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Mangrove and sand cay dynamics on Australian and Indonesian low wooded islands: A 45 year comparison of changes from remote sensing

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ABSTRACT

Changes to coral reef landscapes are driven by regional processes that are unique to particular localities, yet much of our global knowledge about how landscape changes manifest in coral reef environments is generalised from work undertaken on the Great Barrier Reef. We compare observations of 45 years of change on sand cays and mangroves associated with low wooded islands in Australia and Indonesia. We draw on field observations from ground referencing campaigns, alongside remote sensing technology, including satellite images and unmanned aerial vehicle campaigns. Four low wooded island sites are compared: two in the Great Barrier Reef (GBR), Australia (Nymph Island and Two Isles) and two in the Spermonde Archipelago, Indonesia (Sabangko and Tanakeke Island). The Spermonde and GBR sites can be distinguished in relation to the process regimes that entrain, distribute and deposit sediments on the reef surface thereby providing a substrate for further mangrove colonisation, particularly the presence or absence of cyclones as a key determinant of sediment transport. The influence of human populations inhabiting these sites is also an important control on their geomorphology. In the Spermonde Archipelago, local communities have altered sand cays through the development of infrastructure and converted mangroves to shrimp farms, while sand cays and mangroves have remained largely unaltered by humans on the GBR. This comparative evaluation of changes to sand cays and mangrove forest across low wooded islands emphasises the importance of considering changes within the context of their local geographic setting, inclusive of natural environmental and anthropogenic drivers of change.

1. Introduction

Globally, reef islands are extremely significant land areas on which small island developing states have built substantial infrastructure to support populations in the Atlantic, Pacific and Indian Oceans. The upper surfaces of coral reef platforms are highly dynamic coastal environments in which sand cays migrate, mangrove forests extend and contract, and the terminal spits of sand cay beaches and shingle ridges move substantially. A better understanding of reef island responses to environmental and anthropogenic influences is critically important for people whose homes and livelihoods depend on the goods and services they provide.

It is widely thought that environmental changes such as sea level-rise will cause reef islands to erode or even disappear by the end of the century. This idea is both supported and refuted by recent shoreline changes studies in the Pacific and Indian oceans (McLean and Kench, 2015). The stability of reef islands relies on a locally-defined relationship between sea level and the hydrodynamic and carbonate production processes that produce and transport sand in and around reef flats. These processes fundamentally control sand cay formation and sedimentation, which facilitates mangrove propagule establishment (Smithers and Hopley, 2011). All of these factors are geographically structured in the sense that sea level histories vary regionally, along with contemporary environmental processes, including cyclone frequency and intensity, the hydrodynamic climate (tidal range and wave power) and the ways in which local human populations have inhabited and interacted with the reef island landscapes. Thus, an understanding of recent changes on reef top landforms at both the global and regional scale calls for an

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awareness of the geographic distribution of the factors of importance to these landforms, how these are realised locally, and also the limits to which insights gained in one geographic area can be reliably applied elsewhere.

Found throughout the Caribbean, Pacific and Indian Oceans, low wooded islands are a distinct type of island that forms on reef platforms, with a sand cay on the leeward reef flat and mangroves on the exposed reef flat (Hopley et al., 2007; Kench, 2011). We focus on low wooded islands because the interrelations between the leeward sand cay and reef flat mangrove depend on their local environmental setting.

Historically, much of the work done on the geomorphic behaviour of low wooded islands has been carried out on the Great Barrier Reef (GBR) as a result of two Royal Society Expeditions in 1929 (Steers, 1929) and 1973 (Stoddart, 1978a), as summarised in Hamylton et al. (2019). Stratigraphic evidence and sediment dating at Bewick and Pipon Islands have identified a 'reef platform process window' of coral reef development and formation during which a critical water depth over the reef platform enhanced sediment production and transport to form islands within a rapid timeframe, some 5000-4000 yrs B.P. (Kench et al., 2012; Perry et al., 2017).

On the GBR, it has been suggested that low wooded islands form on top of planar reefs, at the end of a geomorphic evolutionary sequence in which underlying reef platforms grow upward to sea level from a Pleistocene basement, then expand laterally while their upper surface undergoes sediment infill. This is followed by development of a leeward sand cay, reef flat mangroves and shingle ramparts, which commonly form across the windward shoreline (Hopley, 1982; Steers and Kemp, 1937). Carbonate sediment deposition initiates a set of rapid geomorphic changes that can replace bare reef flats with a complex array of landforms over decadal timescales, invariably filling up the entire reef flat over longer periods (Stoddart et al., 1978). Once this point at the end of the proposed evolutionary sequence is reached, minor changes to low wooded islands reflect adjustments to localised fluctuations in hydrodynamic and climatic conditions, within a broader equilibrium with local environmental conditions (Spender, 1930).

It is difficult to propose a unifying model of low wooded island evolution that incorporates the global range of environmental conditions observed in different regional sites. The aforementioned equilibrium described on the GBR is contingent on the islands being unmodified. Yet in many countries, low wooded islands are heavily populated and adjustments to the reef top landforms also reflect the activities of communities inhabiting and deriving their livelihoods from islands.

We adopt a comparative approach to evaluate geomorphic changes to low wooded islands from different geographic settings that are subject to unique localised anthropogenic and environmental processes. Comparative approaches have a long standing place in geographic enquiry that draws useful explanatory power and insights from regional case studies that enable islands to be systematically categorised and compared within their geographic setting. Sites in both the Australian GBR and the Indonesian Spermonde Archipelago represent distinct environmental settings that fall under different anthropogenic regimes. Although both sites support low wooded islands within inshore, turbid environments, the differences and similarities in their emergent landform behaviours may yield new insights about low wooded island geomorphic behaviour that apply across a broader geographic range than has hitherto been the case.

The need for a better understanding of both the environmental and anthropogenic controls that govern the ongoing morphodynamics of islands at seasonal to decadal timeframes has been emphasised for both the GBR (Hamylton et al., 2019) and the Spermonde Archipelago (Kench and Mann, 2017). Early comparisons between these island groups arose from the Great Barrier Reef Expedition (1928–29) and the Snellius Expedition to the eastern part of the Netherlands East Indies (1929–1930) (Kuenen, 1933; Spender, 1930), which noted the similarity in these inshore islands, concluding that they could both be classified broadly as low wooded islands. Since then, the rapid development of housing infrastructure on sand cays and mangrove aquaculture across reef flats in the Spermonde Archipelago has resulted in markedly different coastal changes in these different settings. Here, we update those comparisons using satellite and unmanned aerial vehicle (UAV) remote sensing approaches to evaluate 45 years of sand cay and mangrove dynamics as a basis for exploring and comparing the processes underpinning both geomorphic and anthropogenic changes in these distinct environments. The following comparisons are drawn for two low wooded islands from each site: Nymph Island and Two Isles on the GBR and Sabangko Island and Tanakeke Island in the Spermonde Archipelago (Fig. 1):

1. Changes to the position of shorelines around sand cays, including seaward accretion and inland erosion. For the Indonesian sites, we track the development of infrastructure across sand cays.
2. Changes to the boundaries of the reef top mangrove forest. For the Indonesian sites, we track the conversion of mangrove forest to aquaculture ponds across the reef flat.
3. Three dimensional characteristics of the sand cay shorelines and mangroves are evaluated for both of the Australian sites and one of the Indonesian sites (Sabangko) from available high resolution digital elevation models (DEM).

1.1. *Study sites and environmental setting*

1.1.1. *The Great Barrier Reef (GBR), Australia*

The GBR is the largest reef province in the world. It stretches over 2000 km of latitude, with >3000 individual reef patches extending from the mainland coast some 250 km offshore to the continental shelf edge. These reef patches provide a foundation for over 1000 reef islands, including 350 coral cays (Smithers and Hopley, 2011). These include 47 low wooded islands, on the inner shelf of the northern GBR.

The GBR is situated in the centre of the Indo-Australian plate, imparting tectonic stability to this region. The last glacial transgression produced varying relative sea level histories along and across the continental shelf of the GBR, resulting in a variable time range over which islands have accumulated (Hopley et al., 2007). The reefs in this region grew up from the shallow continental shelf (<50 m water depth) to current sea level over the mid to late Holocene (i.e. the last 6.5 k years), providing an intertidal platform for upper and lower terraces of island deposition dating back some 3000-4000 years, as indicated by radiocarbon dates of island sediments on the northern GBR (Hopley et al., 2007; McLean and Stoddart, 1978).

Semidiurnal tides flow on and off the continental shelf, resulting in a considerable movement of water along an east–west axis, with a tidal amplitude ranging from 2.5 in the northern and southern extents, and reaching a maximum of 6.1 m in the southern region of Broad Sound (Wolanski, 2018). Tropical cyclones form between Cape York and Brisbane, with a pronounced late-summer peak when sea conditions are hottest between November and April (Harmelin-Vivien, 1994; Short and Woodroffe, 2009). The eastern boundary of the GBR intercepts swell waves from the Pacific Ocean (Gallop et al., 2014). Most islands are subject to small trade wind waves generated within the GBR lagoon, with inner reefs experiencing significant wave heights of up to 0.8 m for locally wind-generated waves (Larcombe et al., 2001). WaveWatch III (WW3) Global Wave Model data (Tolman, 2009) for the period 2013–2019 indicate yearly average significant wave heights of 0.51 m for Nymph Island and 0.63 m for Two Isles, with prevailing winds come from a southeasterly direction for the majority (85%) of the year, except during summer months (December to February) when the northwest monsoon dominates. This monsoon is characterized by heavy rainfall, occasional cyclones and a dominant southeasterly swell that transports carbonate sediments length-wise across many reef platforms, (i.e. in a northwesterly direction) (Hamylton et al., 2019). Carbonate sediments

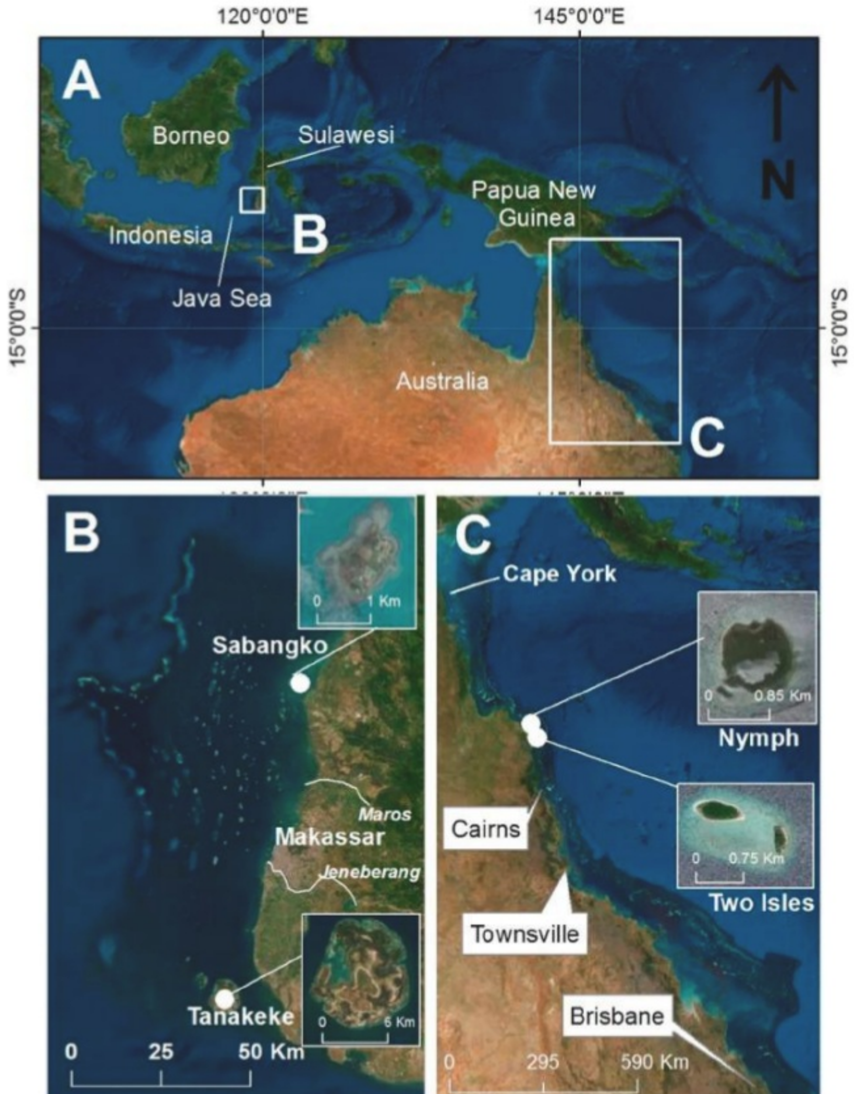

Fig. 1. Regional setting for the low wooded islands in the present study. A. The location of the Makassar Strait and the Great Barrier Reef within the Indo-Pacific region, B. The Spermonde Archipelago, Makassar Strait (Indonesia), and C. The Great Barrier Reef, Australia. Locations of the low wooded islands evaluated in this study are shown in white.

are derived from the periphery of the shallow outer reef slope, particularly on the windward side. High energy events including storms and cyclones generate and remobilize sediment around the reef flats of several low wooded islands in the northern portion of the GBR, often forming shingle ridges comprising coarse coral fragments, around windward reef margins (Moorhouse, 1936; Perry et al., 2014). During the passage of cyclones, significant wave heights rise to around 1.9–2.2 m, as indicated by WW3 data for cyclone Cyclone Ita, which passed close to both Nymph and Two Isles in 2014.

1.1.2. The Spermonde Archipelago, Indonesia

The Makassar Strait opened up in Central Indonesia some 20,000 years ago with the separation of Borneo from Sulawesi (Imran et al., 2013). On the eastern coast of the Strait, the 30–50 km wide Spermonde Shelf sits along the shore of south-western Sulawesi. The Spermonde Archipelago consists of approximately 54 reef islands that have formed over coral reef patches across this shelf. The nearest major city is Makassar on an adjacent alluvial coastal plain, which has a population of 2.75 million (Fig. 1).

Relative to the GBR, the Spermonde Shelf is in a tectonically active area, situated close to the confluence boundaries of the Philippine Sea plate, Eurasian plate and the Indo-Australian plates. This is just outside the 'Pacific Ring of Fire', a region subject to frequent earthquakes and volcanoes that cause uplift and tsunamis.

Approximately 137 coral reefs are supported by the Spermonde Shelf, which can be subdivided into the inner, middle and outer zones with localised environments characterised by distinct water depths, hydrodynamics and fluvial influence from the adjacent coastline (Nurdin, 2019). Two major rivers discharge onto the Spermonde shelf, the Jeneberang which runs along the southern margin of Makassar City and the Maros River, approximately 20 km to the north. These deliver clastic sediments to inshore reefs and islands, (<4 km from the coast), reducing

Fig. 2. **A.** Coral rubble employed to reinforce coastal walls, and B. Dead corals employed to build walls of aquaculture ponds. Both photographs taken by Sarah Hamylton at Sabangko Island, July 2019.

the clarity and elevating levels of nutrients of coastal waters.

The ages of fossil microatolls in the Makassar Strait indicate that the reef platform reached current sea level here some ~6500–6000 years ago (Mann et al., 2016). This is in agreement with Umbgrove's view that the present coral reefs on the Spermonde shelf must have originated at the end of the Pleistocene, rising from a depth of 30 fathoms (approx. 50 m) to form the many submarine reef platforms, patch reefs and cays in variable stages of development that are seen today (Umbgrove, 1928).

Population growth across the Spermonde Islands has increased substantially since the 1940s, with extensive housing development on 50 of the 54 islands (Fig. 2). Interviews with community members on the most populated island, Barrang Lompo, which is located 12 km west of Makassar city and, according to the Central Indonesian Bureau of Statistics housed some 3696 people in 2018, indicate that it was first populated 74 years ago (Nurdin, 2019). Communities living on the islands depend on coastal resources for their livelihoods. Key sources of income include coral reef fisheries, seaweed farming, aquaculture (prawn farming) and the collection of crabs, squid, octopus and shellfish (Fujii, 2019; Glaser et al., 2015). Reef flats are commonly covered with live coral and seagrass, although dynamite fishing and the run-off of pollution from Makassar have led to regional declines in coral health (Edinger et al., 1998; Fujii, 2017; Nurdin et al., 2015).

The movement of surface water currents across the Spermonde platform depends on the velocity of monsoon-driven winds and tides (Jalil, 2011). Tides are semidiurnal within the Makassar Strait with a small range, typically between 0.2 and 0.3 m. Sulawesi sits at 5° south, around 500 km to the north of the tropical cyclone belt. As a result, shingle ridges are less well developed on many of the patch reefs in the Spermonde Archipelago, reaching modest proportions in the places they do exist, where 'no part is exposed at normal low water' (Verstappen, 1954).

Monsoons have a strong, seasonal influence on regional winds and waves. Another key influence on regional hydrodynamics is the large volume of water known as the Indonesian Throughflow (ITF) passes through the Strait, which provides a major conduit of largely southward flowing water between The Pacific Ocean and the Indian Ocean (Jompa, 1996). The monsoonal regime drives winds to the southeast during the southern hemisphere summer (December–February), with corresponding currents from the north that flow down from the northern Pacific. During the winter (June–August), winds blow toward the northwest with surface currents coming up from the Java Sea to the south, flowing against the ITF.

In general, the northern Spermonde Archipelago falls within a region of low to moderate wave energy (mean significant wave height 0.7 m), with the Sulawesi mainland moderating the influence of easterly wind patterns (Umbgrove, 1929). Tanakeke occupies a more exposed position, approximately 10 km off the far southwestern tip of Sulawesi with wave heights commonly reaching 2 m. Further north in the centre of the Spermonde Shelf, Sabangko lies some 4 km offshore and experiences a relatively consistent annual average significant wave height of 0.2 m (Tolman, 2009).

2. Materials and methods

Table 1 summarises all field and remote sensing data used in the evaluations of low wooded island changes. Changes to sand cays and mangroves were evaluated over a 45-year period for all four sites. The

Table 1
The field and remote sensing information employed in the evaluation of 45 years of change for each low wooded island site.

Site name, assessment period	Location	Field and remote sensing data employed
Nymph Island (45 yrs, 1973–2018)	S −14.65382° E 145.25289°	• 1973 Map of reef top features from *in-situ* compass traverse surveys • June 2018 UAV survey (DJI Phantom 4) with ground referencing
Two Isles (45 yrs 1973–2018)	S −15.02280° E 145.44172°	• 1973 Map of reef top features from *in-situ* compass traverse surveys • June 2018 UAV survey (DJI Phantom 4) with ground referencing
Tanakeke Island (45 yrs, 1973–2018)	S −5.49491° E 119.28371°	• 1973 Landsat MSS image of reef top features • 2018 Worldview-2 image of reef top features with ground referencing
Sabangko (45 yrs, 1974–2019)	S −4.70563° E 119.47315°	• 1974 Landsat MSS image of reef top features • June 2019 UAV survey (DJI Phantom 4) with ground referencing

larger size of Tanakeke Island (approximately 68 km^2) rendered it impractical to survey with an UAV, so the contemporary record of landform configuration was interpreted from a World-View2 satellite image (spatial resolution 2 m).

2.1. Fieldwork: UAV flights and ground referencing

UAV flights and ground referencing took place during site visits to the GBR from the 3rd to the 10th of June 2018 and the Spermonde Archipelago from the 2nd to the 6th of July 2019, with previous work having been undertaken at the Tanakeke site in 2013. *In-situ* ground cover photographs were collected across a representative range of ground cover types at all sites to assist with the interpretation of landscape features.

UAV surveys were flown at Nymph Island, Two Isles and Sabangko Island with a DJI Phantom 4 (camera model FC330 3.61 mm, 12 megapixels) following a method that has been report in detail elsewhere (Hamylton et al., 2019; Hamylton, 2017). Aerial survey flight paths were planned with the Map Pilot for DJI Application to include 75% front and side overlap, at a flying altitude of 120 m. This yielded detailed aerial photographs in which both the reef platform and emergent features, including sand cays, mangroves and, where relevant, shingle ridges were clearly visible.

To establish accurate ground positional control (*x, y, z*), the locations and heights of notable features that were visible in the aerial images, such as the corners of buildings and intersections of banks delineating aquaculture ponds were recorded. Where possible, on three of the four islands, positions were recorded using the Trimble GeoXH 2008 GPS (positional error $<$10 cm).

All images were processed in the photogrammetry software AgiSoft Photoscan Professional (version 1.3.4). Images were stitched together to produce an orthomosaic from a combination of georeferencing followed by feature matching to create a point cloud as the basis of an image mosaic. Ground control positions (GCPs) were imported and their place marker positions on the UAV photos were refined to correspond with visible features for which the locations had been recorded with the GPS. After photos had been aligned, dense point clouds were constructed via the feature matching process that triangulated identical features that were visible on multiple images. Finally, a continuous mesh was produced from the point cloud, from which the high resolution orthomosaic and DEM were produced.

2.2. Analysis of sand cay shorelines and mangrove forest boundaries

To compare the reef top features before and after the evaluation period, polygon files were digitized around the sand cay and mangrove forests from historic and contemporary records. All digitization was carried out using ArcMap (version 10.4.1) at a scale of 1:1500. For each polygon, the difference between the area of the historic outline (as depicted in the Landsat image) and the recent outline (as depicted in the UAV mosaic or satellite image) was measured to estimate the magnitude of areal changes to these reef top landforms. Rates of observed change were measured at 100 m intervals around the sand cay or mangrove boundary, and calculated as the total distance of movement divided by the evaluation time period (myr^{-1}). Maximum and minimum rates of shoreline movement were measured.

To estimate the error associated with these steps, a similar approach was adopted to that used by Ford (2011) for calculating the error of shoreline change estimates on Majuro Atoll. Error was calculated as the square root of the sum of the constituent digitizing and pixel errors squared. Digitizing error was the standard deviation in shoreline positions from repeated digitization of the same section of coast at a scale of 1:1500 and the pixel error related to the spatial resolution of the images used (see Table 2 in Hamylton and East, 2012).

2.3. Three dimensional evaluation of reef flat sand cays and mangroves

After processing to high resolution DEMs (see 2.1), cross sectional profiles were extracted for reef flat sand cays and mangroves at each site using the 3D Analyst tool in ArcGIS and plotted in Excel.

3. Results

3.1. Overall summary of area changes to sand cays and mangroves

A comparison of the mapped reef top area cover for sand cays and mangroves is presented in Table 2 as measured in 1973/1974 from historic records, and more recently in 2018/2019 from Worldview-2 satellite image and UAV. Overall changes between those time periods are plotted for all four sites in Fig. 3.

Table 2 summarises the rates of sand cay shoreline change observed at each site. The GBR sites of Nymph Island and Two Isles experienced variable changes around different parts of the sand cays, including both accretion and erosion. Both of the islands evaluated in the Spermonde Archipelago underwent consistent erosion around all of their shorelines. Excluding the two protruding spits in the south, which have some small remaining areas of vegetated land, the greatest rates of erosion ($-$8.18 $m.yr^{-1}$) were observed along the northern shoreline of Tanakeke Island, while the greatest rates of accretion were seen on the northeastern peripheral sand spit at Two Isles.

3.2. Analysis of changes to sand cay shorelines

3.2.1. Sand cay shoreline positions

Fig. 4 illustrates the changes to sand cay shorelines at each of the four sites, while Table 2 indicates the range of shoreline change rates observed at each site. The sand cay at Nymph Island has increased slightly in area by 7% of the initial area, or 0.02 km^2, (20,000 m^2). This expansion is the result of beach sand accretion along the northwest (leeward) side of the island.

At Two Isles, the sand cay appears to have maintained a constant area. Movements to the nodal end points of the roughly oblong sand cay have occurred in which terminal node points have switched from a north-eastern protrusion to a south-eastern protrusion along the eastern side of the cay, accompanied by a shift from west to northwest

Table 2
A summary of the area of sand cays and mangroves for historic and contemporary assessments of reef top character, including the range of sand cay shoreline change rates observed across the four study sites for the 45 year evaluation period. Error estimates, provided italicised in parentheses, are based on image spatial resolution and digitizing error.

Site	Reef top characteristic	1973/1974	2018/2019
Nymph	Area of sand cay (km^2)	0.30 *(0.001)*	0.32 *(0.0007)*
	Area of mangrove (km^2)	0.31 *(0.0015)*	0.34 *(0.0002)*
Two Isles	Area of sand cay (km^2)	0.197 *(0.003)*	0.192 *(0.0002)*
	Area of mangrove (km^2)	0.083*(0.0027)*	0.080 *(0.0001)*
Tanakeke	Area of sand cay (km^2)	8.53 *(0.47)*	7.18 *(0.048)*
	Area of mangrove (km^2)	25.00 *(1.02)*	9.50 *(0.06)*
Sabangko	Area of sand cay (km^2)	0.038 (0.13)	0.033 (0.0005)
	Area of mangrove (km^2)	0.87 *(0.07)*	0.08 *(0.0006)*
Site	**Range of sand cay shoreline change rates**		
Nymph	$-$0.29 m yr^{-1} (internal lagoon)		
	+1.4 m yr^{-1} (peripheral beach/casuarina)		
Two Isles	$-$1.52 m yr^{-1} (southeastern peripheral sand spit)		
	+2.07 m yr^{-1} (northeastern peripheral sand spit)		
Tanakeke	$-$8.18 m yr^{-1} (northern point)		
	- 1.62 m yr^{-1} (southern point)		
Sabangko	- 1.93 m yr^{-1} (western periphery)		
	- 0.17 m yr^{-1} (southern point)		

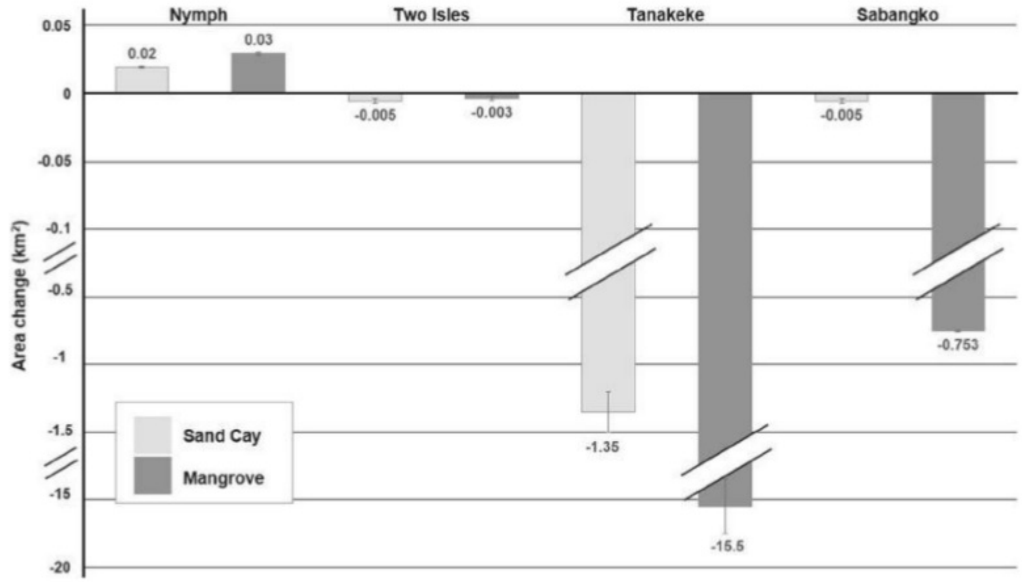

Fig. 3. Histogram illustrating area changes to reef top features for the four sites evaluated. Break marks indicate vriations to the scale on the y-axis. Error bars indicate standard error estimates for the multi-temporal remote sensing evaluation based on repeat digitisations and pixel resolution.

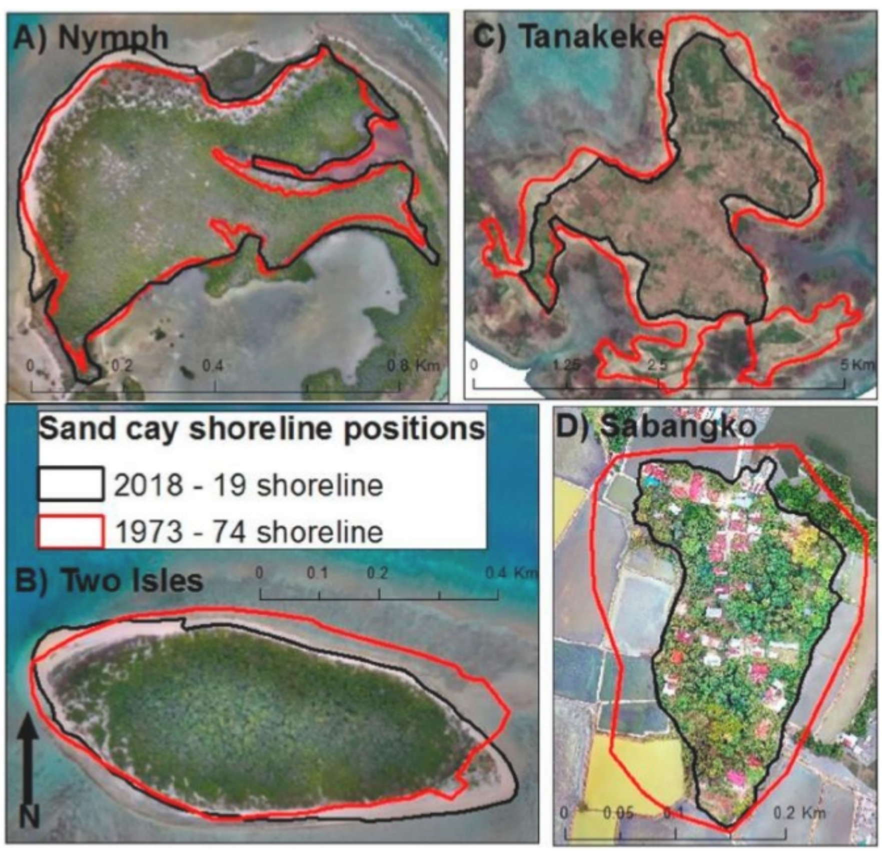

Fig. 4. Changes to the area coverages of reef top sand cays evaluated from high resolution remote sensing datasets summarised in Table 1 at A) Nymph sand cay, B) Two Isles sand cay, C) Tanakeke sand cay, and D) Sabangko sand cay. Background images are from recent 2018/2019 surveys (A, B and D) and a high resolution satellite image for the Tanakeke site (C).

protrusion along the western shoreline of the cay (Fig. 4B).

At Tanakeke there has been a reduction in sand cay area by some 16% of the initial area, or 1.35 km^2 due to a consistent belt of shoreline loss (average width 154 m) all the way around the island.

Sabangko sand cay has also reduced by some 0.005 km^2 (or 5000 m^2), which equates to a loss of approximately 13% of its original size as estimated from the Landsat image. As with Tanakeke, this takes the form of a consistent belt of shoreline loss around the island.

3.2.2. Development of sand cay infrastructure

Fig. 5 shows the development of housing infrastructure across the sand cays at the Indonesian sites of Tanakeke and Sabangko. No settlements were recorded for Tanakeke on the sand cay in 1974, although small clusters of buildings had been erected in other areas of the reef flat. By 2019, approximately 110 buildings covering some 0.22 km^2 ($\pm$ 0.05 m^2), or 3% of the sand cay area, were established along a simple road network traversing the sand cay (Fig. 5B).

At Sabangko, the 1974 settlement covered an area of approximately 600 m^2, comprising 4–5 dwellings in the north western side of the island. By 2019 the UAV imagery indicated that this had expanded to approximately 50 houses down the centre of the island and to the south east, covering some 5790 m^2 ($\pm$ 100 m^2), or 16% of the sand cay area.

3.3. Reef top mangrove forest

Fig. 6 illustrates the mapped changes to reef top mangrove at each of the four sites. At Nymph Island, the area of mangrove has increased since 1974 by some 10% of the original forested area, or 0.03 km^2, (i.e. 30,000 m^2). Most of the new mangrove growth has occurred as infill around the interior periphery of the large central and comparatively smaller north-eastern lagoons. Localised extension has also occurred around isolated patches of mangrove in the north and southeast of the island, while what were previously isolated trees along the eastern periphery have become a continuous narrow line of forest along the exposed coastline.

At Two Isles the observed small reduction in mangrove area (2000 m^2) fell within the uncertainty of the historic mapping using compass-traverse methods (Stoddart, 1978b). No statistically significant changes to the mangrove areal extent could therefore be discerned.

In Tanakeke there has been a dramatic reduction in the extent of mangrove cover with 62% of the original forest area lost (from 25 km^2 in 1973 to 9.5 km^2) by 2018, due to the construction of aquaculture ponds for prawn farming across the central reef flat (Figs. 6C and 7A). Large, continuous swathes of mangrove trees were removed from the centre of the reef flat during this time period, leaving small, isolated mangrove patches spread around the north eastern side of the reef flat in 2019.

At Sabangko there has also been a dramatic 91% reduction in the area of the reef flat covered by mangrove area due to clearance and removal for the construction of aquaculture ponds. While the reef flat was completely covered by mangroves, i.e. 0.87 km^2 of mangrove cover, in 1974 (see red line marking outer boundary in Fig. 6D), it has now been converted into approximately 70 ponds that are subdivided by raised coral banks to support prawn farming (Figs. 2 and 7B). These remain surrounded by a peripheral mangrove borders on all sides, which has contracted inwards by between 50 and 70 m around the exterior. Along the southern and south-eastern coastline, remnants of narrow prawn ponds outside the mangrove boundary indicate that these too have been removed for aquaculture. However, Sabangko villagers reported that along the south-western coastline, the mangroves are being naturally eroded, resulting in the construction of a defensive wall some 60 m long and 2 m high built from coral rubble.

3.4. Three dimensional evaluation of reef flat sand cays and mangroves

Fig. 8 shows the reef flat elevations at Two Isles and Nymph. At Two Isles, the sand cay in the west and the mangrove forest in the east are clearly distinguishable on the reef flat as two isolated features of relative elevation. The sand cay woodland is higher than the mangrove, reaching a height of 25 m across the cay interior, while the mangrove was at its highest elevation in the west (ca 10 m), where the mangrove forest is well formed and continuous. On the eastern, windward side, lower mangroves are interspersed with shrubs and grasses. Stretching approximately 1.5 km across the northern reef flat is a continuous shingle ridge around 2 m high, with inner and outer peaks in the east (see B1–B2, Fig. 8).

At Nymph, there is a less distinguishable boundary between the wooded sand cay and mangrove across the central reef flat. Over half of the reef flat is vegetated, reaching a maximum height of 21 m above sea level. As with Two Isles, the height of the mangrove forest reduces along to the eastern, windward coastline. To the southeast of the reef flat, a prominent shingle ridge reaches a height of approximately 3 m along the outer periphery of the reef flat, some 20 m inside the reef crest (see F1-F2, Fig. 9).

Fig. 9 shows the elevation of the shallow portion of the Sabangko reef

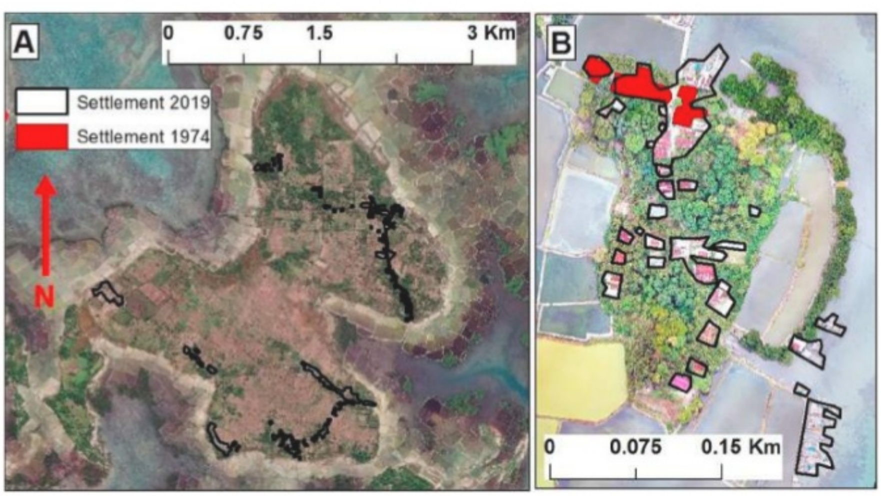

Fig. 5. Development of housing infrastructure between 1974 and 2019 on the sand cays at the Indonesian sites of Sabangko and Tanakeke, Spermonde Archipelago. Building outlines are digitised from a combination of satellite imagery and UAV imagery (see Table 1).

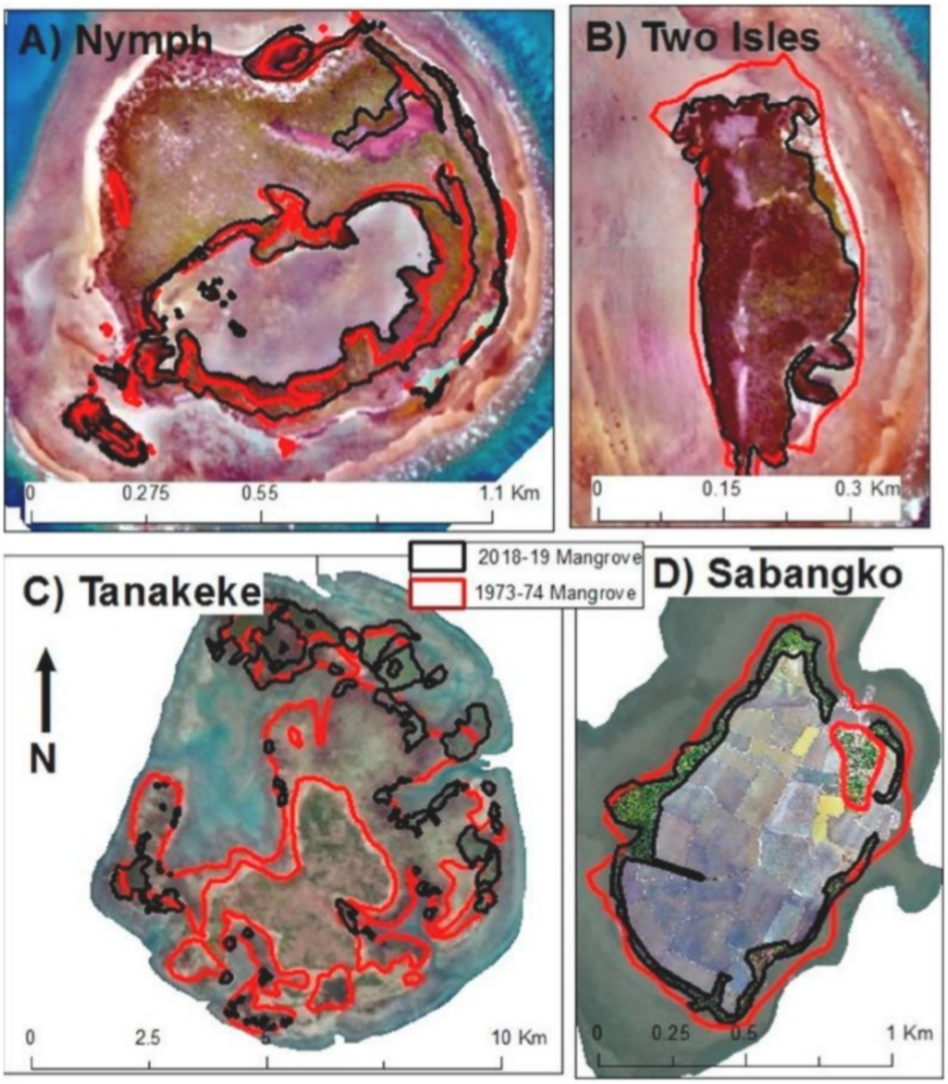

Fig. 6. Changes to the area coverages of reef top mangroves evaluated from remote sensing datasets summarised in Table 1 at A) Nymph Island, B) Two Isles, C) Tanakeke, and D) Sabangko. Background images are from recent 2018/2019 UAV surveys (A, B and D) and a high resolution Worldview-2 satellite image for the Tanakeke site (C).

flat, incorporating the area covered by mangrove and the sand cay (inset). The central sand cay reaches some 32 m high, which corresponds to one of the buildings in the centre of the cay. The marginal band of mangroves around the edge of the reef flat is variable in width and reaches a height of approximately 25 m.

4. Discussion

4.1. Sand cay shoreline positions: seasonal sediment movements and cay migration

The GBR sites experienced both accretion and erosion at rates ranging from 0.29 to 2.07 m yr^{-1}, while the Spermonde sites had largely experienced shoreline loss. Shoreline changes at Two Isles appeared to be distinctive seasonal movements of beach sands around reef island peripheries, as have been observed elsewhere on the GBR (Hopley et al., 2007) and in the Spermonde Archipelago (Umbgrove, 1929). Similar seasonal along-shore movements of peripheral beach sand have been recorded at other sites on the GBR, including Heron Island (Flood, 1974, 2018), Erskine Island (Flood, 1986), Two Isles (Hamylton et al., 2019). Comparable seasonal changes to the morphology of the islands within the Spermonde following the season were first noted by de Klerk (1983), who observed that the primary axis of the northern shoreline of Kodingarengkeke Island either lay in an east-west direction in the dry season (April to August) or a north-south direction in the wet season (September to March).

In the Spermonde Archipelago, Umbgrove (1929) noted the clear influence of the east monsoon on the shape of islands, particularly the unvegetated cays, which were crescent shaped with their convex sides adopting a sand dune profile that turned to the east. However, this was of limited influence on the shingle walls or the growth of coral on the submerged reef platform, which were shaped by the west monsoon, which blows 'unhampered on these islands across the Java Sea and Makassar Straits' (Verstappen, 1954). In Jakarta Bay, Verstappen (1954)

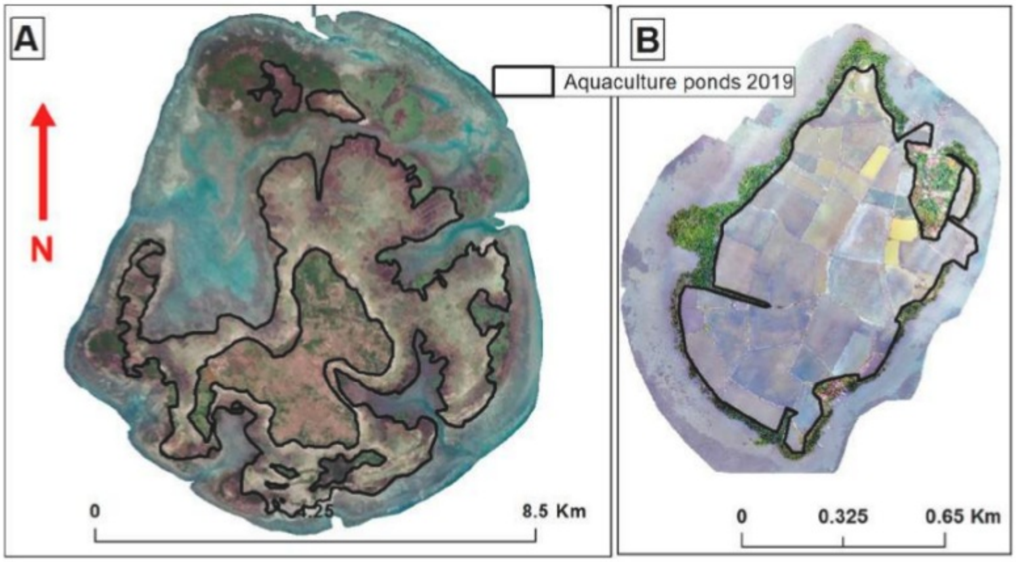

Fig. 7. Construction of aquaculture ponds between 1974 and 2019 on the reef flats at Sabangko and Tanakeke, Spermonde Archipelago. Aquaculture pond outlines are digitised from a combination of satellite and UAV imagery (Table 1).

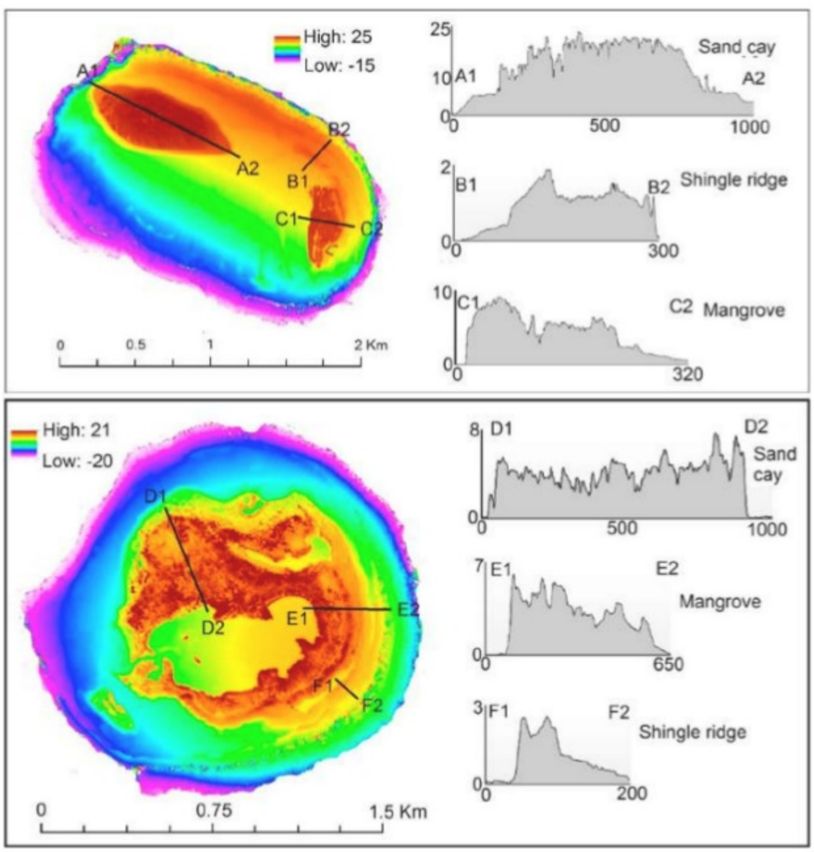

Fig. 8. Reef flat digital elevation models of Two Isles (top) and Nymph (bottom) illustrating profiles of the sand cays, mangroves and shingle ridges. All heights are provided in metres above sea level.

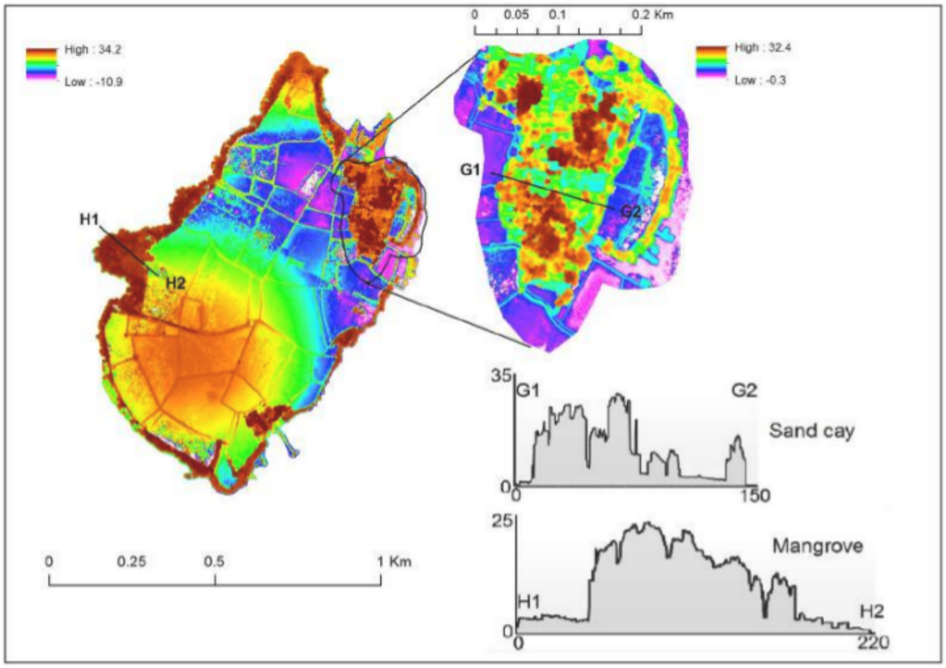

Fig. 9. Digital elevation model of Sabangko showing the full reef flat (left) and the sand cay (inset, right) illustrating profiles of the sand cays, mangroves and shingle ridges.

demonstrated the influence of winds on coral islands, noting that sand cay accretion occurs on the leeside. These patterns were attributed to the different behaviour of fine and coarse sediments, the former being transported prior to deposition while the latter tends to be deposited on the exposed side of the reef. A similar situation can be seen at Nymph Island, where the sand cay appears to have accreted some 30–40 m on the western, leeward side of the island.

In spite of their unconsolidated nature, the sand cays at both Nymph Island and Two Isles appear to have maintained a relatively constant area (Table 2), with only minor erosion and accretion at both sites over the evaluation period. Such island stability may arise from the proposed equilibrium for reef top landforms on the northern Great Barrier Reef. Given enough time to develop, these become geomorphically balanced with their localised environmental conditions (Spender, 1930). Within this equilibrium, observable changes represent small fluctuations (e.g. shoreline erosion and accretion) in response to prevailing winds and waves, with episodic storms and tropical cyclones (Hamylton and Puotinen, 2015). More recently, this has become increasingly influenced by climate change and related processes such as coral bleaching and cyclones, which drive the production, breakdown and transport of carbonate sands to shape coral reef landforms (Hamylton, 2014).

Anthropogenic disturbances to the natural regime at the Indonesian sites, including the development of buildings across the sand cays, removal of both live coral and rubble from the reef platform for the construction of housing foundations and the erection of protective sea walls on the western, windward shorelines of many islands may decouple sand cay shoreline movements from seasonal environmental influences (see Fig. 2A).

Such disturbances to the natural development of Spermonde cays were noted back in 1933 (Kuenen, 1933, pg10), and housing foundations continue to be constructed from coral rubble, which has increasingly been used as a building material to reinforce the raised banks surrounding aquaculture ponds since the 1980s. The declaration of the GBR as a World Heritage Site in 1981 has meant that many islands on the GBR lack comparable pressure from a human population. Nevertheless, there are islands where the relationship between shoreline positions and seasonal conditions has been confounded by anthropogenic influences. For example, at Green Island, offshore from Cairns, the man-made structures such as rock walls and groynes have interrupted movements of sand around the island to cause down-drift erosion (Hopley et al., 2007).

4.2. *Reef top mangrove forest*

The mangrove change dynamics observed at the Australian and Indonesian sites indicate either extension or relative stability for Nymph and Two Isles on the GBR, with substantial losses of mangrove forest at the Indonesian sites of Tanakeke and Sabangko in the southern and northern Spermonde respectively.

The extension of mangrove forest at the two Great Barrier Reef sites of Nymph Island and Two Isles suggests that they may be influenced by shingle ridges, which alter reef top water flow. Substantial shingle ridges were observed at both Two Isles and Nymph sites (Fig. 9, transect profiles B and F). At Nymph Island, shingle and rubble deposits reached some 2.5 m high and ran for a total of 2.6 km in length. Such ridges focus wave breaking and act as protective barriers to reduce wave energy on the reef flat, thereby inducing carbonate sediment deposition (Stoddart et al., 1978). Resulting upward accretion of the reef flat to an intertidal height suitable for settlement and colonisation of *Rhizophora* seedlings, likely encourages extension of the mangrove forest periphery.

Shingle ridge formation on the northern GBR is driven by high energy storms and cyclones (Moorhouse, 1933, 1936). During the evaluation period (1973–2018), four cyclones passed through the region: two to the south, Cyclone Peter (1978) and Cyclone Dominic (1981), which passed 10 km and 6 km respectively from Two Isles, and two to the north, Cyclone Ita (2013) and Cyclone Nathan (2014), which passed 10 km and 5.5 km respectively from Nymph Island (see Fig. 10A). With associated significant wave heights approaching 2.5 m, these cyclones have likely contributed to shingle ridge formation, which underpins mangrove stability and may encourage their extension at Nymph and at

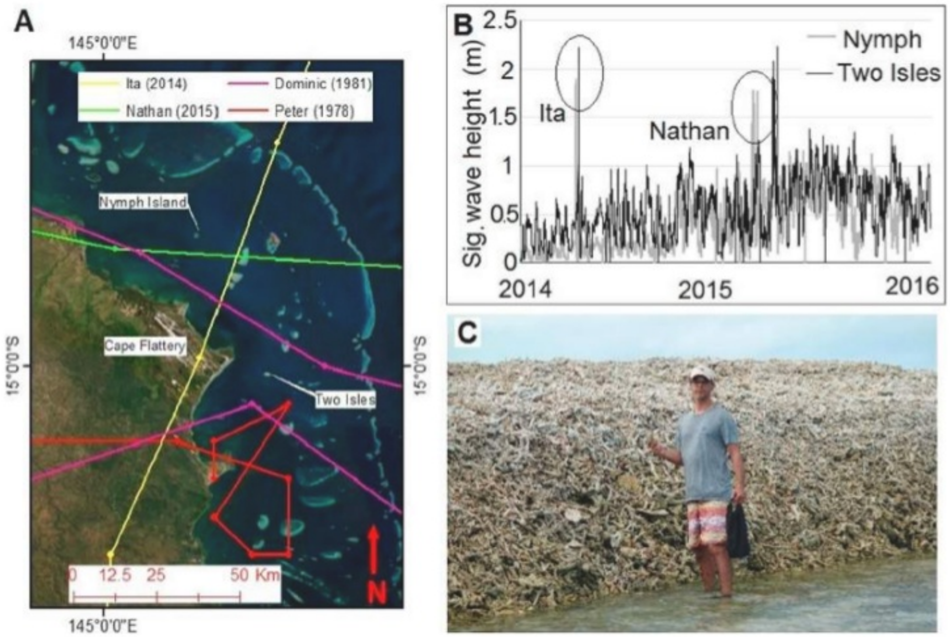

Fig. 10. A. Regional cyclones crossing close to the Great Barrier Reef study sites of Nymph Island and Two Isles throughout the period for evaluation of reef flat change to mangroves and sand cays, B. Significant wave heights measured at Nymph Island and Two Isles for the passages of Cyclones Ita and Nathan, C. Shingle ridge observed on the windward side of Nymph reef.

Two Isles.

Shingle ridges are less well developed in the Spermonde Archipelago. Here, their historic development on the reef flats has been variously described as either '*frequently seen… on many reefs no part is exposed at normal low water and at high water probably no ramparts are left uncovered*' (Kuenen, 1933, pg 9), or earlier observations from Umbgrove, who visited the region at the end of the East monsoon season, state that, the few shingle walls they saw 'were all found at the west side of the sandy islands, their convexity turned to the west' (Umbgrove, 1928, pg 245). These analogous linear shaped deposits of coarse coral rubble forming on the windward side of reef platforms appear to be more transitory in the Spermonde Archipelago than their GBR counterparts.

Stark reductions in reef top mangrove cover were apparent at both of the Indonesian sites, as appears typical of the broader region. It has been estimated that Indonesia has lost more than 12,000 km^2 of mangrove since 1980. Much of this loss in south Sulawesi (from 2140 km^2 to 230 km^2) has been driven by pollution, removal for charcoal production and aquaculture development (FAO, 2007).

Sixty percent of Sulawesi's mangrove loss since the 1980s can be attributed to the conversion of mangrove into brackish water aquaculture ponds. This took place in a period of focussed and sustained aquaculture expansion known as the 'blue revolution', driven by a government policy that instructed the provincial offices of local fisheries and maritime affairs to intensify shrimp cultivation, which was then a profitable export commodity (Akbar, 2014). Limited access to electricity on the offshore coral reef islands has prevented adequate aeration of aquaculture ponds, which become anoxic and redundant (Nurdin, 2019).

While this study draws on the best cartographic information available, it could be improved with the use of historic aerial photographs for the Indonesian sites. The historic archive of Landsat images stretches back to the early 1970s, providing a useful, consistent tool for tracking mangrove changes over time that is often the only available historic information on reef top cover. However, their use a baseline record against which change can be evaluated must be treated with caution. The reliability of Landsat satellite data for evaluating changes to sand cays and mangroves on low wooded islands depends on the magnitude of the changes to be evaluated. Because Landsat images have a relatively coarse spatial resolution of 30 × 30 m pixels, small changes such as the development of individual houses on sand cays, may fall within the range of detection error from the Landsat images. It is therefore impossible to discern whether changes evaluated correspond to actual sand cay or mangrove movements, or are an artefact of the techniques employed for the evaluation.

Where substantive changes have taken place, for example, the removal of large areas of coastal mangroves across much of southeast Asia, these likely fall outside the margin of error associated with their detection. To this end, Landsat images have been successfully used to track mangrove loss in Thailand (Charupphat and Charupphat, 1997), the Philippines (Long and Giri, 2011), Vietnam (Son et al., 2014). Elsewhere in Indonesia, Landsat images have tracked the accompanying expansion of agriculture and aquaculture into mangroves of Segara Anakan lagoon (Java) (Ardli and Wolff, 2009) and mangrove deforestation as a result of aquaculture, housing and industry in Kalimantan (Sukarna and Syahid, 2015). A Landsat study of the whole south east Asia region indicated that in Sulawesi, conversion to aquaculture was the dominant cause of land use conversion, however, elsewhere in the region, rice and oil palm farming also significantly underpinned mangrove removal (Richards and Friess, 2016).

Through comparative approaches, the variation in environmental conditions present at different geographic settings can be interrogated to yield insights on the causes of shoreline change. The Spermonde Archipelago and the GBR each have distinct monsoon signals, localised current and wave patterns and rates of relative sea-level rise. While it was not the aim of the present study, such an analytical framework could establish empirical links between the morphological evolution of islands and regional meteorological, hydrodynamic and oceanographic (sea level) processes. A study of 103 sand cays on the GBR proceeded in this manner to explore the influence of latitudinal and cross shelf gradients in regional oceanographic and local physical factors on island areas and volumes (Hamylton and Puotinen, 2015). This approach could profitably be expanded to a global comparative study of reef islands to leverage this geographic variation and further elucidate the drivers of reef island morphological changes across similar (i.e. decadal) timescales. Such an approach would need to account for local anthropogenic influences, as emphasised by findings of the present study.

5. Conclusion

The changes evaluated across these low wooded islands were of variable magnitude, ranging from small fluctuations in the area of sand cays (e.g. losses of 0.005 km^2 from peripheral beaches were detected at Two Isles and Sabangko) to major reconfigurations of reef flat mangrove forest at Tanakeke included (removal of 15.5 km^2 of mangrove) for the establishment of aquaculture ponds.

This comparative evaluation of 45 years of reef flat changes to sand cays and mangrove forest across low wooded islands in the Spermonde Archipelago and on the GBR emphasises the importance of considering the geomorphic behaviour of low wooded islands within the context of their local geographic setting, inclusive of natural environmental and anthropogenic drivers of change. In evaluating reef top geomorphic changes to low wooded islands, the Spermonde and GBR sites must be distinguished in two key regards. Firstly, one of the marked differences between the Australian and Indonesian settings for these low wooded islands is that of the process regime that entrains, distributes and deposits sediments on the reef surface. The presence or absence of cyclones as a key determinant of sediment transport creates a fundamentally different baseline scenario for geomorphic processes in these different settings. A related key control of reef top landform change appears to be the presence of shingle ridges, which alter hydrodynamic regimes to induce mangrove extension. Secondly, the influence of human populations inhabiting the Indonesian sites has resulted in a markedly different regional disturbance regime that has seen sand cay shorelines reinforced by coral rubble, thus altering their natural seasonal and longer term movements. Moreover, landcover changes include the development of human settlements and mangroves converted to shrimp farms in Indonesia. These have remained largely unaltered by human influences on the GBR. These two important distinguishing features invite greater consideration of the geographic setting in which low wooded islands are situated in the evaluation of changes to their sand cays and mangroves.

CRediT authorship contribution statement

S.M. Hamylton: Funding acquisition, Writing - original draft, Conceptualization, Methodology, Formal analysis. **N. Nurdin:** Funding acquisition, Project administration, Data curation, Formal analysis. **R.C. Carvalho:** Writing - original draft, Data curation, Formal analysis. **J.J. Jompa:** Project administration. **Muhammad Akbar AS:** Project administration, Data curation, Formal analysis. **M. Nur Fitrah:** Project administration, Data curation, Formal analysis. **Mahatma Lanuru:** Project administration, Data curation, Formal analysis. **Khairul Amri:** Project administration, Data curation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. A Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2020.106912.

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