Aeolian Research 25 (2017) 107–121

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Coastal dune activity and foredune formation on Moreton Island, Australia, 1944–2015

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A R T I C L E I N F O

Article history:
Received 27 October 2016
Accepted 30 March 2017

Keywords:
Dune stabilization
Aerial photos
Remote sensing
Drift potential
Wave height
El-Niño Southern Oscillation

A B S T R A C T

The stabilization process of coastal dunes is complex, involving feedback mechanisms and lag times between changes in climatic conditions, vegetation establishment and dune movement. In this study our aim was to examine changes in dune activity and in the establishment of foredunes on Moreton Island, Australia. We used historical aerial photos, satellite images and Lidar data to quantify changes in bare sand areas, dune movement rates, foredune development and coastline changes between 1944 and 2015. We used wind data (1957–2016), to quantify changes in sand drift potential (DP) and in wind directionality, and wave data (1977–2016) to examine changes in wave height and wave direction. We found that transgressive dunes on Moreton Island have started stabilizing in the early 1970s, after a series of continuous foredunes developed on the eastern coast of Moreton Island, in spite of the increase in DP values. Foredunes have started establishing in the 1960s and 1970s during a period of lower wave height and decreased wind directionality. Once established, these foredunes have diminished sand supply to the transgressive dunes, causing a phase shift in the state of dune activity on the island. Coastal dune activity should therefore be examined over time scales of several decades at least, in order to quantify trends and to understand the underlying and causes to observed processes. Understanding the factors responsible for foredune formation is important for explaining dune stabilization on Moreton Island.

1. Introduction

The beach-dune system represents a highly dynamic biogeomorphic ecosystem where shifts between active and stable states can take place over several years (Hugenholtz and Wolfe, 2005), and where both active and stable dunes can co-exist under the same climatic conditions (Tsoar, 2005). Within this ecosystem, three separate areas may be distinguished on land: (1) the sandy beach which is shaped by the waves, the sediments they deposit and erode, and the wind which can entrain sand grains (Bauer et al., 2009; Defeo et al., 2009); (2) the foredunes, which are formed behind the beach, if the conditions for vegetation growth and trapping of sand by vegetation are met (Hesp, 2002; Dillenburg et al., 2016); (3) the back dunes, which may be composed of a variety of aeolian features, including blowouts, relict foredune plains, beach ridge plains, parabolic dune fields, as well as transgressive dune fields (where active sand dunes migrate inland, burying vegetation on their way; Hesp and Thom, 1990; Hesp, 2013).

Research on dune activity has developed climatic indices (mostly based on rainfall, evaporation and wind regime) to explain the shifts between active and stable states of sand dunes (Fryberger and Dean, 1979; Lancaster, 1988; Tsoar, 2005). Later models and indices recognized the biogeomorphic and hysteretic nature of this ecosystem, and that there are lag times representing the time it takes for the dunes to respond and recover from disturbances to dune vegetation (Hugenholtz and Wolfe, 2005; Thomas et al., 2005; Yizhaq et al., 2007; Hesse et al., 2017). In addition to climatic variability, human activity can also be driving shifts in the state of activity of coastal dunes, with certain human activities favouring dune stabilization (e.g., intentional dune fixation; Avis, 1989; Hilton, 2006), and others leading to dune reactivation (e.g., over grazing; Levin and Ben-Dor, 2004). While the central role of foredunes within the ecosystem of coastal dunes has been noted (Short and Hesp, 1982; Short, 1988; Hesp, 2002), relatively few studies have aimed to quantify recent changes in foredunes' size, the factors driving those changes, and the consequences of changes in the foredunes on the transgressive dunes behind the foredunes (see Curr et al., 2000; Seeliger et al., 2000; Claudino-Sales et al., 2008; Miot da Silva and Hesp, 2010; Keijsers et al., 2015).

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http://dx.doi.org/10.1016/j.aeolia.2017.03.005

The coastal dunes in south east Queensland represent one of the world's oldest, largest and continuous systems of coastal dunes (Miot da Silva and Shulmeister, 2016). This coastal dune system stretches from the Gold Coast to Fraser Island (over 400 km), has started forming about 750,000 years ago (Tejan-Kella et al., 1990; Lees, 2006; Ward, 2006; Queensland Parks and Wildlife Service, 2007), and is comprised of several major complexes: South and North Stradbroke Islands, Moreton Island, Bribie Island, Cooloola and Fraser Island (Fig. 1). The undisturbed and isolated nature of Moreton Island affords scientific opportunities to study the island's flora, fauna, and natural ecosystems, especially the geomorphological mechanisms involved in dune processes and coastal environs (Queensland Parks and Wildlife Service, 2007). Understanding the significance of these mechanisms may provide important information for the management of coastal zones under future climate variabilities. Understanding coastal dynamics is also pertinent for managing human settlements, and this is particularly true for south east Queensland where Moreton Island is situated. Population growth and coastal urban centers make this region one of Australia's most vulnerable to climate risk. Accordingly the region and has been a focus for climate adaptation research (McAllister et al., 2014) and our study contributes to an integrative understanding of coastal dynamics and potential future scenarios for coastal settlements (e.g., Stewart et al., 2014; Fletcher et al., 2016; Traill et al., 2011).

Most research on the geomorphology of the coastal dunes of south east Queensland was focused on their geology and paleoclimate (e.g., Thompson, 1992; Longmore, 1997; McGowan et al., 2008; Moss et al., 2013; Petherick et al., 2017). The few studies devoted to the recent geomorphology of these dunes, have quantified some of the dynamics of these dunes (Stock, 1990), have modelled the dynamics of these dunes (Yizhaq et al., 2013), explained differing morphologies of the transgressive dunes as a function of spatial variability in wind regime (Levin et al., 2014), attributed changes in dune activity to changes in tropical cyclones (Levin, 2011) and noted the effects of grazing by macropods (Ramsey and Wilson, 1997) and disturbance by human activity to foredunes (Thompson and Schlacher, 2008).

The goal of this paper was therefore to examine dune activity and dune formation on Moreton Island since the 1940s, and to understand the factors driving these processes.

More specifically, we aimed to address the following questions:

1. What were the dynamics of dune activity and foredune formation on Moreton Island?
2. What were the relationships between foredunes and transgressive dunes' activity on Moreton Island?
3. Can the observed changes in dune activity and foredune formation on Moreton Island be explained by climatic factors?

2. Methods

2.1. Study area

Moreton Island is a wedge-shaped sand island located about 40 km east of Brisbane (Queensland, Australia). It forms the eastern part of Moreton bay on the south east coast of Queensland, Aus-

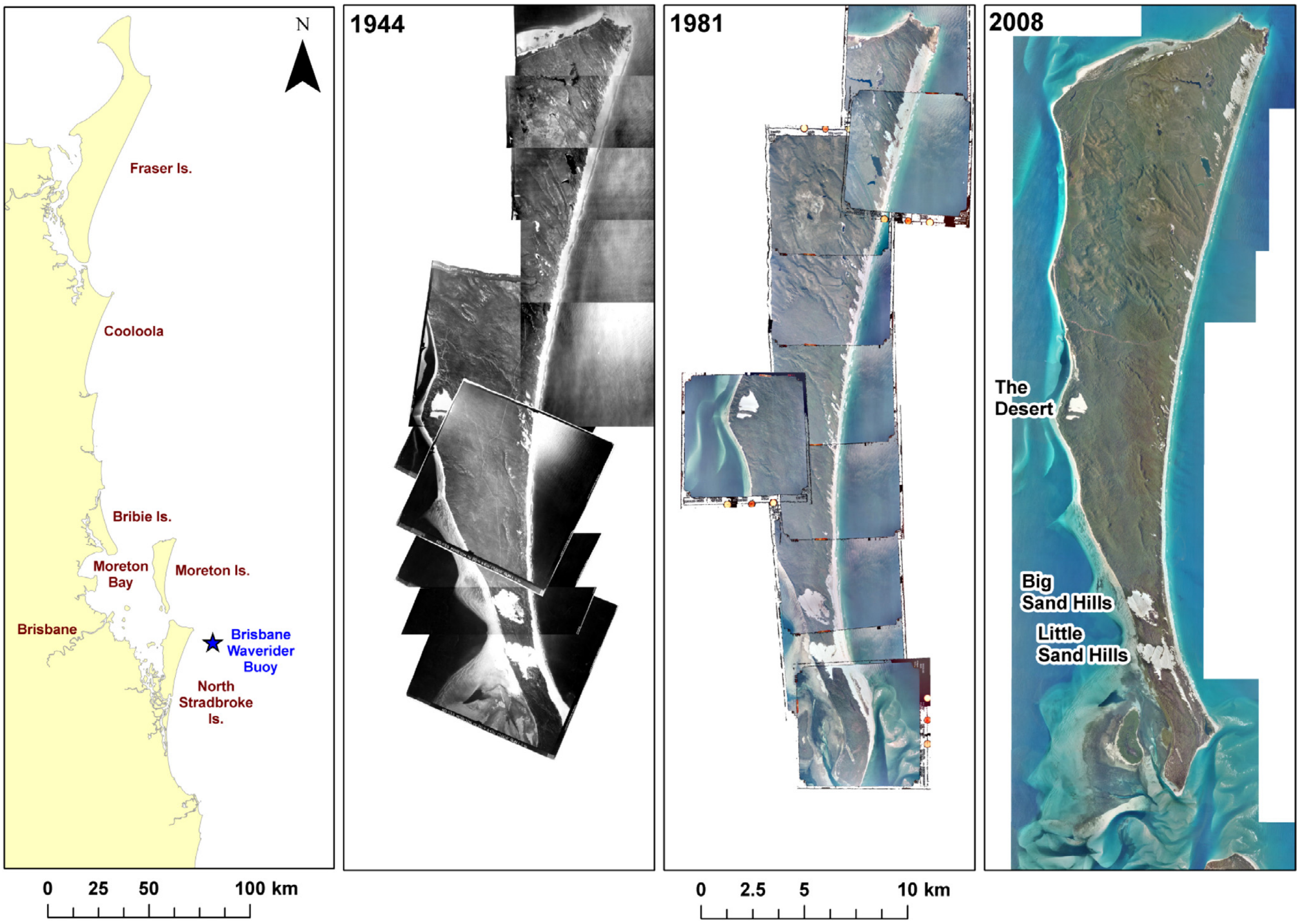

Fig. 1. Location map of Moreton Island (southeast Queensland, Australia), and mosaics showing the active dune areas in 1944, 1981 and 2008.

tralia (Fig. 1). The island is 37 km long, about 10 km wide covering a total area of about 186 km^2. The highest point on the island is Mount Tempest, presumably the highest permanent coastal sandhill in the world, rising over 280 m above sea level. About 95% of the island has been declared a National Park since 1966 (Levin et al., 2014). Moreton Island has a humid subtropical climate, with an average monthly precipitation ranging from 178 mm in March to 65 mm in September for a mean annual rainfall of 1495 mm (Stock, 1990), however, annual rainfall has been declining in eastern Australia in recent decades (Speer et al., 2011). The dominant winds are from the south-east (as along most of the coast of eastern Queensland; Pye, 1982), however the wind regime can be very different between the western and eastern sides of the island, especially during the winter months (Levin et al., 2014). Moreton Island can occasionally be subject to tropical cyclones (the cyclone season in Queensland being between November and April), which

Table 1
Historical aerial photograph and remote sensing datasets used in the study.

Year	Number of photos	Image type	Height (m)	Scale	Focal length (mm)	Median no. of ground control points	Rectified spatial resolution (m)
1944	14	Historical aerial photography	5181	1:34,000	153.4	23	1
1958	12	Historical aerial photography	3810	1:24,000	152.09	21	2
1966	2	Corona satellite photograph	185,000	1:303,000	609.6	19	3.5
1969	3	Historical aerial photography	7620	1:85,000	88.23	32	4
1972	22	Historical aerial photography	3657	1:24,000	152.23	20	1
1981	10	Historical aerial photography	3850	1:22,000	152.09	19	2
1982	23	Historical aerial photography	1830	1:12,000	152.12	18	0.5
1983	4	Historical aerial photography	6496	1:40,000	152.02	17	4
1994	3	Orthophoto					2.5
2002	3	Orthophoto					2.5
2006	2	Orthophoto					2.5
2008	1	Orthophoto		1:30,000			2
2009		LIDAR					1
2015	1	Ziyuan-3 satellite image					2

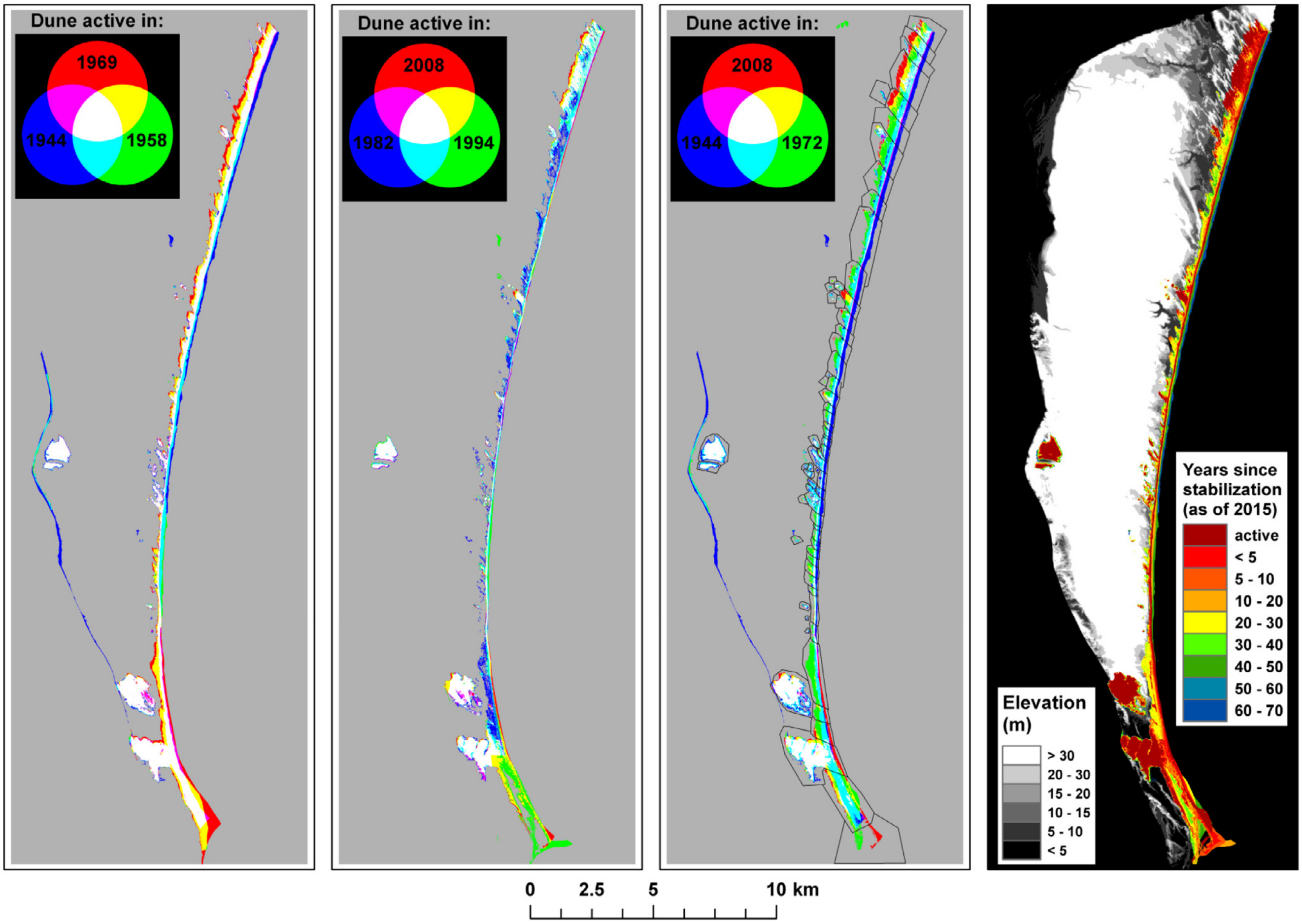

Fig. 2. Maps showing the years in which transgressive dunes were active on Moreton Island. The red, green and blue (RGB) composites present dune activity for three combinations of three different years (where a white colour indicates that a dune was active in all three years). The right-hand map presents the number of years which passed since a dune has stabilized (as of 2015), as well as the ground elevation. The black polygons on the second map from the right show the 69 dune areas which were analysed in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in a previous study have been shown as important for understanding dune activity on Fraser Island (Levin, 2011). However, Moreton Island is located at the southern edge of the activity of tropical cyclones, which are relatively less active in recent centuries in the Australian region (Haig et al., 2014). Besides being subject to tropical cyclones, south east Queensland is also affected by East Coast Lows. East Coast Lows are formed over cold air systems and have a much shorter lifespan (of only a few days) than tropical cyclones. Although the wind speed is not as strong as in tropical cyclones, East Coast Lows can also provoke significant damage (Hopkins and Holland, 1997; Speer et al., 2009). The frequency, proximity, duration and intensity of the weather systems that control local winds and the wave conditions along the Moreton Island coast are also controlled in the longer term (5–10 years) by large-scale ocean-atmosphere cycles, specifically the southern oscillation (Ranasinghe et al., 2004; Barnard et al., 2015). ENSO and LaNiña periods have bene recognized as producing different breaking wave and sandy beach states along the section of east Australian coast south of the study area (Phinn and Hastings, 1992, 1995; Harley et al., 2011).

This study focuses on the active dune areas, which are predominantly limited to the eastern part of the island, two dune fields in the western part of the island (the larger of these locally known as "The Desert"), and two large transverse dune fields, locally known as the Big and Little Sand Hills, which are crossing the island from east to west at the south of the island (Fig. 1). The foredunes are being created on the eastern side of the island. The western side of the island is the location of four small settlements (Bulwer, Cowan Cowan, Tangalooma and Kooringal), with a total population of about 300 people.

2.2. Spatial datasets

The data used in this study to reconstruct dune activity consisted of aerial photos and satellite images from 1944, 1958, 1966, 1969, 1972, 1981, 1982, 1983, 1994, 2002, 2006, 2008,

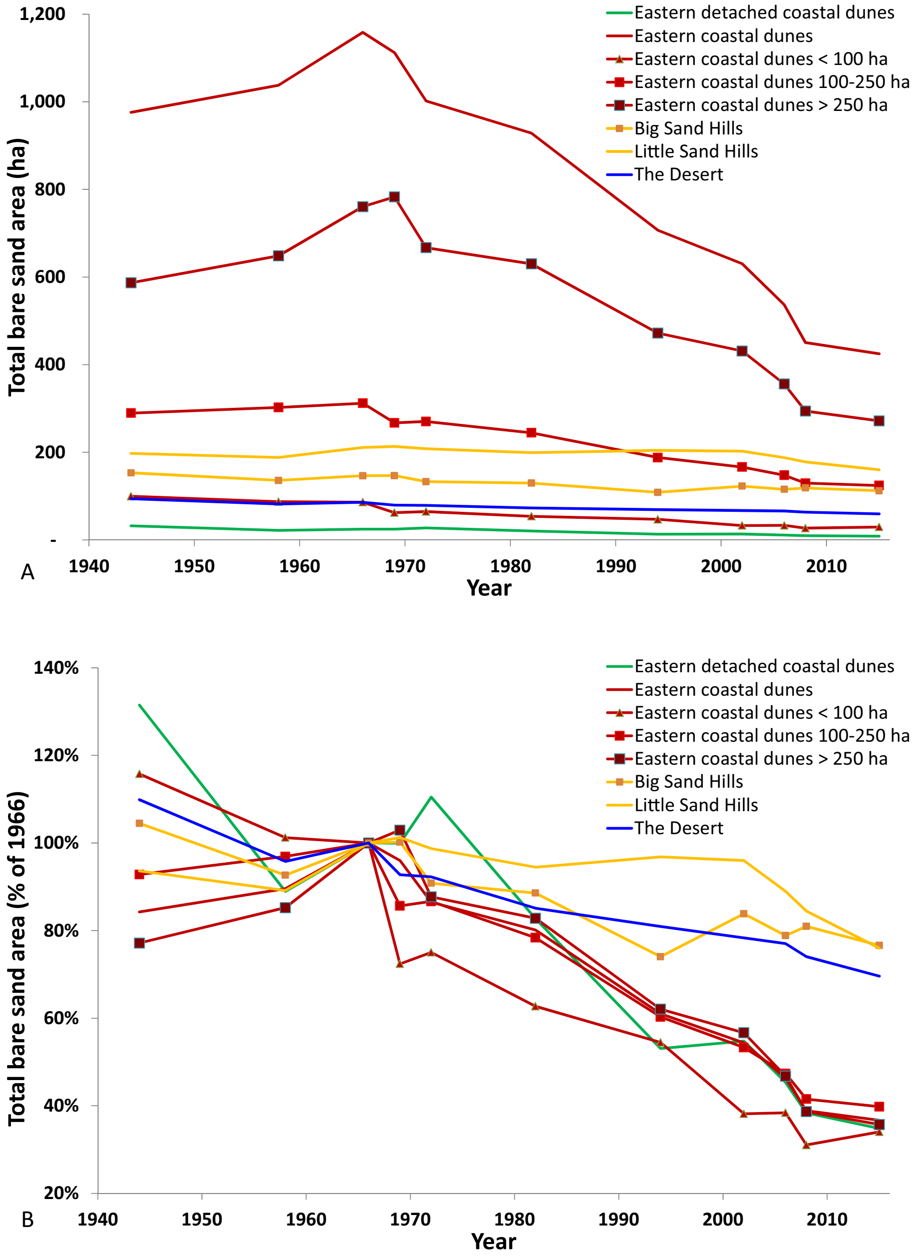

Fig. 3. Changes in the bare sand area of dune fields on Moreton Island in hectares (A) and as percentage of their area in 1966 (B).

2015 a topographic map (1:25,000; 1990) and a Digital Elevation Model (DEM) obtained by Lidar in 2009 with a 1 m resolution (Table 1). For the years 1944–1983 (with the exception of 1966), historical aerial photos were used. For the year of 1966, photos from the American Corona satellite were used (McDonald, 1995). Historical aerial photos and satellite images were chosen with at least one image for each decade since the 1940s. All historical aerial photos were scanned at a resolution of at 600 dpi and were

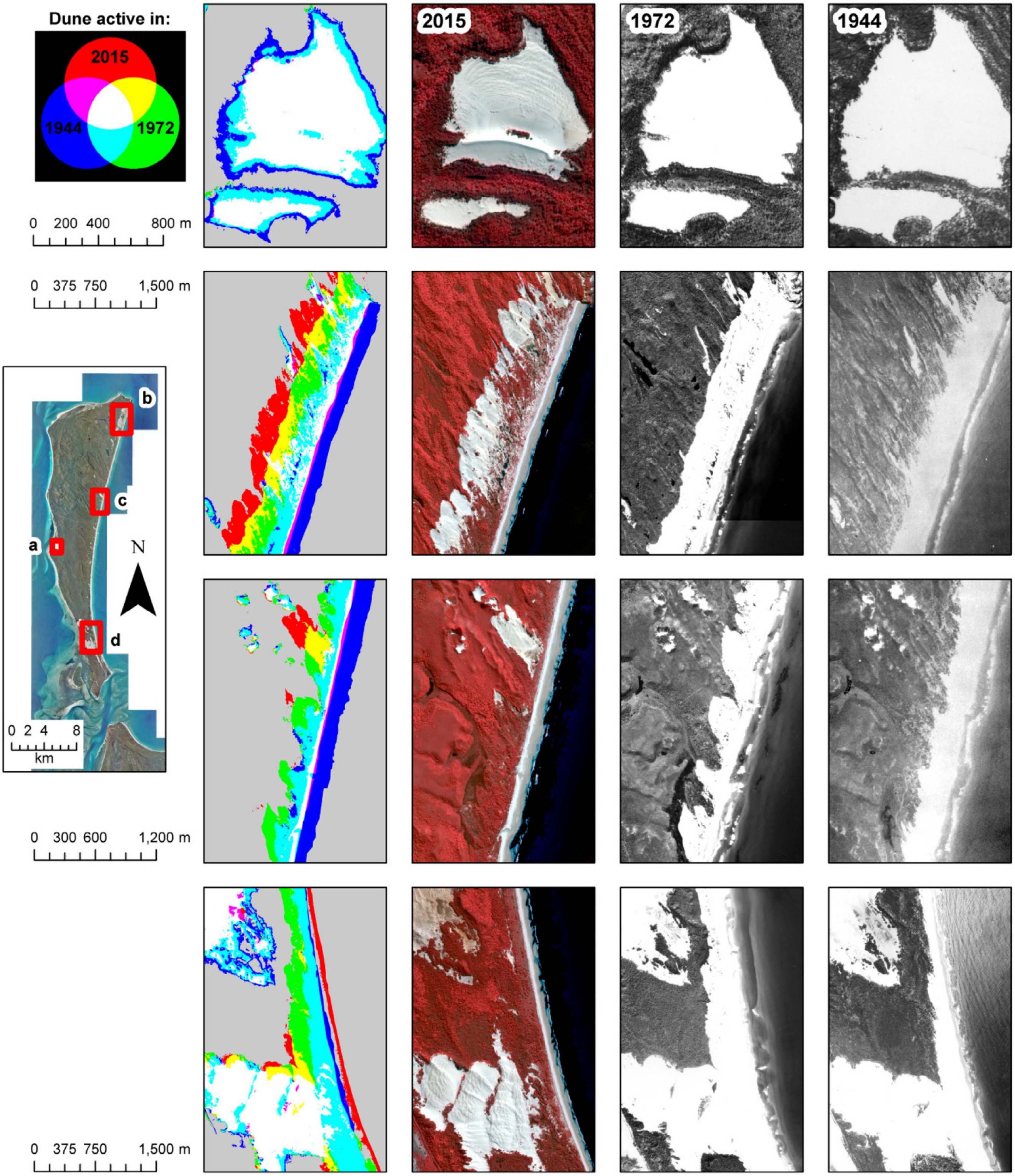

Fig. 4. Maps showing changes in bare sand areas in four sites on Moreton Island in the years 1944, 1972 and 2015 (described from top to bottom): (a) The Desert, (b) dunes near Cape Moreton (north-eastern corner of the island), (c) dunes along the eastern coast of the island, (d) the Big and Little Sand Hills at the south of the island. The RGB composites present dune activity for three combinations of three different years (where a white colour indicates that a dune was active in all three years). The 2015 pan-sharpened Ziyuan-3 satellite image is a false colour composite, showing vegetated areas in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

orthorectified with a Camera Model in ERDAS Imagine™ based on a digital elevation model and a present-day orthophoto.

2.3. Quantifying dune dynamics

Dozens of active transgressive and parabolic dune fields (locally known as sand blows) exist on Moreton Island, mostly initiated as blowouts following disturbances along the beach (Pye, 1993; Hesp, 2002; Levin, 2011). In our study we included all transgressive dune fields along the eastern side of Moreton Island, as well as "The Desert" and the Big and Little Sand Hills, resulting with an overall number of 69 transgressive dune fields. For some of the statistical analyses, these transgressive dune fields were analyzed based on their size (<100 ha, 100–250 ha, >250 ha), their location (north, center, south), and as "coastal sand dunes" if they were in direct contact with the beach in 1958, or as "detached dunes" if they were disconnected (by vegetation) from the beach already in 1958. For each of these dune fields, we calculated the following geomorphological variables: area of bare sand (in a given year), dune movement rate (between consecutive years for which there were aerial photos), the number and length of foredunes between the dune field and the coastline (in a given year), and changes in the position of the coastline (between consecutive years for which there were aerial photos).

The area of the dune fields was identified in each of the images with a minimum distance supervised classifier, as applied in ENVI 3.4 (Research Systems Inc., 2006). The results were reviewed visually, and mis-classifications (e.g., shaded areas that were not classified as sand, or bright areas such as wave breakers which were misclassified as sand) were corrected manually by digitization. The coastline for each year was digitized, defined as the high water line (Pajak and Leatherman, 2002). The coastline can be identified on aerial photos as the line separating between bright sand (dry) and dark sand (wet) (Shoshany and Degani, 1992). This coastline was applied as a mask on the binary image of the bare sand in order to obtain the final bare sand areas on each photo.

Change detection between binary images of bare sand areas was done by an overlay operation of the classified sand area from two time periods. Following this step the vegetated area that was covered by advancing sand dune and the dune field area that was stabilized by vegetation were calculated, for deriving dune movement rates. Dune movement rates (m/year) were analyzed for each of the eastern coastal dune fields based on the net rate of their advancement to the north–west:

$$v = \frac{S}{t \times L} \tag{1}$$

where v is the movement rate, S is the area covered by the sand dunes between successive years, t is the time between successive aerial photographs and L is the dunes' front length (i.e., the width of the dune field) (Levin and Ben-Dor, 2004; Levin, 2011; Hugenholtz et al., 2012).

The changes in the location of the coastline between successive aerial photographs were calculated (m/year) using the high waterline, so as to quantify whether the shoreline has prograded (positive values) or eroded (negative values). Skeleton lines representing the foredunes were digitized from each of the historical aerial photos as well as from the LIDAR DEM. In order to compare the amount of foredunes between dune fields of different sizes, foredunes lengths are presented as the percentage of dune's length cover. The foredune length for every dune was thus divided by the beach length along a dune field, as shown in Eq. (2):

$$f = \frac{l}{B} \times 100 \tag{2}$$

where l is the total foredune length in a given year and B is the beach length along a dune field. Therefore, if there was one foredune that covered the entire width of a dune, this dune field will be assigned an f value of 100% for that year. If there were two parallel foredunes covering the entire width of a transgressive dune field, it will get an f value of 200%, etc.

2.4. Climatic datasets

Meteorological data (rainfall, wind strength and direction) was obtained from the Cape Moreton meteorological station, situated at the northernmost tip of Moreton Island, for the years 1957–2016 (rainfall data being available from 1887). The indices of drift potential (DP) and of resultant drift potential (RDP) developed by Fryberger and Dean (1979) have been used in former studies (Bullard, 1997; Tsoar, 2005; Levin, 2011; Hesse et al., 2017) to quantify dune activity, distinguishing between vegetated and

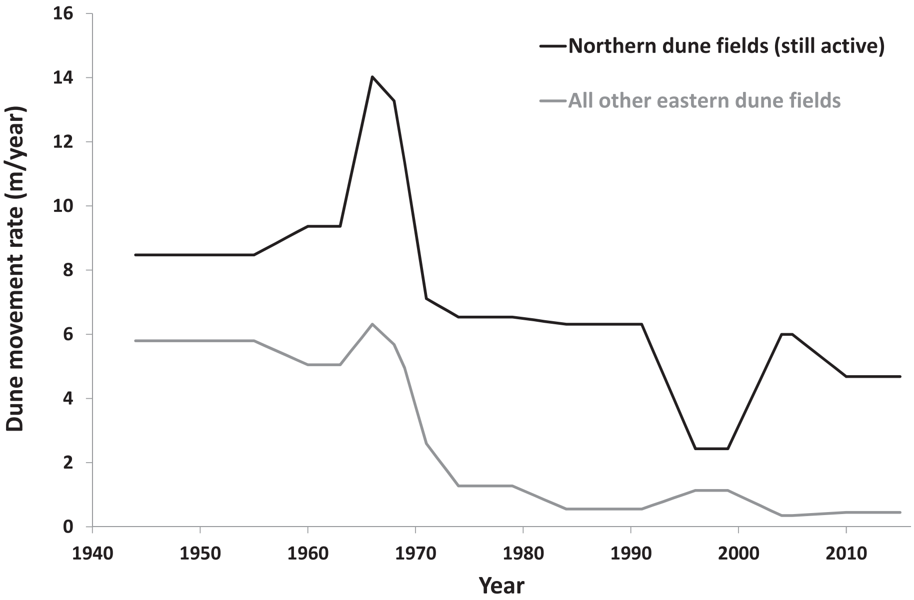

Fig. 5. Dune movement rates (m/year) of the eastern coastal dune fields of Moreton Island.

un-vegetated dunes in regions where annual rainfall is greater than 50 mm (the threshold assumed for vegetation growth on sand dunes; Tsoar, 2005). The equation for calculating DP is as follows:

$$DP = \sum \frac{U^2(U - U_t)}{100} \times t \qquad (3)$$

where U is the wind velocity (in knots) measured at a height of 10 m above ground, U_t is the threshold wind velocity (=12 knots; an average grain sand diameter of 0.25–0.30 mm was assumed; Fryberger and Dean, 1979) and t is the percentage of time that wind velocity was above U_t. The DP was calculated separately for each wind direction (banded into the eight principal compass sectors) that is above the threshold velocity (U_t) and given a value known as a vector unit (v.u.). DP is a parameter that describes the maximum potential amount of sand that could be eroded by wind from all directions over a time period. Hence, DP is a measure of the potential wind power in a sandy area. The various vector units can be resolved into a single resultant, known as the resultant drift potential (*RDP*) (see Fryberger and Dean, 1979). The resultant drift direction (*RDD*) expresses the direction to which sand will be moved by the resultant wind. We calculated the mobility index of Tsoar (2005) based on annual DP and RDP/DP values to estimate the overall potential mobility of these dunes. Monthly values of the Southern Oscillation Index (SOI) were downloaded from the Australian Bureau of Meteorology (ftp://ftp.bom.gov.au/anon/home/ncc/www/sco/soi/soiplaintext.html; accessed October 20th, 2016), because ENSO impacts climatic variation in Australia (Power et al., 1999) and because in previous studies it was found that ENSO affects both wind power (Levin, 2011) and coastal embayment rotation (Harley et al., 2011).

Wave data was downloaded from https://data.qld.gov.au/dataset/coastal-data-system-waves-brisbane (Department of the Environment (1997); accessed August 24th, 2016). It provides information about different variables such as: energy density

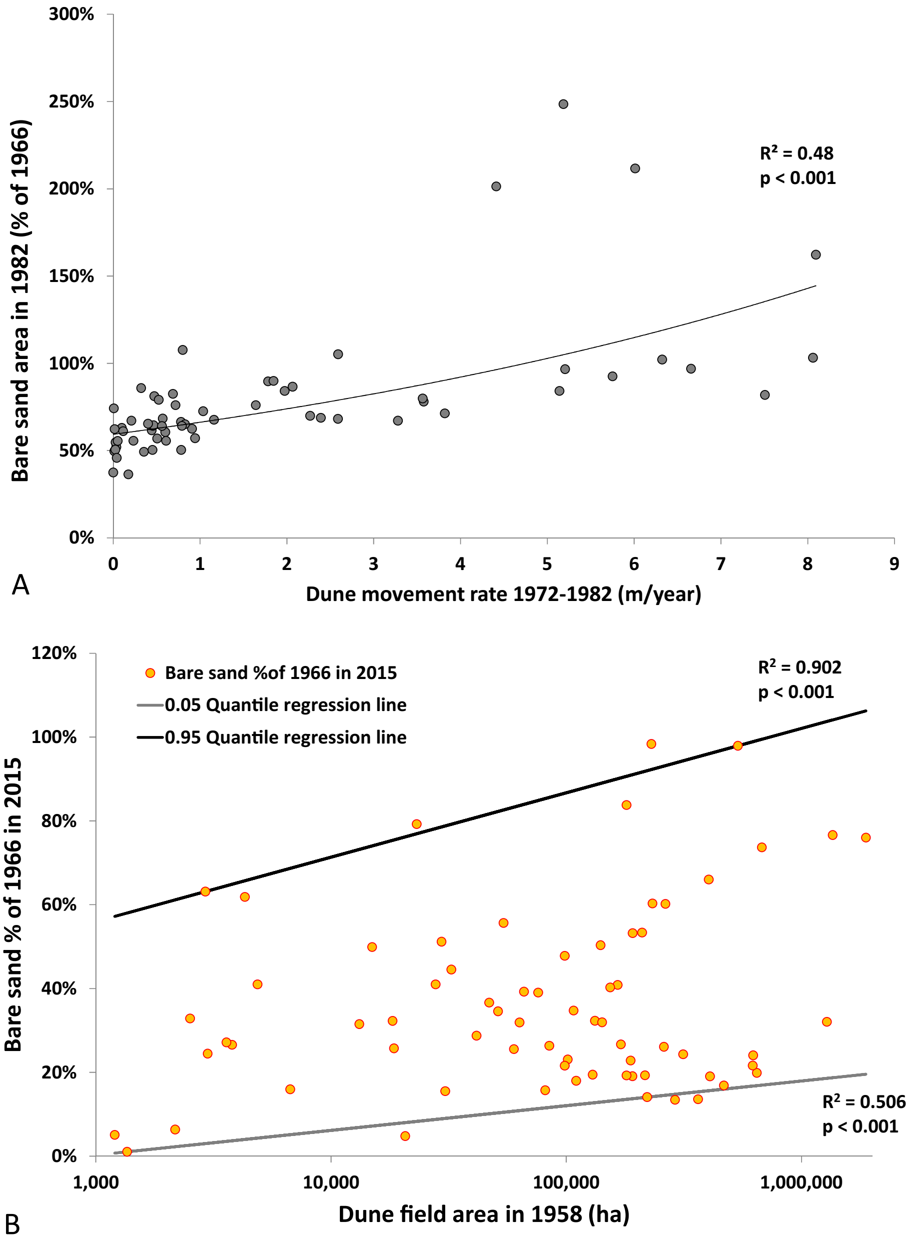

Fig. 6. (A) The correspondence between the dune movement rate (1972–1982) of dune fields on Moreton Island, and changes in the bare sand area of those dune fields. (B) The correspondence between transgressive dune field size in 1958, and changes in the bare sand area of those dune fields.

spectrum, significant wave height, highest individual waves on record, root mean squares of wave heights on record, and wave period. The significant wave height (*Hs*), is the average height of the waves which comprise the highest 33% of waves in a given sample period. The wave periods correspond to the peak of the energy density spectrum. The dataset provides information about the average wave period, and the significant wave periods. Wave data was recorded using a Datawell Waverider buoy, twice daily until 1982, each recording lasted for 20 min and was recorded at 0300 h and 1500 h Australian Eastern Standard Time. From 1982 to 1991 wave data was generally recorded four times a day at 0300, 0900, 1500 and 21 00 h. Between 1991 and 1997, wave data was recorded daily. The position of the buoy and the recording station can be seen on Fig. 1.

2.5. Statistical analyses

Spearman rank correlation coefficients (*Rs*), Pearson correlation coefficients (*R*), quantile regression (Cade and Noon, 2003) and Mann-Kendall non-parametric slope detection and significance testing were calculated using XLSTAT version 2015.4.01.21101 (Copyright Addinsoft 1995–2016), in order to examine possible links and relationships between climatic and geomorphological variables. Spatial differences in the movement rate of the dune fields were statistically examined using initial bare sand area of a dune field as an explanatory variable.

3. Results

Overall most of the dune fields on Moreton Island were undergoing stabilization processes, as evidenced from the decrease in the area of bare sand (Fig. 2). Most dune fields were active and increased in size until the mid to late 1960s, and started decreasing in size from the 1970s onwards (Figs. 2 and 3). However, there were clear differences in the rates of changes in bare sand areas between different classes of active dunes on Moreton Island. Overall, the coastal dunes on the eastern side of Moreton decreased in area since their peak size in the 1960s, down to about 40% of their area in 1966 as of 2015, regardless of their original size and regardless of whether they were detached from the coast in 1958 or not (Figs. 3 and 4). The two adjacent dune fields of “The Desert” at the western side of Moreton Island experienced a continuous decrease in size since 1944, to about 70% of their area in 1966 as of 2015 (Figs. 3 and 4). The two southern dune fields of the Big and Little Sand Hills, remained the most active dune fields, decreasing to just about 76% of their area in 1966 as of 2015 (Figs. 3 and 4).

While most of the dune fields on the eastern side of Moreton Island have considerably decreased in their area, those at the northern stretch of Moreton’s eastern coast, where the ground elevation is mostly below 20 m, remained active (Figs. 2 and 4). In the 1940s–1950s, dune movement rates along the eastern coastal dune fields were about 6 m/year (slightly more than that in the northernmost coastal dunes; Fig. 5). Whereas the majority of the northernmost coastal dune fields along Moreton’s eastern coastline are still active at present with movement rates of about 4.5 m/year, the rest of the eastern coastal dune fields on Moreton Island underwent quick stabilization, with their movement rates decreasing to about 1 m/year since the early 1970s (Figs. 4 and 5). A positive correlation was observed between dune movement rates and bare sand areas, with dune fields whose dune movement rates were lower, decreased in their size more than dune fields with faster dune movement rates (Fig. 6A). Using quantile regression, a positive correlation was found between the initial size of a transgressive dune field and its stabilization rate, with smaller dune fields stabilizing faster than larger ones (Fig. 6B).

While in “The Desert” dune fields on the western side of Moreton Island vegetation was encroaching on the bare sand areas from all sides of the dune fields, a different process was observed along the eastern side of Moreton Island (Figs. 2 and 4). Along the eastern coast of Moreton Island foredunes were first detected on the aerial photos of 1958. Foredunes were present in front of 60% of all east coast dune fields by 1972, and since the early 1980s series of multiple parallel foredune ridges were observed along Moreton Island’s eastern coastline (Figs. 7 and 8). Foredunes along Moreton Island’s eastern coast were more developed to the north compared to the central coast, and were most developed (with more than six parallel foredunes) along the southern coast of Moreton Island

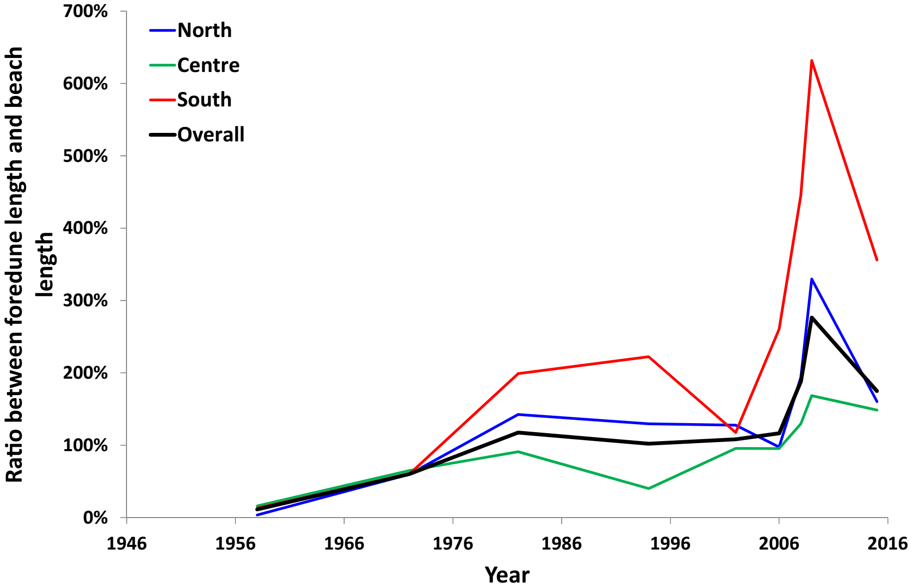

Fig. 7. Development of foredunes along the eastern coast of Moreton Island, shown for the entire coast (“overall”), and for the northern, central and southern stretches of the eastern coast. Data from 2009 were based on Lidar data, which enabled better delineation of foredunes than from the aerial photos and satellite images, where it is more difficult to identify remnant dune ridges as time passes by Levin et al. (2009). Foredunes are quantified using the ratio between foredune length and beach length, with values above 100% indicating more than one foredune present for a certain beach section.

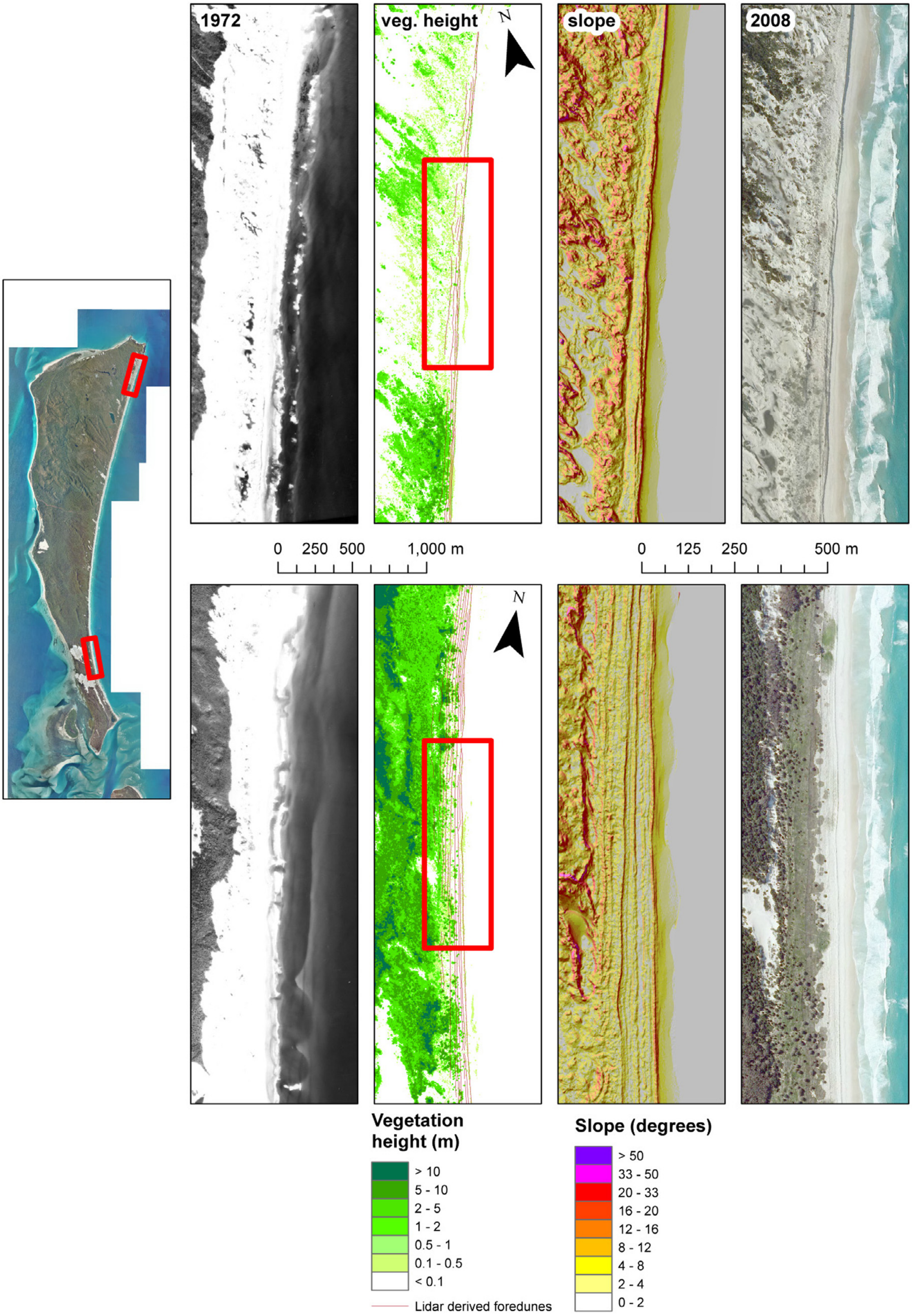

Fig. 8. A focus on foredunes in the northeast (top) and southeast (bottom) of Moreton Island, showing from left to right: early development of foredunes in 1972; Lidar derived vegetation height as of 2009; Lidar derived surface slope as of 2009; fully developed foredunes in 2008.

(Figs. 7 and 8). Beach sections where foredunes started developing already in the late 1950s, were more likely to have a greater number of parallel foredune ridges observed on the 2009 Lidar image (Fig. 9; $R^2 = 0.36$, $p < 0.001$). In addition, dune fields in which foredunes developed earlier, were more likely to stabilize at a faster rate (Fig. S1).

While the coastline was quite dynamic until the late 1960s, since the early 1970s the position of the coastline was more stable, with the southern stretches of eastern coastline of Moreton Island steadily prograding (moving towards the sea) between 1 and 2 m/year (Fig. 10). The steady progradation of the southern coastline of Moreton Island was apparently related to longshore sediment transport from the south, from the direction of North Stradbroke Island (see Supplementary movie showing Landsat images between the years 1984 and 2012, based on Google Earth Engine Timelapse: https://earthengine.google.com/timelapse/).

Monthly and annual DP and RDP values as measured in Cape Moreton station were high throughout the period for which data are available (from 1957 onwards; Fig. 11A). Annual DP and RDP showed a statistically significant increase with time ($Rs = 0.639$ and 0.617, respectively, both at $p < 0.001$), with annual RDP values mainly increasing since the late 1990s (Fig. 11A). As a consequence of the increase in wind power, values of Tsoar's (2005) mobility index increased with time ($Rs = 0.636$, $p < 0.0001$; Kendall's Tau = 0.444, $p < 0.0001$), in conjunction with a decrease in annual rainfall since the 1970s ($Rs = -0.625$, $p < 0.0001$; Kendall's

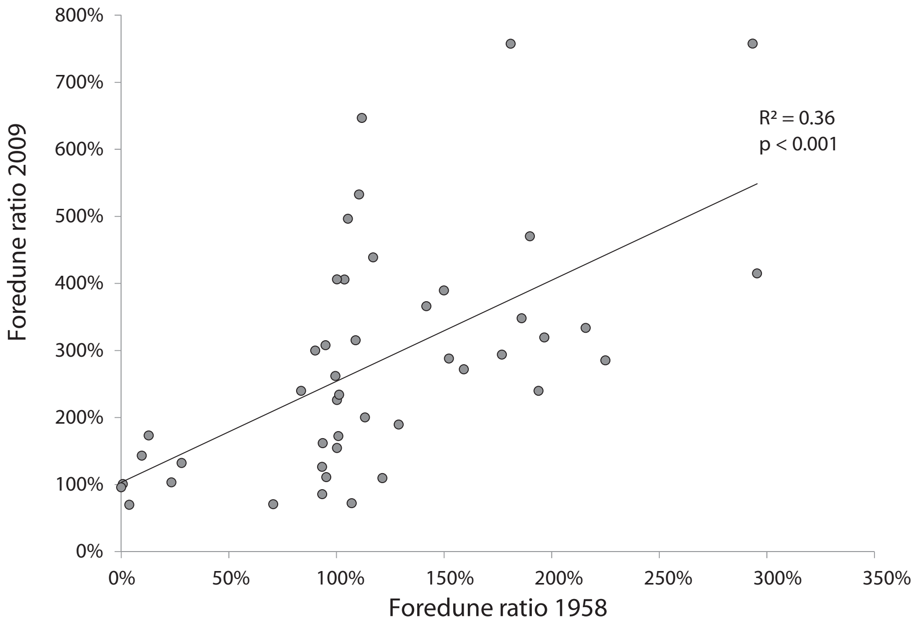

Fig. 9. The correspondence between foredune ratio (the ratio between the total length of foredune ridges and the length of the beach, in front of a coastal dune field) in 1958 and foredune ratio on the 2009 Lidar image.

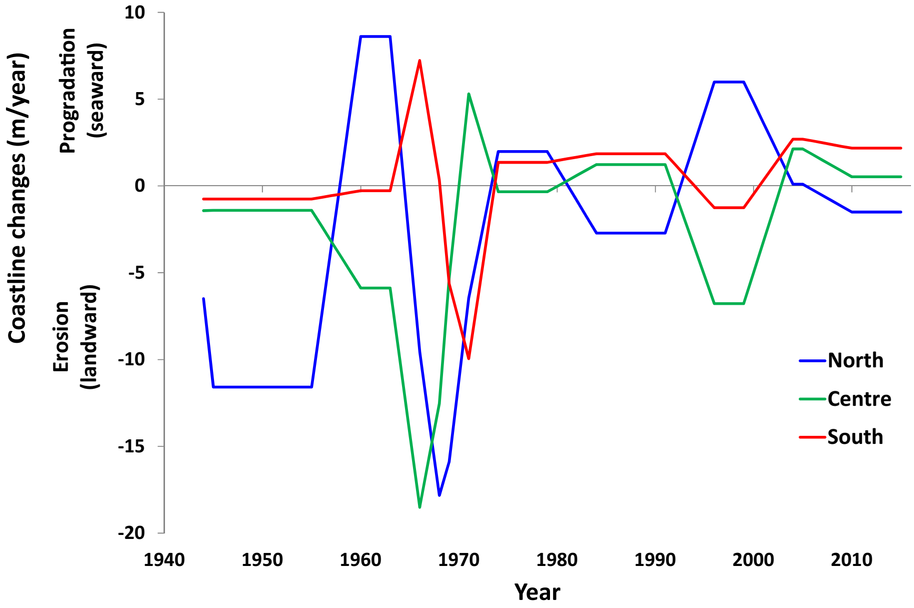

Fig. 10. Changes in the position of the coastline along the eastern coast of Moreton Island, shown for the northern, central and southern stretches of the eastern coast. Positive changes indicate coastal progradation (build up), whereas negative changes indicate coastal erosion.

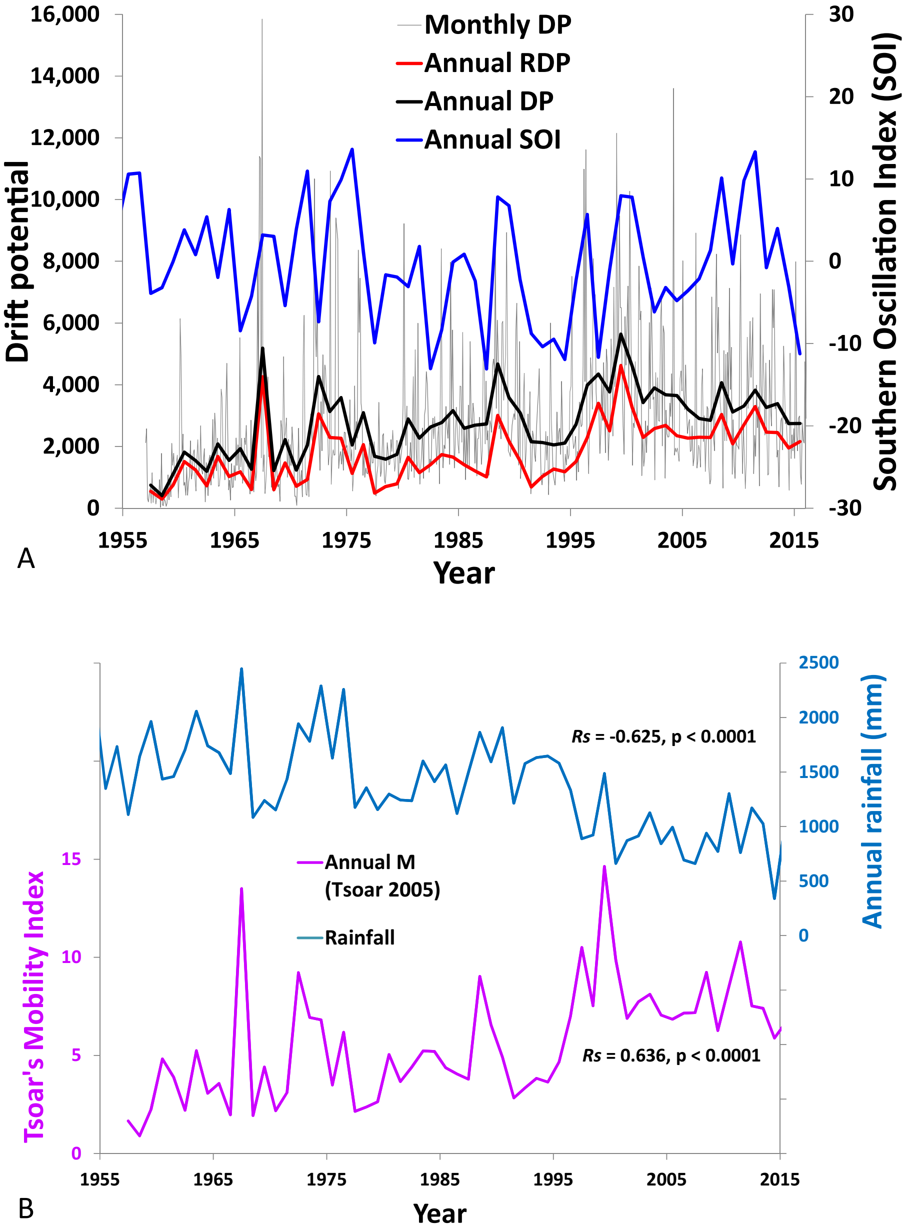

Fig. 11. (A) Monthly and annual values of DP and RDP as measured in the Cape Moreton meteorological station, and annual values of the Southern Oscillation Index (SOI). (B) Rainfall as measured in Cape Moreton (from 1945 onwards), and the mobility index of Tsoar (2005).

Tau = −0.425, $p < 0.0001$; Fig. 11B). Annual values of mean and maximum significant wave height showed a statistically significant increase with time (for the period 1977–2015; $Rs = 0.578$ and 0.767, respectively, both at $p < 0.001$; Fig. 12). Annual mean and maximum significant wave height were positively correlated with annual RDP values ($R_S = 0.689$ and 0.694, respectively, both at $p < 0.001$). While wind and wave directions did not vary significantly with time, wind directionality (RDP/DP) was below 0.6 (indicating a wind regime which is not unidirectional) in 68% of the years between 1966 and 1996, and in 77% of the years between 1975 and 1996 (Fig. 13). Annual values of the Southern Oscillation Index (SOI) were positively correlated with values of annual DP ($R = 0.557$, $p < 0.001$), annual RDP ($R = 0.573$, $p < 0.001$), annual RDP/DP ($R = 0.457$, $p = 0.003$) and mean annual significant wave height ($R = 0.409$, $p = 0.01$), between the years 1977 and 2015 (Figs. 11 and 13), with higher waves, stronger winds and a more unidirectional wind regime associated with La-Niña periods. The period when wind directionality increased (i.e., RDP/DP values decreased) in the 1960s–70s, coincides with the period when foredunes started emerging and building along the eastern coast of Moreton Island, and with the initiations of stabilization processes of Moreton Island's coastal dunes (decrease in dune movement rate and in bare sand area) (Fig. 14).

4. Discussion

Wind power is often claimed to be one of the major controls on dune activity, in areas where rainfall is not a limitation for vegetation growth, and where human activity is minimal (Tsoar, 2005). Indeed, in the case of nearby Fraser Island, coastal dune stabilization has been attributed to a decrease in tropical cyclone activity and correspondingly to a decrease in drift potential (DP; Levin, 2011). However, in the present study we found that DP values

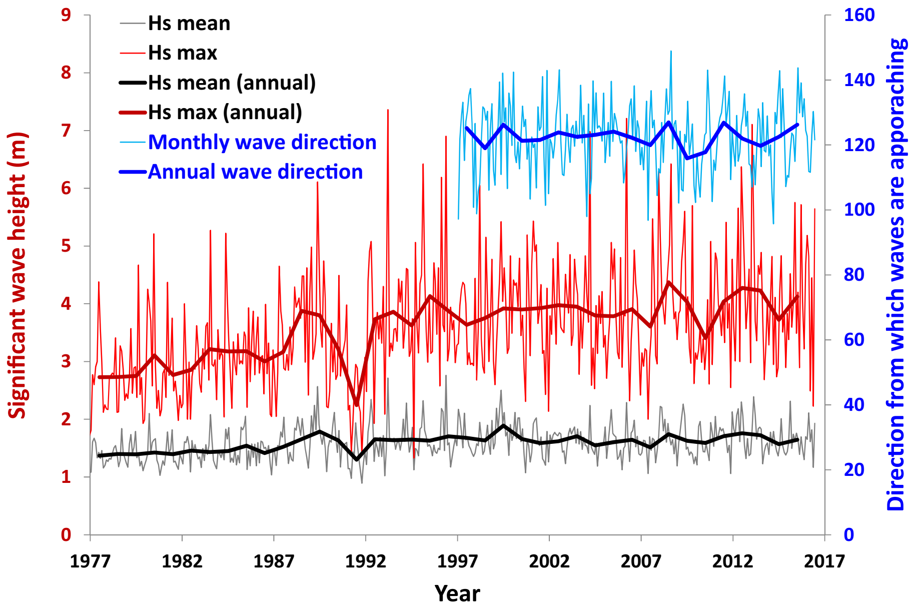

Fig. 12. Monthly and annual values of mean and maximum significant wave height (Hs), and of wave direction, as measured by the Brisbane Waverider buoy, southeast of Moreton Island.

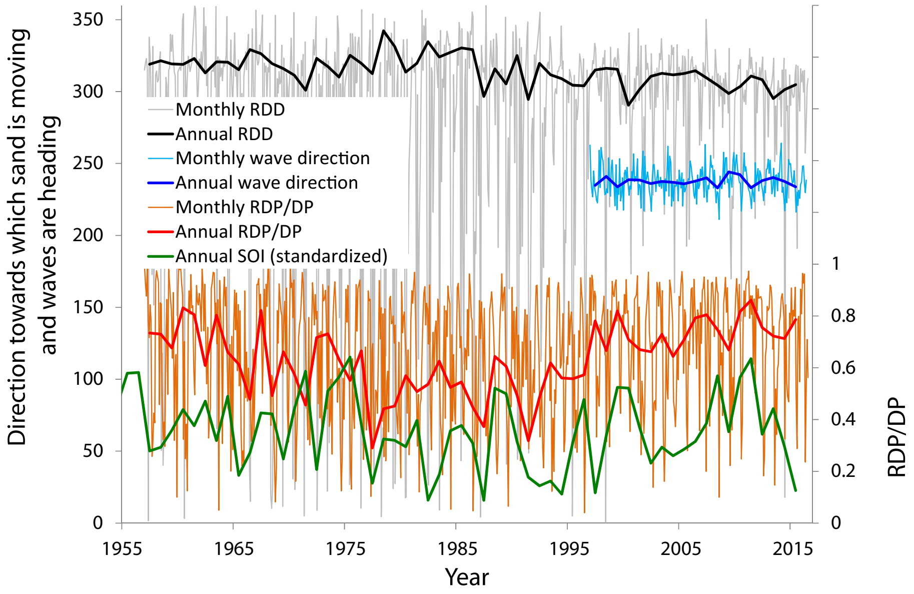

Fig. 13. Monthly and annual wave direction, resultant drift direction (RDD), the RDP/DP ratio (indicating wind directionality), and annual values of the Southern Oscillation Index (SOI; standardized between to ease comparison with RDP/DP).

increased with time, and in spite of the steady increase in wind power, coastal dune fields on Moreton Island are undergoing stabilization. We found that dunes on Moreton Island have started stabilizing (with a decrease in dune movement rates and in bare sand areas) around 1970 (Fig. 14). During the late 1960s – early 1970s wind directionality (RDP/DP) on Moreton Island (as measured at the Cape Moreton meteorological station) increased. According to Tsoar (2005), lower RDP/DP values are associated with decreased dune activity. However, this increase in the variability of wind directionality was not very high, and values of Tsoar's (2005) mobility index present a steady increase in the potential for dune activity.

The stabilization process of active dunes on Moreton Island corresponds with the development of a continuous series of foredunes along the eastern coast of the island, thus disconnecting the coastal dune fields from additional sand supply from the beach. The same process has been described for Fraser Island, that when a coastal dune field is deprived of sand supply due to the formation of foredunes, it will then start stabilizing (Pye, 1983; Levin, 2011). The formation of a series of parallel foredunes on Moreton Island went on during a period of increased onshore wind power and decreased variability in wind directionality, two factors which are known to contribute to the formation of foredunes (Miot da Silva and Hesp, 2010; Durán and Moore, 2013). While foredunes may be washed over and obliterated during strong storms (Hosier and Cleary, 1977; McLean and Shen, 2006), this has not been observed as a wide phenomenon on Moreton Island, probably because the island is not located within the track of tropical cyclones. Although increasing exposure to wave and wind energy was reported to decrease vegetation cover on foredunes (Miot da Silva et al.,

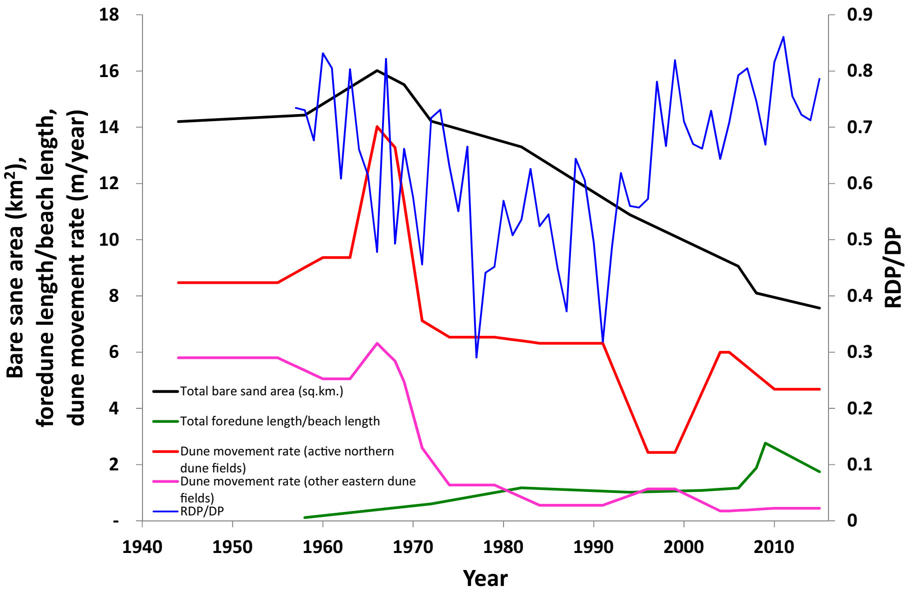

Fig. 14. Correspondence in time between the increase in wind directionality (i.e., decrease in RDP/DP values) in the 1960s–70s, and the increase in foredune length and dune stabilization processes.

2008), foredunes continued to develop on Moreton Island in the past decades.

While wave data was only available from 1977 onwards, it seems that significant wave height was lower in the late 1970s and early 1980s. It may be assumed that wave height was even lower also during the 1960s and 1970s (due to the correlation between annual significant wave height and annual wind power, with annual DP and RDP values being generally lower in the 1960s), when foredunes started forming. Longer term studies of beach profiles and widths on the eastern coast of Australia have recorded prolonged periods of stability and onshore movement of sandbars matching these periods in the later 1970s and early 1980s (Phinn and Hastings, 1995; Ranasinghe et al., 2004). The stable conditions in these years, correspond to El-Niño periods, and result in increased beach widths, which would favour conditions to enable foredune development.

While we do not have supporting data to explain why did the foredunes on Moreton Island start to develop in the 1960s, once a system of foredunes had been established on Moreton Island, it is clear that there was a phase shift in dune activity on Moreton Island, from a system of active coastal dunes to a system of stabilizing coastal dunes. Overall it is more likely for dunes to stabilize than to become reactivated. This was first suggested on a theoretical basis by Tsoar (2005) as part of the hysteretic nature of dune activity, where high intensity disturbances are required to reactivate stabilized dunes. In addition, the likelihood of dune fields to stabilize was described as part of the life cycle of active dunes, with smaller transgressive dune fields predicted to stabilize faster than larger ones, in a spatiotemporal model (Yizhaq et al., 2013), a pattern which was also found here.

Dune stabilization rates varied between dune fields located in different parts of the island, with dune fields situated at the northern part of the Moreton Island's eastern coast still being active, similar to the sand hills in the south of the island. The transgressive dune fields on the eastern side of Moreton Island are actually climbing over previous generations of vegetation dunes. The steeper is the prevailing topography, it can be expected that there will be less saltation (Tsoar and Blumberg, 1991; Tsoar et al., 1996), which may be an additional reason for the faster stabilization of the dunes located on the center of the eastern coast of Moreton Island, where topography is steeper (Fig. 2). An additional explanation for the northern dunes on Moreton Island's eastern coast remaining more active, may be related to beach orientation, as the resultant drift direction is more perpendicular to the beach there. As found by Miot da Silva and Hesp (2010) shoreline orientation has a major role in directing wave energy, and higher potential RDP was correlated with foredune volume.

The spatial variability in dune stabilization rates may also be partially explained by the spatial variability of the wind regime, which can differ over relatively short distances (Hesp et al., 2007), as is the case on Moreton Island (Levin et al., 2014). The southern part of Moreton Island is much narrower and lower in elevation than the islands' center (Fig. 2), and thus surface roughness is lower in the south of Moreton Island. Additionally the dunes of the Big and Little Sand Hills are also exposed to western winds coming from Moreton Bay during winter months, winds which do not affect the dunes on the eastern side of the island (Levin et al., 2014). While wind power, as archived based on the measurements at Cape Moreton, has steadily increased with time, Levin et al. (2014) demonstrated that this station does not represent well the wind regime in all parts of the island. In addition, as the initial size of the two southern dune fields is much larger, they can be expected to stabilize at a slower rate than the smaller dune fields along the eastern side of Moreton Island (Yizhaq et al., 2013). The greater abundance of foredunes in the southern part of Moreton Island can be associated with the more consistent beach progradation over there (which is enhanced by sand drift from the North Stradbroke Island, to the south of Moreton Island). This finding corresponds with empirical measurements (Saye et al., 2005) and with numeric models (Durán and Moore, 2013), who reported that accreting dunes are associated with wider beaches, low angle beaches. Further research is needed to understand the complex relationships between waves, sediment budget and wind, and the conditions under which foredunes will start developing on beaches were no foredunes were previously found.

5. Conclusions

Using a combination of remote sensing techniques and climatic time series, we examined the climatic controls of wind regime and wave height on geomorphological properties of foredunes and the stabilization process of transgressive dune fields. Studies of dune stabilization recognize the existence of lag times between changes in climatic variables and the response of the dune system, partly because of the time required for vegetation to become established and modify sand drift. However, such studies often emphasize the role of wind power on dune activity. Here we found that the establishment of foredunes played a major role in switching the system from that of active transgressive dunes, to stabilizing dunes, despite an increase in wind power. The location of the foredunes between the beach and the dunes, highlights the need to better understand the effects of changes in wave climate, which is modulated by climatic oscillations such as the El Niño Southern Oscillation, on dune stabilization and reactivation processes.

Acknowledgments

We thank the anonymous reviewers and the Editor whose suggestions contributed to the manuscript. We thank Arnon Accad and Tim Ryan, from the Queensland Herbarium for assistance in obtaining historical aerial photos and orthophotos.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeolia.2017.03.005.

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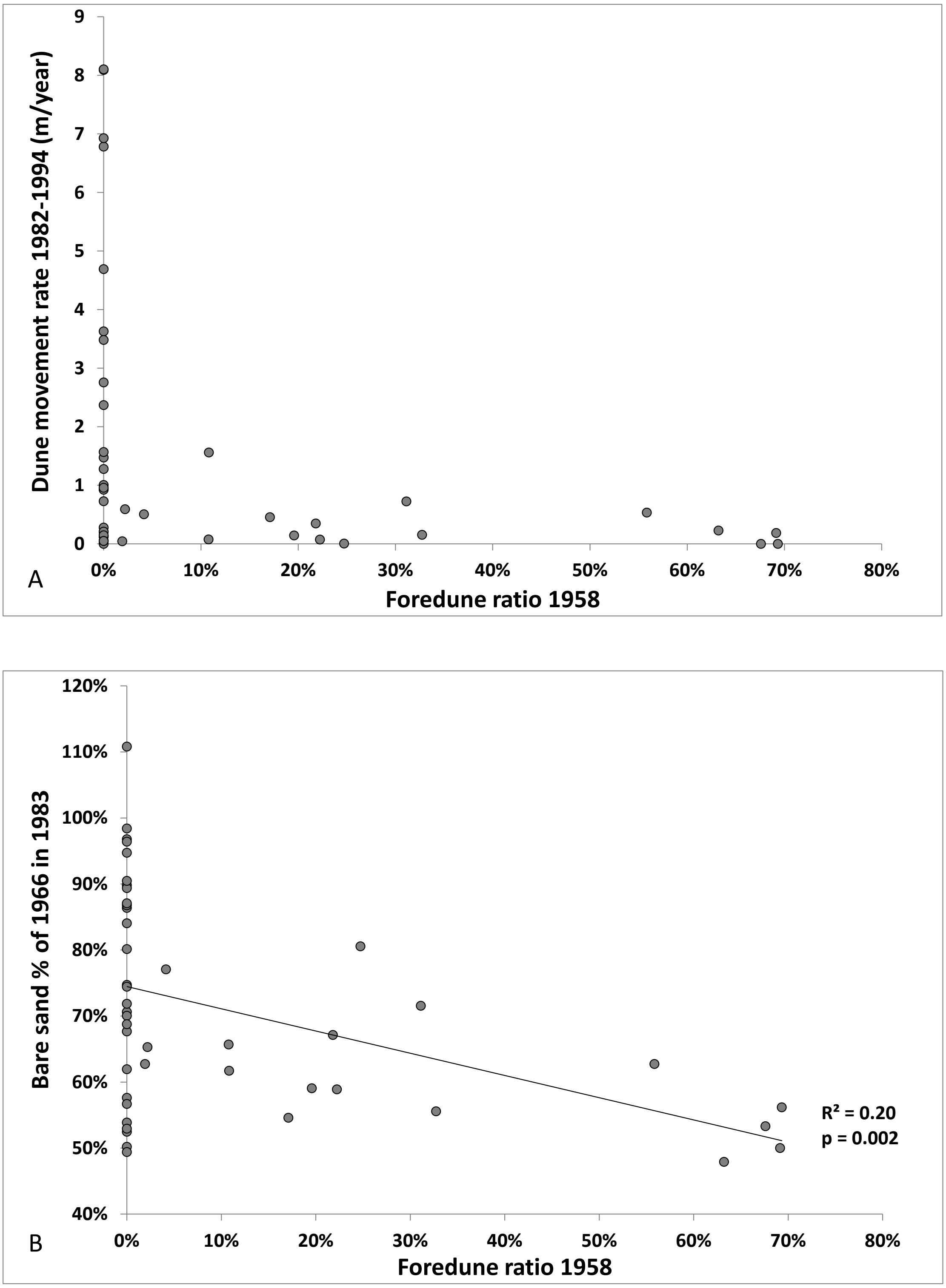

Figure S1: Dune movement rate (1982-1994) and the percent of bare sand area in 1983 (relative to 1966), as a function of foredune ratio in 1958 (the ratio between the total length of foredune ridges and the length of the beach, in front of a coastal dune field).