High-resolution remapping of the coastal dune fields of south east Queensland, Australia: a morphometric approach

Nicholas R. Patton, Daniel Ellerton, and James Shulmeister
School of Earth and Environmental Sciences, University of Queensland, St Lucia, Australia

ABSTRACT
The sand islands and shore-attached dune fields of south east Queensland form the world’s oldest and largest coastal sand dune system. Here we present updated morphological maps for the dune fields based on topographic expression and geomorphic relationships. Individual dunes were delineated using high-resolution elevation data and were grouped into morphosequences based on the elevation, drainage characteristics and slope characteristics of the individual dunes. The slope characteristics focused on high resolution derived slope-curvature and slope-elevation parameters. Morphosequences were recognised from cross-cutting relationships and relative position in the dune field. Our method was developed for the Cooloola Sand Mass and then applied to Fraser Island, Moreton Island and North Stradbroke Island, the other major sand islands in south east Queensland. In total, five Holocene and four Pleistocene units have been identified. The new mapping underpins current work on the geomorphic evolution of the dune fields.

1. Introduction

The dune fields of south east Queensland comprise one of the largest coastal sand dune systems in the world, incorporating North Stradbroke (Minjerribah), Moreton (Moorgumpin), Bribie and Fraser (K’gari) Islands and the shore-attached Cooloola Sand Mass (Miot da Silva & Shulmeister, 2016; Ward, 2006). They include the world’s largest sand island (Fraser Island – 1820 km²) and are associated with the longest downdrift sand accumulation system in the world (Figure 1). The net northward longshore sand transport is approximately 500,000 m³/year, with the sand sourced from the rivers of central New South Wales more than 1000 km south of Fraser Island (Boyd, Ruming, Goodwin, Sandstrom, & Schröder-Adams, 2008; Roy & Thom, 1981). The dune fields, especially the Cooloola Sand Mass, have been the target of much research, primarily on the soils and biota. The giant podzols of Cooloola are regarded as some of the thickest and most developed soils in the world (Thompson, 1981, 1983). The dune fields have been previously mapped by Ward (2006) who produced a map of all the major dune sequences. His maps were based on aerial photographs and extensive field-mapping. More recently, the dune fields have become the focus of renewed geochronological (e.g. Brooke, Pietsch, Olley, Sloss, & Cox, 2015; Walker, Lees, Olley, & Thompson, 2018) and paleoenvironmental investigations (e.g. Barr et al., 2013; Cadd et al., 2018; Chang et al., 2015; Levin, 2011; Levin, Jablon, Phinn, & Collins, 2017; Moss, Tibby, Petherick, McGowan, & Barr, 2013; Petherick, McGowan, & Moss, 2008). Previous investigations of the south east Queensland dune fields have defined dune building phases by the soil landscapes (Chen et al., 2015; Thompson, 1981), the periods of active deposition (Tejan-Kella et al., 1990) and morpho-stratigraphic relationships (Ward, 2006). Here, we use geomorphic properties along with these previously used characteristics to describe, identify and map the dune morphosequences of coastal south east Queensland. This study has taken advantage of the improved remotely sensed imagery that is now available for the entire dune fields, most notably complete LiDAR coverage which has permitted a significant refinement of the previous mapping.

Remote sensing has long been an invaluable tool for studying dune fields and has provided researchers with the means to map the global distribution of dune fields (McKee, 1979), study the interaction between sediment supply and wind direction (Roskin, Katra, & Blumberg, 2013; Wasson & Hyde, 1983) and quantify dune morphodynamics (e.g. Ewing & Kocurek, 2010; Hugenholtz & Barchyn, 2010). More recently, LiDAR enables data resolutions down to sub-metre scales and permits the recognition of smaller scale geomorphic features. In the case of sand dunes, it facilitates the recognition of ripples and other small-scale features of dune fields based on topographic expression and geomorphic relationships.
structures on dune surfaces and can be used to track their gradual disappearance with increasing age. We took advantage of such features to examine surface roughness patterns to aid in the individual dune mapping at a much finer scale than was previously possible. This enabled us to distinguish areas of similar geomorphic characteristics within the dune field at a finer scale, thereby enabling us to distinguish late-Holocene units that appear identical on gross morphology. The technique presented in this study provides the foundation for future work to map and quantify phases of dune activity within stable dune fields as well as investigate how dune landscapes evolve through time.

2. Study site

The sand islands of south east Queensland form an extensive series of coastal sand dune fields that include Moreton Island (Moorgumpin) and North Stradbroke Island (Minjerribah) to the south and the Great Sandy Region to the north which comprises of the Cooloola Sand Mass (presently attached to the mainland) and Fraser Island (K’gari) (Figure 1). North Stradbroke Island, situated offshore of Brisbane at ~27.4°S forms the southern extent of these dune systems while Fraser Island forms the northern extent at ~25.5°S. The dune fields are large, with the Cooloola Sand Mass, Moreton Island and Stradbroke Island reaching lengths of approximately 40 km and widths of approximately 12 km. Fraser Island is significantly larger with a length of approximately 120 km and an average width of 24 km. The total land area of the dune fields is ~2350 km² and elevation ranges up to 285 m above sea level.

The entire region has a humid subtropical climate (Köppen classification Cfa) with warm, wet summers and mild and dry winters (Peel, Finlayson, & McMahon, 2007). Mean annual precipitation varies from ~1200 to ~1700 mm. February and March are the wettest months. South easterly winds persist year round with a more southerly component during the winter months and north-easterly winds occur during the spring (BOM, 2017).

The dune fields are notable for containing the world’s largest area of rainforest on tall sand dunes (Fraser Island) (Gontz et al., 2015; Wardell-Johnson et al., 2015). Vegetation along the coastal eastern margin of the dune fields comprises of coastal shrubland and grasses that can tolerate strong winds and salty conditions. Moving inland, low open woodland gives way to tall open and closed forest with notophyllous
vine forest in the swale areas. Along the western flanks of the dune fields, vegetation is dominated by open shrubland and heath communities (Donders, Wagner, & Visscher, 2006; Gontz et al., 2015; Longmore, 1997; Longmore & Heijnis, 1999).

The dune fields are composed predominantly of stable parabolic dunes with localised blowouts and several small active transgressive dune sheets. The sediments of the dune fields are homogenous, well sorted, and rounded siliceous sands derived from granites and Mesozoic metasediments from the tablelands of eastern New South Wales (Pye, 1983; Roy & Thom, 1981; Thompson, 1981). Bedrock exposures are limited to small rocky outcrops that mostly make up headlands at the northern ends of the dune fields. All of the dune field deposits have formed over successive phases of dune emplacement that have occurred since at least the middle Pleistocene (Pye, 1983; Thompson, 1981; Ward, 2006). The dune emplacements have formed a series of onlapping dune units that increase in age moving away from the present coastline. Ward (2006) recognised nine periods of dune building based on soil development and morphological characteristics. More recently, Walker et al. (2018) identified 10 units at the Cooloola Sand Mass and used single grain optically stimulated luminescence (OSL) dating to identify periods of activity. They found that the oldest units at Cooloola date to about 725 ka, confirming earlier work by Tejan-Kella et al. (1990) and they also observed that dune emplacement has continued episodically.

Soil development across the dune fields ranges from weakly developed podzols to well-developed giant humus podzols that are primarily composed of siliceous sands with <2% heavy minerals, including zircon, rutile and ilmenite (Thompson, 1983). This composition reflects the sand delivered to the coast by the longshore drift system along the east Australian Coast. Marine-derived sands extend to tens of metres below modern sea level (Ball, 1924). Mean grain size ranges between 180 and 210 µm and have high porosity at >600 mm h⁻¹ (Reeve, Thompson, & Fergus, 1985; Thompson & Moore, 1984). Marked increases in soil development occur across the dune sequences with thick A₂ and B horizons developed in older dunes located further inland (Thompson, 1981). Thompson (1981) suggested that there is little indication of large climatic, biotic, or lithological shifts within the dune field as indicated by the consistent shape of the dunes and the lack of deviation from podzol soil-forming trends.

3. Materials and methods

3.1. Mapping assumptions and workflow

Here we assume that all the south east Queensland coastal dune fields are part of the same depositional system and experience a similar formation and evolutionary history (Thompson, 1983; Ward, 2006). All changes in the character of the morphosequences are time dependent such that younger dunes will experience similar perturbations as older dunes, with the length of time since emplacement controlling the overall degree of erosion. This results in a unique erosional and depositional history for each dune morphosequence. In addition, we propose that each dune is systematically moving towards a steady state after its emplacement; that is, topography becomes increasingly uniform or ‘smoother’ with time (Bonetti & Porporato, 2017; Montgomery, 2001). Based on these assumptions we use changes in dune morphological characteristics supported by dune ancillary characteristics to map the dune fields (Figure 2). The Cooloola Sand Mass was the optimal location to establish this method because it contains the most complete dune sequence (Lees, 2006), the most ancillary (e.g. soil, chronology) information and has experienced little human disturbance.

3.2. Individual dune delineation

We utilise high-resolution elevation data, satellite imagery, and historical aerial photographs to identify individual dunes. Principally, we used a 5 m digital elevation model (DEM) derived from Light Detection and Ranging (LiDAR) and 1:5000 digital orthophoto imagery data. Elevation datasets for all areas of interest were obtained from the Digital Elevation Model (DEM) 5 m Grid of Australia created by merging 236 datasets collected between 2001 and 2015. Accuracy of elevation data met the Australian ICSM LiDAR Acquisition Specifications with the vertical and horizontal data having an accuracy of no worse than ±0.30 m and ±0.80 m (95% confidence), respectively.

Orthophoto imagery was acquired through Queensland Globe (QGlobe), with a pixel resolution of 0.25 m and an accuracy of ±1.0 m. In addition, historical aerial photographs were obtained through Queensland Imagery (QImagery) to determine any recent anthropogenic disturbances that may have altered the original topography, such as mining or logging, and provide locations and characteristics of previously visible dunes.

Where little to no anthropogenic disturbances occurred in the landscape, we identified individual dunes through large dune morphological features (>10 m²) such as crests, trailing arms, and the slip face of the depositional lobes. An example of this process is provided in Figure 3. In ArcGIS 10.6 (ESRI, Redlands, CA) we delineated each dune at the base of their ridges and crests utilising elevation and slope rasters. For all points, slope was calculated using change in elevation in downhill direction which is presented here as degree slope. Curvature was obtained by the rate of change in slope, at a fixed position in all directions and multiplied by −100 to remove the negative curvature convention (i.e. Patton, Lohse, Godsey, Crosby, & Seyfried, 2018).
3.3. Dune morphosequence delineation and supporting evidence

Following individual dune delineation, we categorised dunes into separate morphosequences utilising cross-cutting and geomorphic relationships. The Cooloola Sand Mass forms a classic onlapping dune sequence where dune units become increasingly older from the coast (east) moving inland (west) (Lees, 2006; Walker et al., 2018). In coastal dune fields, onlapping relationships allow us to determine the relative age sequence of the dune emplacements as younger dunes are superimposed on older units. To exemplify this, we measured the shortest mean distance from the furthest inland dune crest to the coast and the mean elevations for each morphosequence.

Where cross-cutting geomorphic relationships are not easily determined due to landscape complexity, we utilise small (<10 m) internal dune features to help delineate each morphosequence by using the topographic expression to ‘fingerprint’ each dune emplacement phase. The surface characteristics of the landscape can be defined by the relative surface texture, drainage patterns and landform elements present. The topographic fingerprint is best observed by combining and manipulating elevation, slope and curvature rasters. This was achieved by overlaying a 70% transparent slope raster with a white to black (low to high) gradient on an elevation raster with a continuous brightness colour ramp (Figure 4). Similar to elevation, we combined a transparent slope raster on a curvature raster with a diverging colour ramp. Due to the normal distribution of curvature around planar surfaces (0 m$^{-1}$) a diverging colour ramp utilising quantile bins, is best suited to emphasise changes from convergent (hollows and valleys) to divergent (ridges and

Figure 2. Schematic flow chart of the mapping and validation procedures for dune morphosequence delineation.
noses) topography (Figure 4). In combination, both rasters act as visual aids to identify the unique fingerprint of each depositional phase.

This approach allows a simple visual comparison between each individual dune, permitting them to be delineated into separate morphosequence units; however, some discrepancies may still occur. Where internal dune features are limited or difficult to interpret due to depositional complexity, changes in base level or proximity to higher energy environments (such as Tin Can Bay, Noosa River or the Tasman Sea) (see Figure 1) we used the available soil (Thompson, 1983), vegetation (Queensland Herbarium) and drainage direction data to complement and support our interpretations. Soil information helps provide a relative age sequence of the dunes based on the increasing degree of pedogenesis.

Figure 3. Visual sequence of dune delineation using part of North Stradbroke Island as an example. Panel a shows elevation from the DEM. Panel b shows the derived slope map from the DEM. Panel c is an air photo of the same area with dune outlines overlaid. It highlights the areas of human disturbance (mining). Panel d is an example of historical air photo that allows us to map areas currently disturbed and modern dunes.
with time (Chen et al., 2015). Field data was also used to confirm the onlapping relationships of each dune morphosequence (Our unpublished data).

We have opted to use the naming convention of Ward (2006) for the dune morphosequences. We use this convention rather than the numerical convention employed by Thompson (1981) and Walker et al. (2018), as using a number based system can lead to issues if a new unit is identified or an existing unit is eliminated, as happened in our new mapping.

3.4. Mapping validation and supporting evidence

To validate our approach for delineating dune field morphosequences, we focus on the Cooloola Sand Mass. Validation was achieved by cross referencing each dune morphosequence with available unpublished chronological data and Walker et al. (2018). This was done to confirm the age relationships of each morphosequence using the weighted mean of the OSL ages. Each morphosequence was plotted as the explanatory variable against mean distance from coast, mean elevation and extracted topographic indices. The topographic indices for each dune morphosequence were determined from ArcGIS zonal statistics as the mean and standard deviation of slope and the standard deviation of curvature. To eliminate any discrepancies that may have altered the original topographic expression, portions of the landscape such as anthropogenic disturbances (e.g. roads), rock outcrops, and free-standing water were identified and removed from the analyses, along with an additional 10 m buffer.

A complementary assessment of our mapping efforts involved a comparison to the traditional, independently derived geomorphological map by Ward (2006). His study primarily used aerial imagery, soil data and field observations to map the Cooloola Sand Mass and extrapolated his findings across the remaining south east Queensland dune fields. We evaluated and compared each matching morphosequence between the studies. We acknowledge that this is by no means a true validation, however, comparisons of each map provide novel insight into the two techniques. To achieve this, Ward’s map was digitised in the ArcGIS georeferencing tool and we report the percent similarity of matching dune morphosequences.

3.5. Mapping extrapolation

We extrapolated our approach to the adjacent dune fields. In all dune fields, we delineated individual dunes and then grouped into the appropriate morphosequences based on the same topographic expression and geomorphic relationships seen at the Cooloola Sand Mass.
4. Results

4.1. Cooloola morphosequence delineation and validation

We recognise nine dune morphosequences at the Cooloola Sand Mass composed of five Holocene (Modern, Cape, Station Hill, Freshwater and Triangle Cliff) and four Pleistocene units (Bowarrady, Yankee Jack, Awinya and Cooloola) see main map (Figures 5 and 6). This study recognises an additional Holocene unit that was not mapped by Ward (2006), which we have named Freshwater. We have also removed one of Ward’s Pleistocene units, Garawongera, which was not found in this study. Holocene morphosequences are characterised by decreases in crest sharpness and surface roughness, increases in podzolisation,
They display little to no stream incision. Pleistocene units exhibit similar trends but all show evidence of increasing fluvial incision and decreasing crest elevation with age (Table 1).

Our results are consistent with the independent chronology of the Cooloola dune field based on OSL ages from both Walker et al., (2018) and our unpublished dataset. The weighted mean and standard error age for Cape, Station Hill, Freshwater, Triangle Cliff, Yankee Jack and Awinya units are 0.4 ± 0.04 ka, 0.8 ± 0.1 ka, 4.1 ± 0.24 ka, 7.8 ± 0.26 ka, 132 ± 3.9 ka, 648 ± 32 ka, respectively. It should be noted here that OSL dates the last time sand grains were exposed to sunlight and these ages likely reflect the final phase of dune development rather than the time the dune was first initiated. It is likely that the time of initiation predates these ages. The Modern dunes are dunes that are currently active or were visibly active in historical imagery as shown by bare earth (lacking vegetation). The lack of original dune morphology suggests that the Cooloola unit has been extensively reworked, but is older than the Awinya unit (>~650 ka). The Bowarrady unit is recognised in our mapping but no age control is available for this dune morphosequence. Based on its morphostratigraphic position, emplacement

elevation, and distance to coast with increasing age. They display little to no stream incision. Pleistocene units exhibit similar trends but all show evidence of increasing fluvial incision and decreasing crest elevation with age (Table 1).

Our results are consistent with the independent chronology of the Cooloola dune field based on OSL ages from both Walker et al., (2018) and our unpublished dataset. The weighted mean and standard error age for Cape, Station Hill, Freshwater, Triangle Cliff, Yankee Jack and Awinya units are 0.4 ± 0.04 ka, 0.8 ± 0.1 ka, 4.1 ± 0.24 ka, 7.8 ± 0.26 ka, 132 ± 3.9 ka, 648 ± 32 ka, respectively. It should be noted here that OSL dates the last time sand grains were exposed to sunlight and these ages likely reflect the final phase of dune development rather than the time the dune was first initiated. It is likely that the time of initiation predates these ages. The Modern dunes are dunes that are currently active or were visibly active in historical imagery as shown by bare earth (lacking vegetation). The lack of original dune morphology suggests that the Cooloola unit has been extensively reworked, but is older than the Awinya unit (>~650 ka). The Bowarrady unit is recognised in our mapping but no age control is available for this dune morphosequence. Based on its morphostratigraphic position, emplacement

Figure 6. On the left-hand side panels a–d display the final maps for each of the dune fields. Panel a: Fraser Island. Panel b: The Cooloola Sand Mass. Panel c: Moreton Island. Panel d: North Stradbroke Island. Dune fields are not to scale. Panel e contains six graphs showing (i) percent land area for each unit; (ii) mean distance from coast, (iii) mean elevation, (iv) mean slope; (v) standard deviation of slope; (vi) standard deviation of curvature. The black line represents the mean values for all dune fields. Note that in all dune fields the parameters follow the same trends. Also note that for geomorphic characteristics there is a general progression from youngest to oldest morphosequences.
occurred between the Yankee Jack and Triangle Cliff units and based on its morphology, the unit is clearly Pleistocene, as suggested by Ward (2006).

We observe that 90.3% and 97.8% similarity of our Holocene and Pleistocene mapped units, respectively, when compared to the Holocene and Pleistocene boundaries of the original mapping by Ward (2006). Direct comparisons of each morphosequence are complicated by the change in the number of units but we observe 5.3% Modern, 57.6% Cape, 21.4% Station Hill, 66.0% Triangle Cliff, 0% Bowarrady, 71.2% Yankee Jack, 70.7% Awinya, and 98.2% Cooloola congruence between our study and Ward’s (2006). The new mapping of the Cooloola dune field agrees well with the chronology of the dune systems and is largely consistent with past mapping efforts, but provides increased resolution, especially in the Holocene dune units.

4.2. Mapping extrapolation

Like Ward (2006), we extrapolated our morphosequence units across the south east Queensland coastal dune fields. When plotting the topographic indices and geomorphic characteristics against each morphosequence unit, we observe similar landscape relationships between all study sites (Figure 6). The Cooloola Sand Mass contains all of the morphosequences recognised at other dune fields while none of the other dune fields contain the whole sequence. This confirms that the Cooloola Sand Mass is the most complete dune field sequence in south east Queensland and reinforces the need for conservation of this dune field.

5. Discussion

5.1. Geomorphic evolution—foundation of this approach

Our mapping is based on the fundamental concept that all landforms are evolving towards a topographic steady-state, where the balance between processes which create topography and the processes that destroy it are equal and landforms are converging towards the local base level (Willett, Slingerland, & Hovius, 2001). This assumption can be problematic in dune fields as dunes can be easily reworked following a perturbation (Hugenholtz & Wolfe, 2005; Tsoar, 2005), especially in coastal environments (Hesp, 2002). The coastal dunes of south east Queensland show evidence of long term stability despite the deep podsolisation, extensive incision and great antiquity of the Pleistocene units (Lees, 2006; Tejan-Kella et al., 1990; Walker et al., 2018). Following the earliest dune building events, subsequent phases of activation have not fully overrun and reworked previous deposits due to the high elevation and steep slopes of the antecedent topography. It is very likely that there have been periods of reworking
(Walker et al., 2018), however, we argue that this has been more local and has not lead to the complete destruction of previous units. The patterns that we observed from our morphometric analyses at the Cooloola Sand Mass, indicates that these assumptions are reasonable and that, especially in the Holocene dune sequences, the approach allows us a better discrimination of dune units than was previously possible (Figure 5). Consistent with the Cooloola Sand Mass, we observe the same topographic patterns across the south east Queensland dune fields, indicating that our assumptions are reasonable and that all the dune fields are part of the same depositional system (Figure 6).

The previous mapping effort by Ward (2006) successfully delineated dune units based on cross-cutting relationships and large-scale features. This can be seen in the similarity of the Holocene and Pleistocene boundaries in both studies (Figure 5; panels b and c). Where dune units are separated by a significant gap in time (e.g. Awinya and Yankee Jack) he was also able to accurately distinguish between the units. However, limitations with his map occurred in areas with complex terrain, dense vegetation cover and/or where dune units were very similar in age. Where these conditions occurred his maps became less reliable. Our approach helps to improve and update the geomorphic mapping. For example, along the north eastern boundary of the Cooloola Sand Mass where significant dune onlapping and dense vegetation occurs, Ward mapped the entire area as Cape and Station Hill, whereas we were able to individually delineate all Holocene morphosequences in this area.

With respect to limitations of this work, the main constraints are around the manual nature of dune delineation which makes the procedure quite time-consuming. There are specific challenges in areas of complex topography because the mapping requires the operator to identify individual dunes. In areas of heavy drainage dissection or complex dune interactions, this may not always be accurate and depends on the familiarity of the operator with the dune forms. Only a few small areas of the dune field are affected by this phenomenon.

In order to apply this method to other systems, high-resolution elevation data are needed along with an understanding of the processes dominating the landscape. How changes to base level, climate and antecedent topography have influenced the depositional and erosional history is important to understand the patterns observed. An example of this is the role of pre-existing topography on dune unit extent. In areas where high dunes are preserved (e.g. The Cooloola Sand Mass) younger dune units are compressed, as they need energy to migrate up and over the older systems. In contrast, in north-central Fraser Island, early Holocene dunes propagated onto a lower topography and succeeded in migrating many kilometres to the west.

6. Conclusion

Here we have presented a novel method to interpret and delineate dune morphosequences across the coastal dune fields of south east Queensland, Australia based on work from the Cooloola Sand Mass. This study combined traditional approaches with the assumption that landscapes are systematically smoothing through time. We used two primary parameters to undertake this work, topographic expression and geomorphic relationships to define the morphosequences. The mapped units were validated using chronology, topographic indices and field observations. Using these parameters we have been able to successfully sub-divide the dunes into five Holocene and four Pleistocene units.

The mapping approach presented in this study has advantages over visual mapping of the dune morphosequences in that it is (a) semi-objective and (b) could be automated. Based on our analyses, it is likely to be more robust than traditional mapping. Future coastal dune field studies can use the techniques we provide here as a first-order approach to delineate landforms based on relative age. In addition, we were able to extrapolate with confidence across the entire south east Queensland dune fields into areas with little to no previous chronological information. The mapping will help underpin ongoing paleoclimate and geomorphological research in the south east Queensland dune fields.

Software

ESRI ArcGIS 10.6 was used to georeference imagery, digitise, extract data using zonal statistics and generate the morphometric map. Queensland Globe (QGlobe) and Queensland Imagery (QImagery) was utilised for viewing orthophoto imagery and historic photographs.

Acknowledgements

The field mapping at Cooloola was undertaken using permit WITK15791415. We also acknowledge the assistance provided to us by the National Parks and Wildlife Service. Natural Resources and Mines, Queensland Government, Queensland Globe, licensed under Creative Commons Attribution 4.0 sourced on 20th December 2018. We acknowledge the traditional owners of Fraser Island (K’gari), Cooloola, Moreton Island (Moorgumpin) and North Stradbroke Island (Minjerribah) and elders past, present and emerging.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Funding for this study was provided by the Australian Research Council (ARC) grant number DP150101513.
References

Ball, L. E., (1924). Report on oil prospecting, near Teewantin. Queensland Government Mining Journal, 25, 354–360.
Barr, C., Tibby, J., Marshall, J. C., McGregor, G. B., Moss, P. T., Halverson, G. P., & Fluin, J. (2013). Combining monitoring, models and palaeolimnology to assess ecosystem response to environmental change at monthly to millennial timescales: The stability of Blue Lake, North Stradbroke Island, Australia. Freshwater Biology, 58(8), 1614–1630.

BOM. (2017). Climate data online [online] (Vol. 2017), Australian Government Bureau of Meteorology.
Bonomi, S., & Porporato, A. (2017). On the dynamic smoothing of mountains. Geophysical Research Letters, 44, 5531–5539.

Boyd, R., Ruming, K., Goodwin, I., Sandstrom, M., & Schröder-Adams, C. (2008). Highstand transport of coastal sand to the deep ocean: A case study from Fraser Island, southeast Australia. Geology, 36(1), 15–18.

Brooke, B. P., Pietsch, T. J., Olley, J. M., Sloss, C. R., & Cox, M. E. (2015). A preliminary OSL chronology for coastal dunes on Moreton Island, Queensland, Australia — marginal deposits of A large-scale quaternary shelf sediment system. Continental Shelf Research, 105, 79–94.

Cadd, H. R., Tibby, J., Barr, C., Tyler, J., Unger, L., Leng, M. J., … Baldock, J. (2018). Development of a southern hemisphere subtropical wetland (Welsby Lagoon, south-east Queensland, Australia) through the last glacial cycle. Quaternary Science Reviews, 202, 53–65.

Chang, J. C., Shulmeister, J., Woodward, C., Steinberger, L., Tibby, J., & Barr, C. J. Q. S. R. (2015). A chironomid-inferred summer temperature reconstruction from subtropical Australia during the last glacial maximum (LGM) and the last deglaciation. Quaternary Science Reviews, 122, 282–292.

Chen, C. R., Hou, E. Q., Condon, L. M., Bacon, G., Esfandbod, M., Olley, J., & Turner, B. L. (2015). Soil phosphorus fractionation and nutrient dynamics along the Cooloola coastal dune chronosequence, southern Queensland, Australia. Geoderm, 257–258, 4–13.

Donders, T. H., Wagner, F., & Visscher, H. (2006). Late Pleistocene and Holocene subtropical vegetation dynamics recorded in perched lake deposits on Fraser Island, Queensland, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 241(3–4), 417–439.

Ellerton, D., Rittenour, T., Miot da Silva, G., Gontz, A., Shulmeister, J., Hesp, P., … Welsh, K. J. (2018). Late-Holocene cliff-top blowout activation and evolution in the Cooloola Sand Mass, south-east Queensland, Australia. The Holocene, 28(11), 1697–1711.

Ewing, R., & Kocurek, G. (2010). Aeolian dune interactions and dune-field pattern formation: White Sands Dune Field, New Mexico. Sedimentology, 57(5), 1199–1219.

Gontz, A. M., Moss, P. T., Sloss, C. R., Petherick, I. M., McCallum, A., & Shapland, F. (2015). Understanding past climate variation and environmental change for the future of an iconic landscape – K’gari Fraser Island, Queensland, Australia. Australasian Journal of Environmental Management, 22(2), 105–123.

Hesp, P. (2002). Foredunes and blowouts: Initiation, geomorphology and dynamics. Geomorphology, 48, 245–268.

Hugenholtz, C., & Barchyn, T. (2010). Spatial analysis of sand dunes with a new global topographic dataset: New approaches and opportunities. Earth Surface Processes and Landforms, 35(8), 986–992.

Hugenholtz, C. H., & Wolfe, S. A. (2005). Biogeomorphic model of dune field formation and stabilization on the northern great Plains. Geomorphology, 70, 53–70.

Lees, B. G. (2006). Timing and formation of coastal dunes in northern and eastern Australia. Journal of Coastal Research, 22(1), 78–89.

Levin, N. (2011). Climate-driven changes in tropical cyclone intensity shape dune activity on earth’s largest sand island. Geomorphology, 125(1), 239–252.

Levin, N., Jablon, P. E., Phinn, S., & Collins, K. (2017). Coastal dune activity and foredune formation on Moreton Island, Australia, 1944–2015. Aeolian Research, 25, 107–121.

Longmore, M. E. (1997). Quaternary palynological records from Perched Lake sediments, Fraser Island, Queensland, Australia: Rainforest, forest history and climatic control. Australian Journal of Botany, 45(3), 507–526.

Longmore, M. E., & Heijnis, H. (1999). Aridity in Australia: Pleistocene records of palaeohydrological and palaeoclimological change from the perched lake sediments of Fraser Island, Queensland, Australia. Quaternary International, 57-58, 35–47.

McKee, D., (1979). Sedimentary structures in dunes: A Study of Global Sand Seas. U.S. Geological Survey, 1052, 83–134.

Miot da Silva, G., & Shulmeister, J. (2016). A review of coastal dune evolution in Southeastern Queensland. Journal of Coastal Research, 75, 308–312.

Montgomery, D. (2001). Slope distributions, threshold hillslopes, and steady-state topography. American Journal of Science, 301, 432–454.

Moss, P. T., Tibby, J., Petherick, L., McGowan, H., & Barr, C. (2013). Late quaternary vegetation history of North Stradbroke Island, Queensland, eastern Australia. Quaternary Science Reviews, 74(0), 257–272.

Patton, N., Lohse, K., Godsey, S., Crosby, B., & Seyfried, M. (2018). Predicting soil thickness on soil mantled hillslopes. Nature Communications, 9(1), 3329.

Pee, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen–Geiger climate classification. Hydrology and Earth System Sciences, 11(5), 1633–1644.

Petherick, L., McGowan, H., & Moss, P. (2008). Climate variability during the last glacial maximum in eastern Australia: Evidence of two stadials? Journal of Quaternary Science, 23(8), 787–802.

Pye, K. (1983). Formation and history of Queensland coastal dunes. Zeitschrift Fuer Geomorphologie, 45, 175–204.

Reeve, R., Thompson, C. H., & Fergus, I. F. (1985). Studies in landscape dynamics in the Cooloola-Noosa River area, Queensland (4. Hydrology and water chemistry).

Roskin, J., Katra, I., & Blumberg, D. G. (2013). Late Holocene dune mobilizations in the northwestern Negev dunefield, Israel: A response to combined anthropogenic activity and short-term intensified windiness. Quaternary International, 303, 10–23.

Roy, P. S., & Thom, B. G. (1981). Late quaternary marine deposition in New South Wales and southern Queensland — An evolutionary model. Journal of the Geological Society of Australia, 28(3–4), 471–489.
Tejan-Kella, M. S., Chittleborough, D. J., Fitzpatrick, R. W., Thompson, C. H., Prescott, J. R., & Hutton, J. T. (1990). Thermoluminescence dating of coastal sand dunes at Cooloola and North Stradbroke Island, Australia. Soil Genesis, Morphology and Classification, 28, 465–481.

Thompson, C. H. (1981). Podzol chronosequences on coastal dunes of eastern Australia. Nature, 291(7), 59–61.

Thompson, C. H. (1983). Development and weathering of large parabolic dune systems along the subtropical coast of eastern Australia. Zeitschrift Fuer Geomorphologie, 45, 205–225.

Thompson, C. H., & Moore, A. W. (1984). Studies in landscape dynamics in the Cooloola-Noosa River area, Queensland. Divisional Report – CSIRO, Australia, Division of Soils Article, v. 73.

Tsoar, H. (2005). Sand dunes mobility and stability in relation to climate. Physica A: Statistical Mechanics and its Applications, 357, 50–56.

Wasson, R. J., & Hyde, R. (1983). Factors determining desert dune type. Nature, 304(5924), 337–339.

Walker, J., Lees, B., Olley, J., & Thompson, C. (2018). Dating the Cooloola coastal dunes of south-eastern Queensland, Australia. Marine Geology, 398, 73–85.

Ward, W. T. (2006). Coastal dunes and strandplains in southeast Queensland: Sequence and chronology. Australian Journal of Earth Sciences, 53(2), 363–373.

Wardell-Johnson, G., Schoeman, D., Schlacher, T., Wardell-Johnson, A., Weston, M. A., Shimizu, Y., & Conroy, G. (2015). Re-framing values for a world heritage future: What type of icon will K’gari-Fraser Island become? Australasian Journal of Environmental Management, 22 (2), 124–148.

Willett, S. D., Slingerland, R., & Hovius, N. (2001). Uplift, shortening, and steady state topography in active mountain belts. American Journal of Science, 301, 455–485.