MedCrave
Step into the World of Research

Journal of Aquaculture & Marine Biology

Research Article

Open Access

Influence of introduced *Ammophila arenaria* on coastal progradation: assessment by spatial analysis

Abstract

Ammophila arenaria introduction is known to stabilise coastal dunes and promote sand accretion, but assessment using spatial analysis of its contribution to coastal progradation has been limited. This study assessed long term changes 1950-2016 in shoreline position using quantitative spatial analysis methods, of two adjacent beaches in north Tasmania, one infested during this period by *A. arenaria* and the other retaining native vegetation. Seven images from each decade were orthorectified, and the Digital Shoreline Analysis System was used to analyse 20m spaced shore perpendicular transects along 3.4km of coastline, to calculate net shoreline movement and digital linear regression rates. Historical ground photographs were also compared with present. Results showed that since the 1960s the *A. arenaria*-infested beach prograded substantially following introduction at maximum rates of 2.9m a^{-1}, followed by a slowing of rate to reach a halt after 1994, with tall, steep and concave foredunes. The native vegetated beach also prograded, at lower rates of <1.5m a^{-1} that remained consistent over time, retaining convex incipient foredunes. Relative sea level rise also occurred over the period at equivalent to global eustatic rates, but coastal retreat was not evident. Future erosion may be a greater risk with sand supply locked into high volume *A. arenaria*-infested dunes, relative to native vegetated dunes.

Keywords: shoreline change, marram grass, invasive species, progradation, Tasmania, Australia

Volume 7 Issue 5 - 2018

Robert Masterman, Joanna C Ellison

Discipline of Geography and Spatial Sciences, School of Technology, Environments and Design, University of Australia

Correspondence: Joanna C Ellison, Discipline of Geography and Spatial Sciences, School of Technology, Environments and Design, University of Tasmania, Launceston, Tasmania 7250, Australia, Email Joanna.Ellison@utas.edu.au

Received: September 26, 2018 | **Published:** October 01, 2018

Introduction

Native to Europe, the common dune species *Ammophila arenaria* (L.) Link (marram grass) was successfully used for coastal stabilisation following the 1953 Netherlands flood disaster,[1] and for dune rehabilitation in France and Spain following extensive tourist trampling.[2,3] *A. arenaria* was introduced to South Africa in the 1870s,[4] and was successful at stabilising large parts of the shoreline after the 1930's,[5] *A. arenaria* being most vigorous in sites of more recent stabilisation time. In America, its introduction at the same time was found to become a threat to native habitats,[6] with exponential increase in its dominance particularly in foredunes.

A. arenaria was deliberately introduced to Australia and New Zealand in the nineteenth century to stabilise mobile dunes,[7] and caused substantial and adverse changes in dune form and function,[8] encouraging accretion and progradation.[7] In Australia, *A. arenaria* introduction resulted in displacing native dune grasses and native arthropod diversity.[9] In New Zealand, indigenous sand-binding foredune plants such as *Ficini aspiralis* and *Poa billardierei* trap sand to form low incipient foredunes, while the invasive *A. arenaria* rapidly trap sand to form tall, steep foredunes.[10,11]

A. arenaria was introduced to Tasmania early last century,[12] and became common in most dune systems. Dunes invaded by *A. arenaria* displaced native coastal dune grasses, degraded habitats for wildlife, and lowered native biodiversity.[12] Coastal processes were radically and permanently altered by its invasion, with trapping of wind-blown sand causing large steep faced dunes to be created in contrast to the lower angled foredunes associated with native vegetation, likely influencing coastal sediment budgets by trapping more sand.[12]

Remote sensing techniques allow researchers to map large dune sites that otherwise would be impossible to capture in ground based study alone,[13] and has been used to investigate the changing extent of *A. arenaria*, vegetation dynamics, and succession.[1,6,7,11,14,15,16] For time-series analysis of spatial change, foredunes dominated by *A. arenaria* were shown in Northern Ireland to capture 50-70% of sand received off the beach[16] with dune accumulation rates of 0.3-0.4m a^{-1}, causing 200m of progradation over 20+years at c. 8m a^{-1}. In New Zealand, aerial photograph analysis 1940-2000 showed steady progradation until 1954, followed by stability 1955-1960, then erosion 1987-1993, attributed to wind and water movements.[19] However, *A. arenaria* was a minor community at the rear of foredunes. Otherwise, quantitative spatial analysis of *A. arenaria* influences on progradation seems to be little studied, whereas spatial analysis of coastal change has been widely applied to research questions such as sea level rise vulnerability assessment.[20,21]

The aim of this study was to investigate the influences of *A. arenaria* on coastal progradation over the last several decades at two adjacent north Tasmanian beaches, one with marram grass infestation and the other with native vegetation.

Methods

Study location

On the Tasmanian central north coast, Beechford (41°01'30"S; 146°56'42"E) is located 13km east of the main population hub of the area, George Town (population 4,347) (Figure 1). Beechford is at the mouth of Curries River, a wave dominated estuary with a small catchment area of 84km². The study area extends along 3.4km of coastline, with two beaches both of north-westerly aspect, west beach extends west of the Curries River mouth for 1.6km (Figure 1), and east beach extends from the Curries River mouth to the east for 1.8km.

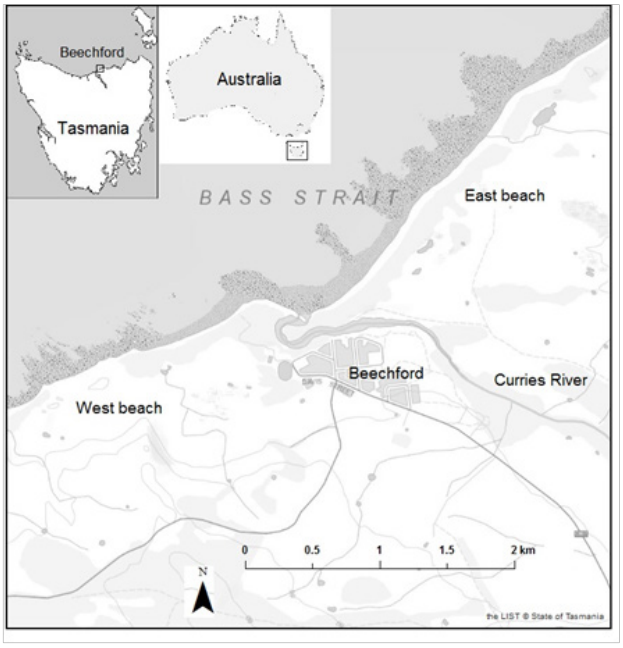

Figure 1 Location of the Beechford study area, Tasmania.

Beechford faces Bass Strait, with weak tidal currents in this central section, and long flushing and resident times adjacent to the Beechford coastline.[23] The central inflection of the north Tasmanian coast brings no longshore drift.[24,25] With shallow bathymetry offshore, wave energy in the Beechford area is low to moderate with wave heights of 1.3–1.4m.[26] Tides are semi-diurnal,[23] with a spring tidal range of 2.4m, and a neap range of 2.0m.[26] Climate has a mean monthly temperature range of 21.2°C in February to 12.7°C in July, and a mean annual rainfall of 677mm with a winter wet season. Prevailing winds are westerly and north-westerly, with 18% prevalence from the northeast.[27]

The dune vegetation history has been analysed 1950-2005, showing differences in *A. arenaria* infestation and native vegetation trends.[15] The non-native dune grass *A. arenaria* was deliberately introduced in the area to stabilise coastal dunes from 1958, and began to dominate the vegetative community on the west beach.[15,28] Native shrubs were beginning to surpass *A. arenaria* to an extent on the west beach, until a fire in 2003 caused shrub removal, facilitating a transition back to *A. arenaria*. *A. arenaria* is also found in small patches on the east beach, but levels remained consistently low over time. Rather, the native *Spinifex sericeus* dominates the east beach dunes.[15]

At least 30 plant species have been observed along the beach and dune areas at Beechford. Native foredune species of conservation significance include *S. sericeus, Acacia longifolia* subsp. *sophorae*, *Actites megalocarpus*, *Poa billardierei*, *Carpobrotus rossii*, *Dianella revoluta*, *Ficinia nodosa*, *Lepidosperma gladiatum, Pimelea glauca* and *Pultenaea tenuifolia.*[15,29] *A. longifolia* subsp. *sophorae* is the dominant shrub in the hind dunes of both beaches, although *Leptospermum laevigatum* is also well established in some sheltered areas. Several other non-native plant species occur, such as the invasive weed *Euphorbia paralias*, *Bromus sterilis*, *Fumaria* sp., *Lysimachia arvensis*, *Oxalis corniculata* and *Prunella vulgaris*.[29]

Spatial analysis

Aerial photography was available for the Beechford coastline dating back to 1950, allowing a 66-year period to be analysed. Seven aerial images from each decade since 1950 were selected to detect changes in shoreline position (Table 1). The images were rectified using a combination of ERDAS ER Mapper 2014 and Global Mapper 17.0 software packages. Orthorectification of the 1994 and 2007 aerial photographs involved importing camera details such as the focal length and principal point into ER Mapper, and identifying the fiducial points on the image. An SRTM-derived 1 Second DEM[30] was utilised for the terrain details. Ground control points (GCPs) including anthropogenic structures and geomorphic features such as rock formations and outcrops were used to meet recommended density requirements. The Tasmanian Orthophoto base map[31] (Figure 1) was used as the reference image for obtaining GCP coordinates.

Table 1 Aerial imagery used in this study

Date	Scale	Height (feet)	Type
--/--/1950	1:16,000	16,000	B&W
7/03/1963	1:50,000	20,000	B&W
28/03/1976	1:30,000	17,000	B&W
27/01/1982	1:20,000	14,000	Colour
24/01/1994	1:25,000	25,500	Colour
24/11/2007	1:24,000	12,300	Colour
9/01/2016	1:24,000	n/a	Colour

For the 1976 and 1982 aerial photographs as well as the 2016 satellite image, orthorectification was difficult owing to lack of data and software incompatibilities, and cubic polynomial rectification was used instead. For this, 25 GCPs were chosen to exceed the recommended density requirements, and the Tasmanian Orthophoto base map was again used as a reference. Global Mapper was used to georeference rectified 1950 and 1963 images into the same coordinate system as the other images.

Data analysis

Digital Shoreline Analysis System (DSAS) was used to compute rate of change statistics,[32] a systematic method used to measure shoreline change rates.[33,34,35] Shore-perpendicular transects at a specified interval between a baseline and historic shorelines can calculate distance measurements, point changes, and regression statistics. The seaward vegetation line was used as the shoreline proxy, being a reliable indicator of shoreline change,[36] whereas the water's edge is subject to daily movement with tides. DSAS transects were spaced at 20m intervals, and statistics were generated at a 95% confidence interval.

Distance measurements include the Net Shoreline Movement (NSM), which is the distance between the oldest and youngest shorelines. Point changes include the Weighted Linear Regression (WLR) that fits a least-squares regression line to all shoreline points along a transect, with the slope of the line being the rate of change. It gives greater weighting to data with lower uncertainty values when determining the best fit.[37] Uncertainties associated with shoreline position were calculated using published methods[38]. Seasonal error (E_s) is the error associated with the cyclical seasonal changes to the shoreline position that may occur due to wave variations and storms. This was calculated by measuring changes in vegetation line position

Citation: Masterman R, Ellison JC. Influence of introduced *Ammophila arenaria* on coastal progradation: assessment by spatial analysis. *J Aquac Mar Biol.* 2018;7(5):268–273. DOI: 10.15406/jamb.2018.07.00219

on several beach profile surveys from subsequent seasons. The values were used to create a uniform distribution, from which the standard deviation was the seasonal error; this was assumed to be the same for all years.

Rectification error (E_r) is calculated from the rectification process in ERDAS ER Mapper as Root Mean Square (RMS) error, which describes the difference between the actual GCP location that is input by the user and the statistically estimated location.[39] Digitising error (E_d) is associated with digitising the shoreline from aerial photography, owing to bad image quality or incorrect interpretation. It was measured by repeating the digitisation of the shoreline five times and finding the standard deviation of the distance differences between these. Pixel error (E_p) is caused by the pixel size of the rectified image, with a pixel size of 0.5m being unable to resolve properly any smaller feature. With these individual errors calculated (Table 2), the total positional error (E_t) was obtained[39].

Table 2 Total positional uncertainty associated with digitised historical shorelines at Beechford

Year	E_s	E_r	E_d	E_p	E_t(± m)
1950	2.46	4.22	1.90	0.5	5.26
1963	2.46	7.33	1.80	0.5	8.32
1976	2.46	4.40	1.80	0.5	5.38
1982	2.46	4.40	1.75	0.5	5.36
1994	2.46	1.92	1.75	0.5	3.61
2007	2.46	1.51	1.60	0.5	3.34
2016	2.46	1.59	1.50	0.5	3.33

Historical ground photography

In addition to aerial imagery, historical ground photographs can provide useful evidence of past dune and beach conditions.[39] Archival research to find such photographs of Beechford was undertaken on databases such as Trove, Library and Museum records. Long-term residents and visitors of the Beechford area were also asked for any relevant photographs they possessed. A visual comparison was then conducted between the best historical and current photographs to show differences over time.

Results

Comparison of shoreline positions 1950-2016 (Figure 2) showed at the west beach, seaward progradation 1950-1976 was rapid, with the greatest progradation 1963-1976. This slowed 1976-1982, and then halted, with the shoreline positions of 1994, 2007 and 2016 being largely superimposed. At east beach, little change occurred 1950-1963 with the shoreline positions mostly superimposed (Figure 2), then steady and relatively slow progradation occurred 1963-2016 along the entire beach.

Figure 3 shows the NSM results at 20m interval transects calculated using DSAS for 1950-2016. Shoreline progradation was greatest on the west beach with greatest movement of over 200m in the central section of c. 600m beach length, reducing to below 100m progradation1950-2016 to the west, and east near the Curries River outlet (Figure 1). On the east beach, shoreline advance was lower relative to the west beach (Figure 3) with a maximum of 100m net shoreline movement east of the Curries River mouth, and reducing towards the east.

Results from weighted linear regression analysis showed variable rates in shoreline change along the 3.4km coast (Figure 4), however with positive trends for both beaches. The west beach showed highest rates of advance of >3.0 m a^{-1} along 800m of beach length, reducing to 0-1 ma^{-1} at the western end. The east beach showed a maximum of 1.5 m a^{-1} east of the Curries River mouth and >1 m a^{-1} for a 900m length of the beach (Figure 5) reducing towards the east (Figure 4). These results are mapped in Figure 5, showing that the greatest rate of change for each beach was located at what were the beach embayments in the 1950's, with the effect of straightening the shoreline over time. The Curries estuary mouth in the centre, and towards the rocky headlands to the west and east of the study area shoreline (Figure 1), showed the least rates of positive change (Figure 4) (Figure 5).

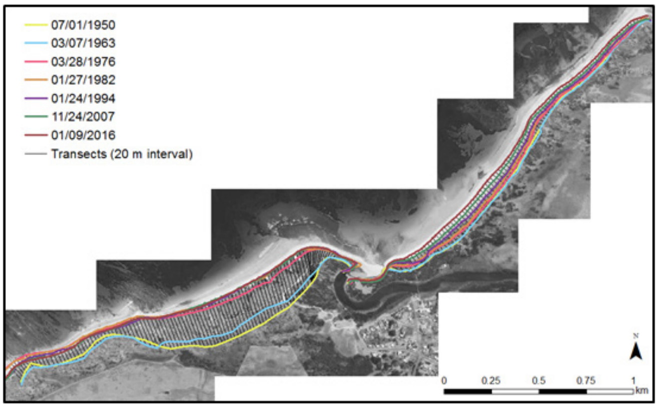

Figure 2 Historical shorelines mapped from aerial imagery and transects cast by DSAS. Background image is LIST State Aerial Photo Basemap.[31]

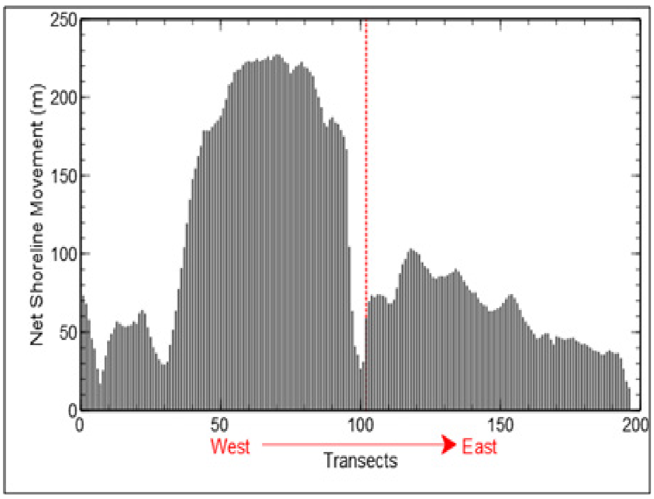

Figure 3 Net Shoreline Movement in metres along the 20m transect intervals. Transects progress from west on the left to east on the right, the dotted line indicates the estuary mouth between the two beaches.

Citation: Masterman R, Ellison JC. Influence of introduced *Ammophila arenaria* on coastal progradation: assessment by spatial analysis. *J Aquac Mar Biol.* 2018;7(5):268–273. DOI: 10.15406/jamb.2018.07.00219

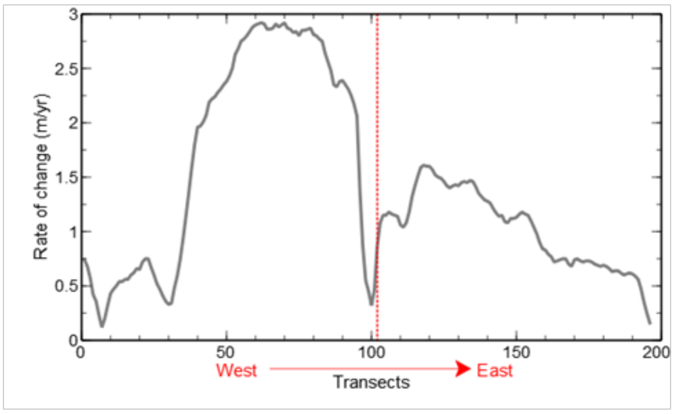

Figure 4 Weighted Linear Regression (meters per year) at 20m transect intervals. Transects progress from west on the left to east on the right, the dotted line indicates the estuary mouth between the two beaches.

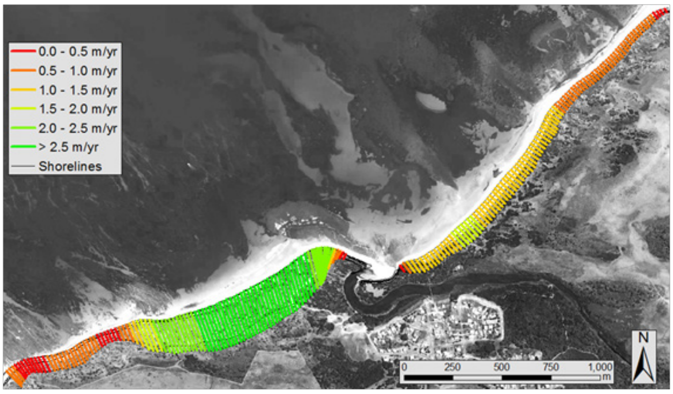

Figure 5 Weighted Linear Regression (meters per year) calculated using DSAS, mapped for Beechford shoreline between 1950 and 2016.

Discussion

The DSAS analysis of net shoreline progradation 1950-2016 (Figure 3), showed different rates on the east and west beaches (Figure 4) (Figure 5), which each have different vegetation histories over that timeframe. After the introduction of the sand-binding grass *A. arenaria* in the late 1950s[15], progradation of the west beach was particularly rapid, particularly in the centre of west beach from 1963 to 1976 (Figures 2,4,5). In 1950, the west beach dunes consisted of bare sand (51%), native scrub (28%) and native sand binders (21%),[15] then *A. arenaria* showed a 17% presence in 1963, and had replaced all the bare sand and native sand binders to reach 68% coverage by 2005. DSAS results showed after rapid progradation in the first 20 years of *A. arenaria* introduction, rates slowed to reach a stable position after 1994 (Figure 2). A 60-year record of vegetation change on South African dunes showed *A. arenaria* to be more vigorous just after colonisation, then succession occurred with its replacement by native dune scrub.[5] Replacement by dune scrub may occur in Tasmania over a similar timeframe if undisturbed, however west beach was disturbed by fire in 2003.[15] From 1976 to 1994, a slower rate of progradation occurred (Figure 2), then shoreline stability was reached after 1994, even though *A. arenaria* remained dominant.

Historical photography (Figure 6) from the middle of last century added information to the results available from spatial analysis. In regards to dune morphology, ground photographic evidence of the west beach showed a gently inclined primary foredune no more than three or four metres in height present during the 1930s to early 1960s (for example Figure 6A). By 2016, these dunes appear to have grown, merged, steepened and increased in height by up to 10 metres along most of the beach (Figure 6B), with a tall and concave dune front.

Figure 6 (A) View towards the east along the west beach during January 1960, and (B) October 2016. A seaward movement of the dunes is apparent, and transition from a low, gentle, convex incline to tall, steep, concave foredunes. (C) View towards the west along east beach in the 1930s and (D) October 2016. The east beach foredune showed a transition from native scrub to sand-binding grasses, while also having appeared to move seaward.

By contrast to the west beach, the east beach shoreline was relatively stable 1950–1963 (Figure 2) (Figure 5), with some small segments of erosion. From 1976-2016 *A. arenaria* remained consistently low at 11-15% cover[15] and steady shoreline progradation occurred to its furthermost seaward position in 2016 (Figures 2) (Figure 4) and (Figure 5), apart from a halt 1976-1982.The east beach ground imagery from the 1930s, by contrast to the west beach, showed many small, vegetated, hummocky dunes (for example Figure 6C), and smaller foredunes with convex shapes and pioneer vegetation. The foredunes increased in height by approximately three metres during this time, with a gentle incline in the foredune slope (Figure 6D).

A. arenaria is known to invade sparsely vegetated dunes and replace native sand binders, and once established, its canopy morphology alters airflow and sediment transport,[41] to encourage accretion of the dune system and build steep, tall foredunes.[7] This study showed using DSAS that rapid progradation of the infested west beach occurred during the early colonisation phase, after 20 years followed by a slowing rate to a halt as the *A. arenaria* established. Tall foredunes developed (Figures 6A) (Figures 6B), likely removing sand available for coastal progradation into tall dune storage. This dune stabilisation by *A. arenaria* has been beneficial in South Africa to prevent blockage of rivers,[5] but has elsewhere been found to starve sediment supply to adjacent sedimentary systems,[11] and this Beechford study showed that *A. arenaria* after 40 years halted coastal progradation, likely for similar reasons of sediment starvation.

On the east beach, vegetation proportions remained fairly consistent through time,[15] with a dominance by native sand binders relative to the west beach. Progradation was steady (Figure 2), and shoreline profiles prograding (Figures 6C) (Figures 6D), as shown by their convex dune profiles.[44] The native sand-binding grass *S. sericeus*, relative to *A. arenaria*, is a lower, more spreading, rhizomatous plant, causing it to be a primary sand-colonizing, foredune species in New Zealand[10] and Australia. It causes a gradual downwind reduction in transport which assists in producing asymmetric dune systems with a short slope downwind, and also reduces dune vulnerability to wind and water erosion[19], and at Beechford, it brought steady and consistent progradation over time (Figure 2). The lack of longshore drift owing to the central inflection of the north Tasmanian coast[24,25] reduces the potential effects of other factors such as longshore drift that may cause differences between east and west beaches.

A. arenaria dominated foredunes in Northern Ireland showed seaward progradation with vegetation stabilisation for about 30 years[17,18] until reduced sediment availability caused later dune cliffing and retreat.[43] Stabilised large dunes formed an impenetrable boundary for windblown sediment supply.[17] This study showed that the west beach showed similar patterns of progradation leading to a stasis of the shoreline position, and shore facing dunes steepening. This rapid progradation leaves the foredunes vulnerable to undercutting and subsequent recession, and also impacts on *A. arenaria*'s own growth as high levels of salt spray are known to inhibit its survival.[8]

Despite recorded relative sea level rise in Tasmania for a number of decades,[44] this study furthermore showed using DSAS from two beaches that recession in the last few decades has not occurred. While beach erosion is a high expectation with continued sea level rise,[45] with active mobile landforms close to high tide levels being the highest coastal erosion hazard,[46] this study showed for this location that these thresholds are not as yet reached. More vulnerable to future erosion, as shown by the halt of progradation since the 1980's, may be the beach infested by *A. arenaria*. Less vulnerable to future erosion, as shown by steady progradation 1950-2016, may be the beach that was largely vegetated by native sand binding vegetation. Further study of other beaches in Tasmania by spatial analysis of change, and more intensive study of spatial change, compared with beach profiles[47] would add to understanding factors involved in beach progradation and erosion.

Conclusion

The study found that the shoreline at Beechford has undergone substantial progradation over the past 66 years. The two beaches show considerable differences in their rates of spatial change and foredune evolution despite their adjacent location and similar aspect. Reasons for this likely relate to the differences in coverage of sand-binding vegetation, with the native vegetated beach showing steady and consistent progradation, while the *A.arenaria* infested beach showed rapid progradation for a few decades that then halted.

Despite relative sea level rise for a number of decades, this study also showed from two Tasmanian beaches that recession has not occurred. This study demonstrates that spatial analysis techniques such as DSAS could be used to quantify changes elsewhere in the Tasmanian coastal zone, by using the shoreline proxy of the vegetation edge. With little work on shoreline spatial change in Tasmania, further studies applying this technique are required to better understand the island's state-wide trends, especially if results are compared with beach profile monitoring.

Acknowledgements

Residents are thanked for providing old photos.

Conflict of interest

Author declares that there is no conflict of interest.

References

1. van der Putten WH, Kloosterman EH. Large–scale establishment of *Ammophila arenaria* and quantitative assessment by remote sensing. *J Coast Res. 1991;*7(4): 1181–1194.
2. Gómez–Pina G, Muñoz–Pérez JJ, Ramírez, JL. Sand dune management problems and techniques, Spain. In: Cooper JAG, Jackson DWT, editors. Proceedings from the International Coastal Symposium 2002 (Temple patrick, Northern Ireland). *J Coast Res. 2002;*SI 36:325–332.
3. Rozé F,Lemauviel S. Sand dune restoration in North Brittany, France: A 10–Year monitoring Study. *Restorat Ecol. 2004;*12: 29–35.
4. Hertling UM, Lubke RA. Assessing the potential for biological invasion–the case of *Ammophila arenaria* in South Africa. *South African J Science. 2000;*96(9–10):520–528.
5. Lubke RA, Hertling UM. The role of European marram grass in dune stabilization and succession near Cape Agulhas, South Africa. *J Coast Conserv. 2001;*7(2):171–182.
6. Buell AC,Pickart AJ, Stuart JD. Introduction history and invasion patterns of *Ammophila arenaria* on the north coast of California. *Conservat Biol. 1995;*9(6):1587–1593.
7. Hilton M, Harvey N, Hart A, et al. The impact of exotic dune grass species on foredune development in Australia and New Zealand: a case study of *Ammophila arenaria* and *Thinopyrum junceiforme*. *Austral Geograph. 2006;*37(3):313–334.
8. Konlechner TM, Hilton MJ,Orlovich DA. Accommodation space limits plant invasion: *Ammophila arenaria* survival on New Zealand beaches. *J Coast Conserv. 2013;*17:463–472.
9. Webb CE, Oliver I,Pik AJ. Does coastal foredune stabilization with *Ammophila arenaria* restore plant and Arthropod communities in Southeastern Australia? *Restorat Eco.2000;l* 8:283–288.
10. Hilton MJ. The loss of New Zealand's active dunes and the spread of marram grass (*Ammophila arenaria*). *N Z J Geograph. 2006;*62:105–120.
11. Hart AT, Hilton MJ, Wakes SJ, et al. The impact of *Ammophila arenaria* foredune development on downwind aerodynamics and parabolic dune development. J Coast Res. 2012;28(1):112–22.
12. Rudman T. *Tasmanian beach weed strategy for marram grass, sea spurge, sea wheatgrass, pyp grass & beach daisy*. Nature Conservation Report 03/2, Nature Conservation Branch, Department of Primary Industries, Water and Environment, Tasmania, 2003.
13. Brownett JM, Mills RS. The development and application of remote sensing to monitor sand dune habitats. *J Coast Conserv. 2017;*21(5): 643–656.
14. Lubke RA. Vegetation dynamics and succession on sand dunes of the eastern coasts of Africa. In: Martínez NL, Psuty NP, editors, Coastal Dunes: Ecology and Conservation. Berlin Heidelberg, Springer; 2008. p. 67–84.
15. Hayes M, Kirkpatrick JB. Influence of *Ammophila arenaria* on half a century of vegetation change in eastern Tasmanian sand dune systems. *Aust J Bot. 2012;*60:450–460.
16. Timm BC, Smith SM, Greenspan SE. Remotely sensed mapping of *Ammophila spp.* distribution and density at Cape Cod National Seashore. *J Coast Res*. 2014;30(4):862–867.

17. Carter RWG,Wilson P. The geomorphological, ecological and pedological development of coastal foredunes at Magilligan Point, Northern Ireland. In: Nordstrom KF, Psuty N, Carter RWG, editors. Coastal Dunes: Form and Process. Chichester: Wiley; 1990; 129–157.
18. Carter RW. Recent progradation of the Magilligan foreland co. Londonderry, Northern Ireland. Les côtes Atlantiquesd'Europe, *évolution*, aménagement, protection. *Publication CNEXO France Actes Colloquium. 1979;*9: 17–27.
19. McKPegman AP, Rapson GL. Plant succession and dune dynamics on actively prograding dunes, Whatipu Beach, northern New Zealand. *N Z J Bot. 2005;* 43: 223–244.
20. Darwish K, Smith SE, Torab M, et al. Geomorphological changes along the Nile Delta coastline between 1945 and 2015 detected using satellite remote sensing and GIS. *J Coast Res. 2015* 33(4): 786–794.
21. Evadzi PI, Zorita E, Hünicke B. Quantifying and predicting the contribution of sea–level rise to shoreline change in Ghana: information for coastal adaptation strategies. *J Coast Res*. 2017;33(6):1283–1291.
22. Edgar GJ, Barrett NS, Graddon DJ. A classification of Tasmanian estuaries and assessment of their conservation significance using ecological and physical attributes, population and land use. Hobart: University of Tasmania; 1999. 199 p.
23. Wijeratne EMS, Pattiaratchi CB, Eliot M, et al. Tidal characteristics in Bass Strait, south–east Australia. *Estuar Coast Shelf Sci*. 2012;114:156–165.
24. Davies JL. Beach sand and wave energy in Tasmania. In: Davies, JL, Williams MAJ, editors. *Landform evolution in Australasia*. Australian National University Press, Canberra; 1978. p. 158–167.
25. Davies JL, Hudson JP. Differential supply and longshore transport as determinants of sediment distribution on the north coast of Tasmania. *Mar Geol*. 1987;77(3–4):233–245.
26. Short AD. *Beaches of the Tasmanian coast & islands: a guide to their nature, characteristics, surf and safety*. Sydney University Press, New South Wales, Sydney; 2006.
27. Bureau of Meteorology. Climate statistics for Australian locations. 2017.
28. Steane D. Waterhouse and the northeast coastal plains: an historical perspective. In: Scientific Report No. 95/5. Hobart, Tasmania: Parks and Wildlife; 1995.
29. DPIPWE. Natural Values Atlas. Department of Primary Industries, Parks, Water and Environment; 2016.
30. Gallant J, Wilson N, Dowling T, et al. SRTM–derived 1 Second Digital Elevation Models Version 1.0. Canberra: Geoscience Australia; 2011.
31. DPIPWE. LIST map and State Aerial Photo Basemap. 2016.
32. Thieler ER, Himmelstoss EA, Zichichi JL, et al. Digital shoreline analysis system (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change: US Geological Survey. 2009.
33. Kuleli T. Quantitative analysis of shoreline changes at the Mediterranean Coast in Turkey. *Enviro Monitor Assess*. 2010;167(1–4):387–397.
34. Ellison J, Zouh I. Vulnerability to climate change of mangroves: assessment from Cameroon, Central Africa. *Biology*. 2012;1(3):617–638.
35. Mujabar PS, Chandrasekar N. Coastal erosion hazard and vulnerability assessment for southern coastal Tamil Nadu of India by using remote sensing and GIS. *Natural Hazards*. 2013;69(3):1295–1314.
36. Boak EH, Turner IL. Shoreline definition and detection: A review. *J Coast Res*. 2005;21(4):688–703.
37. Himmelstoss EA. DSAS 4.0 installation instructions and user guide. In: Thieler ER, Himmelstoss EA, editors. *Digital Shoreline Analysis System (DSAS) version 4.0 – An ArcGIS extension for calculating shoreline change*. Reston: US Geological Survey; 2009.
38. Romine BM, Fletcher CH, Frazer LN, et al. Historical shoreline change, Southeast Oahu, Hawaii; Applying polynomial models to calculate shoreline change rates. *J Coast Res*. 2009;25(6):1236–1253.
39. Intergraph. ER Mapper User Guide. Huntsville, AL: Intergraph Corporation; 2012.
40. Pye K, Blott SJ. Evolution of a sediment–starved, over–stabilised dunefield: Kenfig Burrows, South Wales, UK. *J Coast Conserv*. 2017;21(5):685–717.
41. Hesp P. Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphol*. 2002;48(1–3):245–268.
42. Thom BG, Hall W. Behaviour of beach profiles during accretion and erosion dominated periods. *Earth Surf Proc Landforms*. 1991;16(2):113–127.
43. Carter RW, Stone GW. Mechanisms associated with the erosion of sand dune cliffs, Magilligan, Northern Ireland. *Earth Surf Proc Landforms*. 1989;14(1):1–10.
44. Watson CS, White NJ, Church JA, et al. Unabated global mean sea–level rise over the satellite altimeter era. *Nature Clim Change*. 2015;5(6):565–568.
45. Wong PP, Losada IJ, Gattuso JP, et al. Coastal systems and low–lying areas. In: Field CB, Barros VR, et al. editors. *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge and New York; 2014. p. 361–409.
46. Department of Premier and Cabinet. Coastal hazards technical report. Hobart: Tasmanian Government; 2016. 130 p.
47. Johnston E, Ellison JC. Evaluation of beach rehabilitation success, Turners Beach, Tasmania. *J Coast Conserv*. 2014;18(6):617–629.