are shown in Figure 6, where AHD was set to MSL in 1979.⁴¹

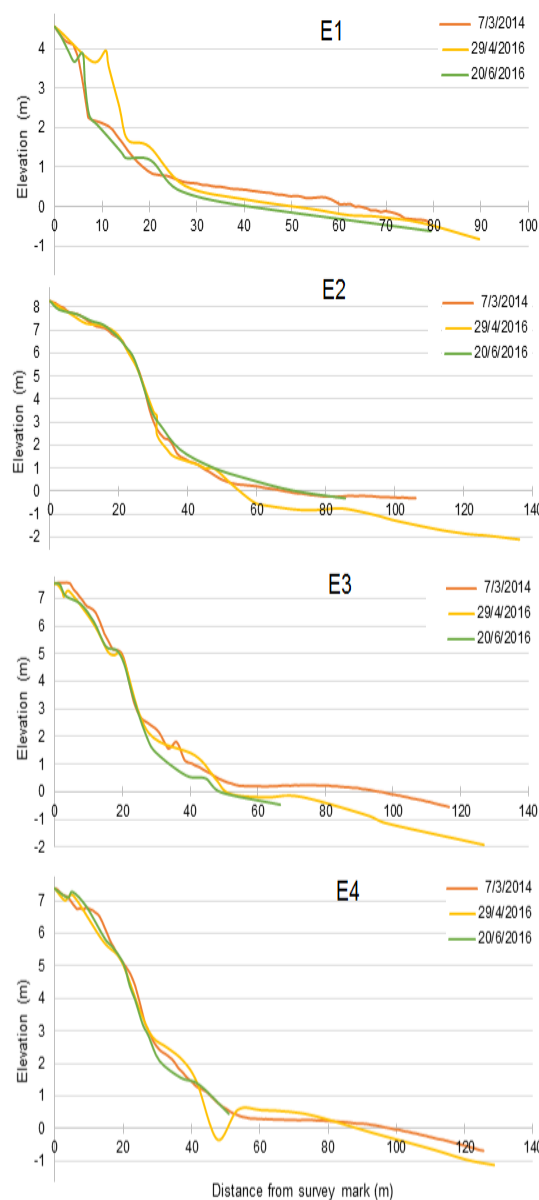


Figure 6 Foredune profiles 2014-2016 of Beechford east beach.

Transect E1 showed a foredune height of up to 8m and a convex profile, and it was the most stable foredune face of all the eastern transects over the timeframe of measurement, with the steepest section between 2 and 6m only showed a gradient of 12.5° (Figure 6). There was an increase in sand volume of 12.3m³ from 7/3/2014 to 29/4/2016 but a variation in height of the beach surface. After the June storm event the 20/6/2016 profile showed that the dune shape had remained stable and that the beach face had been supplied with 32.3m³ of sand. The dune toe however was low throughout the record, at about 0.5-1.0m above AHD.

Transect E2 showed a foredune height of 7m and a stable convex foredune face, with the steepest section between 2.3 and 5m of 32°, but overall between 1 and 7m only 10° (Figure 6). From 7/3/2014 to 29/4/2016 there was a 16.3m³ decrease across the profile, with most lost from the beach surface rather than the foredune. The dune toe elevation lowered by about 1m to close to 0 AHD.

Transect E3 showed a foredune height of 7m and a stable convex dune front with overall gradient of 7° (Figure 6), with little volumetric

change over the period. Most variation was near the dune toe, which showed a small scour that refilled. The dune toe elevation was about 1m above AHD.

Sediment analysis

Grainsize results (Table 3) showed fine sand comprising dune samples on W2 and W3 transects, and medium sand elsewhere including all beach samples. Sorting data showed very consistent results of moderately well sorted (Table 3), with one west beach sample very well sorted. Skewness results showed small variation from symmetrical distributions, with a tendency to coarse skewness in some samples from the west, and fine skewness in most samples from the east. Kurtosis also showed only moderate peakedness in results, with most beach samples from both transects being leptokurtic, indicating better sorting in the central part than in the distribution tails.⁴⁹ Roundness results showed no variation from sub-rounded and rounded in all samples. Carbonate proportion results were very low and consistent at 3-6%. The dominant mineralogy was quartz grains.

Table 3 Sand properties of dune and beach samples from Beechford west and east transects, rounded to 1 decimal place. In each case the samples are X.1 from the foredune top, X.2 from the foredune base, and X.3 from the beach surface. Statistics follow Folk et al.⁴⁷ graphical methods

	West									East								
Sample	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Mean (mm)	2.7	2.6	3.4	2.5	2.8	3.4	2.3	1.8	3.5	2.9	3.0	3.4	3.4	3.4	3.2	3.4	3.0	3.4
Sorting	0.6	0.6	0.6	0.6	0.6	0.8	0.6	0.3	0.6	0.6	0.5	0.4	0.5	0.5	0.5	0.4	0.6	0.6
Skewness	0.1	0.1	-0.1	-0.0	0.2	-0.1	-0.1	0.0	-0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
Kurtosis	0.8	0.7	1.7	0.7	0.8	1.8	0.8	0.7	1.7	1.0	1.1	1.1	1.1	1.1	1.1	1.1	0.9	1.4
Carbonate (%)	4.6	4.3	3.5	5.0	4.6	4.6	3.8	5.9	5.4	3.1	3.9	3.4	3.1	3.8	3.3	6.1	5.3	4.9

Discussion

Since the 1960s, the *A. arenaria*-infested west beach had prograded following introduction at maximum rates of 2.9ma⁻¹, followed by a slowing of rate to reach a halt after 1994, while the native vegetated east beach prograded at lower rates of <1.5ma⁻¹ that remained consistent over time (Figure 1). Intensive investigation of the recent decade both spatially and topographically shows varied foredune changes of the differently-vegetated beaches.

The net shoreline movement and rate of change results 2006-2016 (Figure 4) showed reverse spatial trends to longer term 1950- 2016 trends.²³ Rapid rates of progradation exceeding 2.5ma⁻¹ on the west beach reduced to ±0.5ma⁻¹ in the recent decade (Figure 4B), similar to observations from Northern Ireland that after several decades of *A. arenaria* infestation rapid progradation was not sustained.²⁴ Progradation of the native vegetated east beach was greater than the west beach with rates of mostly 1-1.2ma⁻¹ (Figure 4B), continuing longer term trends calculated over 1950-2016.²³

The west beach profiles showed higher foredunes with more major changes (Figure 5), and the east coast profiles showed lower foredunes with convex profiles and more stability (Figure 6). Foredune profiles W1-3 were concave in shape (Figure 5), indicative of erosion³², and showed sand volume losses. There was a dune recession of 5-10m from 2006 to 2016, which is supported by the WLR calculated by DSAS analysis for several parts of the west beach (Figure 3). Only W3 experienced some accretion to the profile at any time during the decade, which was short-lived (Figure 5).

The most western transect at W1 (Figures 2 and 5) showed the most vertical foredune above the lowest beach surface level, and the foredune moved seaward between 2006-2013 perhaps showing a slump before moving 20 m landwards and lowering in height between 2013-2016. The beach surface level had by then reduced to <1m above AHD which is close to MSL. Intensive LiDAR surveys along the Nurrnbeen-Collaroy beach in New South Wales,⁵⁰ of similar length to the Beechford beaches, showed that the elevation of the beach surface is strongly associated with dune erosion volume. Dune toe elevations of 2-3m above AHD were associated with high dune erosion volumes, whereas beach toe elevations of 4-5m above AHD showed little dune erosion.⁵⁰ By contrast, Beechford dune toe elevations are overall lower (Figures 5 & 6), with all dune toes at most 2-3 m above AHD, but the lower dune toe elevations of profiles W1, W2, E1 and E4 all showed most variability with periods of erosion.

The taller west beach profiles of W2 and W3 (Figure 5) showed foredunes of c. 10m above the upper beach, these dunes vegetated by *A. arenaria*. The *A. arenaria* infestation had been for several decades by 2006, with 68% cover in 2005,¹⁷ and this study shows foredune steepening, instability and retreat (Figure 5) consistent with observations over similar timeframes of infestation from Northern Ireland²⁴ and Whatipu beach in New Zealand.⁵¹ Sediment supply is likely reduced by the tall foredunes with dense vegetation-holding sand, causing storm erosion not to be replaced hence a lowering beach and dune toe. Negative feedback between increasing dune topography and wind flow controls the maximum size of dunes,²⁴ which in the case of *A. arenaria* vegetated dunes on the low energy, microtidal

Beechford shore is 10m, a similar height to observations from New Zealand infested dunes.¹⁶

Contrasting dune profile trends were shown from the east beach, though realising the shorter timeframe. The major differences were in stability/lack of change and profile shape. All east profiles showed foredune face convexity (Figure 6) indicative of accretion trends.³² This section of the beach is vegetated by native dune species,²² such as the sand-binding *Poa billardierei* which encourages development of low and stable foredunes.^{16,17} Fore dune toe elevations were low however at c. 1m, with a lower elevation at E3 associated with upper beach instability, as shown at Nurrabeen-Colloroy beaches.⁵⁰ The beach toe variability at east beach was by contrast relatively minor, perhaps indicating stability provided by native vegetation on a beach system with far fewer human impacts.

Profile data was only available from the east beach for a short timeframe relative to west beach (Figures 5 & 6), which was why the intensive spatial analysis was conducted to show little shoreline change on west beach relative to 1-2 m⁻¹ progradation on east beach. Dune profile results of the last few years can be directly compared. West beach profiles 2013-2016 showed foredune retreat of 15m at W1, 4m at W2 and 5m at W3 (Figure 5), while all east foredune profiles 2014-2016 remained stable and convex over the same time period. This study selected two adjacent beaches with little long shore drift and shared processes of sea level change, wave and wind regime, as well as a low discharge river between rocky headlands, to investigate influences of differing dune vegetation. Similarity of other processes are demonstrated by the grain size results.

Mean grain size results showed all profiles to have finer sand in the dunes and coarser sand on the foreshore (Table 3), as expected from aeolian relative to wave processes. The foredunes exhibited skewness to fine sediment indicative of aeolian deposition.⁵² Results of grain shape found that most samples had high roundness values indicating that the sediment is well-worked by attrition processes,⁵³ and has likely been in the dune/ beach system for a long period of time. The sediment was moderately well sorted (Table 3) which is reflective of low-moderate wave energy,⁵⁴ which is typical of beaches on the north coast of Tasmania.²⁷ Carbonate content of sand showed the lowest CaCO₃ levels, relative to past records from Northern Tasmania beaches.²⁷ Similarity in sediment properties between the beaches (Table 3) confirms the similarity in coastal processes, allowing the vegetation cover comparison. The lack of longshore drift owing to the central inflection of the north Tasmanian coast^{27,28} reduces the potential effects of other factors such as longshore drift that may cause differences between east and west beaches.

Conclusion

Few studies have investigated the impact of *A. arenaria* on foredune development,¹⁷ and a time series of profile measurement combined with spatial analysis has not previously been applied to this question. This study demonstrates quantitatively that *A. arenaria* infestation of dunes halts coastal progradation with steepening dunes, and the rapidly prograding foredunes meet a threshold where they become vulnerable to wave and wind erosion. This vulnerability is manifested in a reduced elevation of the beach surface and dune toe, likely caused by potential sediment supply being locked into abnormally tall dunes. As sea-level rise brings wave action higher up the beach with greater frequency, *A. arenaria* infestation may cause dunes to become more vulnerable to retreat relative to native vegetated dunes, a factor not currently considered in future hazard assessment.⁵⁵ Long

term dune erosion and accretion trends are mainly determined by sediment availability, and sediment is trapped in the over-steepened dunes. More investment in coastal monitoring by extending LiDAR coverage, and further support to community groups surveying coastal transects would allow increased quantitative hazard assessment.

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Conflicts of interest

The author declares that there is no conflicts of interest.

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None.

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