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Impacts of Cyclone Yasi on nearshore, terrigenous sediment-dominated reefs of the central Great Barrier Reef, Australia.

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Abstract: Tropical Cyclone (TC) Yasi (Category 5) was a large (~700 km across) cyclone that crossed Australia's Queensland coast on 3rd February 2011. TC Yasi was one of the region's most powerful recorded cyclones, with winds gusting to 290 km/h and wave heights exceeding 7 m. Here we describe the impacts of TC Yasi on a number of nearshore, turbid-zone coral reefs, that include several in the immediate vicinity of the cyclone's landfall path (King Reef, Lugger Shoal and Dunk Island), as well as a more distally located reef (Paluma Shoals) ~150 km to the south in Halifax Bay. These reefs were the focus of recent (between 2006 to 2009) pre-Yasi studies into their geomorphology, sedimentology and community structure, and here we discuss data from a recent (August 2011) post-Yasi re-assessment. This provided a unique opportunity to identify and describe the impacts of an intense tropical cyclone on nearshore reefs, which are often assumed to be vulnerable to physical disturbance and reworking due to their poorly lithified framework. Observed impacts of TC Yasi were site specific and spatially highly heterogeneous, but appear to have been strongly influenced by the contemporary evolutionary stage and ecological make-up of the individual reefs, with site setting (i.e. exposure to prevailing wave action) apparently more important than proximity to the landfall path. The most significant ecological impacts occurred at King Reef (probably a result of freshwater bleaching) and at Paluma Shoals, where widespread physical destruction of branched *Acropora* occurred. New coral recruits are, however, common at all sites and colony re-growth clearly evident at King Reef. Only localised geomorphic change was evident, mainly in the form of coral fracturing, rubble deposition, and sediment movement, but again these impacts were highly site specific. The dominant impact at Paluma Shoals was localised storm ridge/shingle sheet deposition, at Lugger Shoal major offshore fine sediment flushing, and at Dunk Island major onshore coarse sand deposition. There was little geomorphic change evident at King Reef. Thus whilst small-scale and taxa specific impacts from Cyclone Yasi are clearly evident, geomorphological changes appear minor and ecological impacts highly variable between sites, and there is no observed evidence for major reef structural change. The study suggests that the vulnerability of reefs to major physical disturbance events can be extremely site specific and determined by interacting factors of location relative to storm path, and pre-event geomorphology and ecology.

Key words: Cyclone, Great Barrier Reef, Cyclone Yasi, inner-shelf reefs, reef geomorphology

1. Introduction

Tropical cyclones (termed *hurricanes* in the Atlantic/Caribbean region) are intense low pressure weather systems primarily restricted to the latitudinal belt between 7° and 25° N and S of the equator (Scoffin, 1993). They are associated with very high wind speeds, usually exceeding 120 km/hr, but gusts can exceed 300 km/hr in high intensity (Category 5) events. Significant increases in wave height, in the range 5-15 m along reef fronts, usually accompany these strong winds, and storm surges can exceed 5 m above normal tide levels. Such magnified wave heights and storm surges interact with shallow subtidal and intertidal substrates, and thus cyclones can exert a major influence on both coral reef geomorphology and ecology, and on the morphodynamics of reef-associated landforms such as beaches and reef islands. The resultant modification of reef substrates, and the remobilisation of sediments and coral rubble, can generate a wide range of both erosional and depositional landforms, as well as driving major ecological changes (Scoffin, 1993). One of the major impacts of cyclones on coral reefs occurs through the breakage of corals, especially of branched coral taxa (Woodley et al., 1981; Rogers et al., 1982; Hubbard et al., 1991), although toppling and over-turning of massive taxa also occurs (Mah and Stearn, 1986; Massel and Done, 1993; Bries et al., 2004). Cumulatively, such destruction can radically alter reef community composition in the short term, although relatively frequent physical disturbance events can also help to maintain high levels of coral species diversity (Done, 1992). Furthermore, whilst ecologically destructive, these processes can also facilitate new colony development, at least within some branched taxa, where fragmented corals regenerate (Highsmith, 1982). Coral tissue damage, and subsequent partial or complete colony mortality, may also occur through sediment abrasion (Hubbard et al., 1991), or as a result of floodwaters that can dramatically reduce salinity levels and cause widespread bleaching within the upper parts of the water column (Van Woesik et al., 1995; Perry, 2003). In many cases, the magnitude of ecological change, as a function of physical disturbance, appears partly influenced by the composition of the pre-existing ecological community (e.g., the proportion of branched to massive taxa present), but also by the periodicity of major physical disturbance regimes (Woodley, 1992; Lirman and Fong, 1997), and by reef orientation relative to wind and wave direction (Woodley et al., 1981; Poutinen, 2007).

These same issues also influence the impact of cyclones on reef geomorphology, especially in terms of the reworking and transport, and subsequent deposition, of reef-derived sediment and coral rubble. Major off-reef sediment export has, for example, been demonstrated to occur through the scouring and removal of sediments from submarine canyons and sand channels (Hubbard et al., 1991), and through the off-reef transport of coral rubble from shallow fore-reef environments (Hughes, 1999). Associated removal and stripping of beach sediments and of intertidal rubble substrates can also occur, again depending on exposure and setting (Hubbard et al., 1991; Woolsey et al., 2012). As a function of such sediment movement, major changes in reef island shoreline configuration can occur (Stoddart, 1974), as can large scale changes in shelf sedimentary environments (Gagan et al., 2006). In extreme cases, very large coral blocks (in excess of 2-3 m diameter) can be moved by cyclone-generated waves (Hubbard et al., 1991). However, not all of this reworked sediment is removed from the reef system, because major phases of reef landform construction and onshore sediment deposition can also occur. For example, the deposition of coral rubble ridges or ramparts, and of shingle lobes across reef flats, have been reported (Maragos et al., 1973; Scoffin, 1993), these typically being composed of coral clasts derived from shallow fore-reef or intertidal environments. A limiting factor here is the availability of sufficient coral (usually branched coral) as a source material, but impressive multi-ridge sequences of storm deposits have been identified in some regions (Hayne and Chappell, 2001; Nott and Hayne, 2001; Nott, 2011; Nott et al., 2009). In some cases, these rubble ridges display distinct clast orientations that allow differentiation of both storm surges and return flow events (Spiske and Jaffe, 2009).

Geomorphologically, cyclones are thus an important factor determining the development of various facets of coral reef and adjacent shoreline development. Such influences are evident both through localised patterns of coral destruction, and through the short-term erosion and deposition of sediment and coral rubble, but which can aggregate to influence larger scale and longer-term reef architectural development (Blanchon and Jones, 1997; Riegl, 2001) and the internal depositional fabrics of reefs (Blanchon et al., 1997). Here we report on the impacts of Tropical Cyclone (TC) Yasi on the geomorphology and ecology of a range of coral reefs located within the inner-shelf region of the central Great Barrier Reef (GBR), Australia. The landfall path of TC Yasi meant that it interacted with a number of nearshore coral reefs that have been the focus of on-going studies into their geomorphology since 2005. Although each reef varies in terms of geomorphic setting, size and Holocene age structure, each of the reefs under study is characterised by a mixed carbonate-silciclastic framework fabric that is typically sediment-dominated and poorly lithified (Perry and Smithers, 2006; 2011; Perry et al., 2009; 2012). Thus, in contrast to the framework-dominated and organically bound high-energy reefs that characterise offshore and shelf-edge settings (Hopley et al., 2007), it might reasonably be assumed that these nearshore, often mud-dominated reefs may be far more susceptible to major geomorphic change during high-energy physical disturbance events. To examine this issue, we assessed the impacts of TC Yasi on three nearshore reefs, Lugger Shoal, Dunk Island and King Reef, that were within 20 km of the cyclone eye's path, and one reef - Paluma Shoals – a nearshore reef located ~150 km to the south. The research thus allows us to examine spatial variations in the impacts of TC Yasi across reef sites, and to test recent ideas about the long-term physical resilience of inner-shelf, sediment-dominated reefs to high-magnitude physical disturbance events.

2. Tropical Cyclone Yasi and area of study

TC Yasi was a very large (~700 km across) and powerful Category 5 cyclone that crossed the Queensland coast of Australia on 3rd February 2011. It is among the most powerful tropical cyclones recorded to have hit the Queensland coast. Previous cyclones of a comparable intensity include Cyclone Mahina (1899) in Princess Charlotte Bay ~350 km to the north, and the 1918 cyclones at Mackay and Innisfail. Cyclone Yasi began developing as a tropical low northwest of Fiji on 29th January 2011 and tracked westward attaining a Category 5 status on 2nd February. The eye of the storm was ~35 km wide and passed over the area between Mission Beach and Tully, some 140 km south of Cairns (Fig. 1) between midnight and 1am on Thursday 3rd February. Instrumentation that survived the event recorded a central pressure of 929hPa. In Mission Beach, close to where Yasi made landfall, wind gusts were estimated to reach 290 km/h, and caused widespread damage to coastal infrastructure. The peak storm surge in this area was estimated at ~ 7 m and inundated at least 300 m inland. Further south, around Cardwell, the minimum storm surge height exceeded 5 m (Australian Government Bureau of Meteorology, 2012). Fortunately this surge coincided with a low tide, but nonetheless water levels rose 2.3 m above the Highest Astronomical Tide (HAT) level. Very high rainfall also occurred during the event, the largest rainfall totals were near to, and to the south of, the cyclone track and were generally in the order of 200-300 mm in the 24 hours up to the landfall period, although the highest totals (exceeding 450 mm) were within the Herbert and Tully River catchments (Australian Government Bureau of Meteorology, 2012) and resulted in the generation of large flood plumes.

Our post-Yasi impact study focused on 4 inner-shelf GBR coral reefs for which pre-Yasi geomorphic and ecological datasets and pre-event photographic records were available. The inner-shelf of the GBR is dominated by reworked terrigenous sediments, including soil and fluvial sediments deposited during the lowstand and reworked shoreward during the post-glacial marine transgression to form a seaward-thinning terrigenous sediment wedge between the ~15 m isobath and the coast (Larcombe and Woolfe, 1999). Rivers discharging into the GBR lagoon also continue to deliver sediments to the inner shelf. Wave-driven sediment resuspension generates high turbidity levels within this coastal zone, commonly exceeding 50 mg L^{-1} (Larcombe et al., 1995;

Whinney, 2007; Browne et al. 2013), but coral communities appear generally well adapted to deal with these extrinsic stresses (e.g., Browne et al., 2010). In terms of reef structural development, the main influence of such high terrigenous sediment inputs is the development of reefs where muddy-terrigenous sediments form an important component of the internal reef fabric and which are typically very poorly cemented (Perry and Smithers, 2006). Our study sites were at: (1) King Reef (17° 462' S, 146° 072' E; Fig. 1), which is a large (~3 km^2) mainland-attached fringing reef extending more than 2.4 km offshore from Kurrimine Beach, that has developed in the lee of emergent indurated Pleistocene dune outcrops; (2) Lugger Shoal (17°57.5' S, 146°6.5' E; Fig. 1), which is a small reef platform developed at the southern end of Lugger Bay, immediately north of Tam O' Shanter Point; (3) Dunk Island (146° 09' E, 17° 56' S; Fig. 1), which is an inner-shelf high island located ~5 km offshore from the Queensland coast. Our datasets derive from a fringing reef developed within an embayment on the north-west corner of Dunk Island; and (4) Paluma Shoals (19°5.43' S, 146°33.5' E; Fig. 1), which is a nearshore, turbid-zone coral reef complex, comprising of a series of reef platforms developed along an erosional shoreline in central Halifax Bay. All of these reefs are bathymetrically constrained to seawards by the shallow low gradient seafloor, and extend to depths of no more than 4-5 m below mean sea level (MSL).

3. Materials and Methods

Assessments of the impacts of TC Yasi on these nearshore reefs were conducted during a series of 'rapid' post-impact studies in August 2011, timed to coincide with the spring low tide phase when the reef flats are subaerially exposed. We used one low tide cycle to visit each site. Our geomorphic and ecological assessments are based on comparisons with pre-Yasi data collected between August 2006 and September 2010. We emphasise that our pre-Yasi data were all collected post-Cyclone Larry which had a similar landfall path in March 2006. Although our visits were conducted ~7 months after TC Yasi, we are confident given our extensive knowledge of these sites (based on multiple visits to each reef either by ourselves or co-workers throughout the period 2006-2010) that our observations accurately reflect the major and preservable features associated with TC Yasi. Reef-wide assessments for evidence of both erosional and depositional features were undertaken at each site, as well as repeat photo transects for assessing benthic community changes. Our assessments included comparisons between extensive photographic records collected at each site between 2006-2009.

Additional data were also collected to allow assessments of pre- and post-event changes in surficial sediment distributions in the vicinity of two of the sites, Lugger Shoal and Dunk Island. Sediment samples were collected from the same GPS-fixed locations (horizontal accuracy of 2-3 m) across each reef flat at both sites and in adjacent shallow sub-tidal environments. At each site approximately 100 g of sediment were recovered, either by hand at low water across the exposed reef flats and intertidal environments, or using a hand auger deployed from the boat in sub-tidal areas. Following collection, all samples were soaked in distilled water to remove extraneous salts and then 'cleaned' in a 5% sodium hypochlorite solution to neutralise the organic fraction. Sediment texture was determined by wet sieving the 8 mm to 63 μm size fractions (methods in McManus, 1994) and using the program GRADISTAT (Blott and Pye, 2001), to determine values of mean grain size and sorting (descriptive nomenclature of Udden-Wentworth is used). $CaCO_3$ content was determined from sub-samples of known weight (ranging from 4-5 g) that were treated in a 2M HCl solution until no discernible reaction with the carbonate could be detected. Samples were then filtered through pre-weighed Whatman 42 filter papers and oven dried. Replicate samples indicated that results were reproducible to within 3%. Carbonate content is given throughout as % dry weight of the dried original sample.

4. Results

4.1 Pre-Yasi conditions and impacts on reef flat geomorphology and ecology

4.1.1 King Reef

King Reef is the largest mainland attached fringing reef on the GBR, and during spring low tides an extensive reef flat, covering an area of ~3 km^2, is sub-aerially exposed (Fig. 2A). Although a living coral community occurs along the seaward reef flat margins and on the reef front slope that extends to the surrounding sea floor (depths of 5-6 m), King Reef is in a 'senile' evolutionary stage (sensu Hopley et al., 2007), with reef initiation having occurred between ~5,600 and 5,800 cal yBP (calibrated years before present), and reef emplacement having largely ceased by ~ 4,500 cal yBP (Perry and Smithers, 2011; Roche et al., 2011). The central and landward areas of the reef flat at King Reef form a more or less horizontal surface (Fig. 2B) at an elevation of between ~0.2-0.4 m above LAT level. In its pre-Yasi state (based on data collected in 2009), much of the substrate across the main reef flat was dominated by a mixed carbonate-terrigenoclastic sediment veneer (Fig. 2B) with abundant abraded coral rubble clasts and rhodoliths present. This surface was also colonised by isolated coral heads (numerous small *Goniastrea* colonies to ~40 cm diameter) and occasional colonies of *Turbinaria* (Fig. 2B). The seaward reef flat exhibits a subtle increase in topography as the relief between the substrate and the tops of exposed fossil *Porites* microatolls increases (these dating from ~ 4,500 cal yBP; Roche et al., 2011). Along this seaward reef flat margin, pre-Yasi assessments documented living coral cover of ~30%, and a coral community dominated by *Montipora digitata*, *Porites rus* and *P. lobata*, *Echinopora* sp. and *Acropora pulchra* (Fig. 2C) (Roche et al., 2011). Numerous living *Porites* bommies also occurred that formed a field of flat topped colonies extending across an area of ~150 m with an increasing relief offshore between the bommie tops and the reef substrate (Fig. 2D). Data on the gently sloping reef front are more patchy, but underwater observations made in 2009 suggest extensive colonisation of the substrate by large colonies of *Acropora*, *Montipora*, *Turbinaria* and *Echinopora*.

TC Yasi had little or no impact on reef flat geomorphology at King Reef. Major reworking of the reef flat surface did not occur, and we could find no evidence for major sediment scouring or erosion along either the seaward reef flat or across the expansive main reef flat environment. Indeed, across the central and landward areas of the reef flat evidence for the passage of the cyclone is extremely limited. Only rare broken or over-turned corals were observed, and the small *Goniastrea* and *Turbinaria* coral heads that were abundant pre-Yasi were generally not visibly affected (Fig. 3A). More conspicuous geomorphological effects are seen in the seaward reef flat areas, but again these are relatively minor, and restricted to scattered coral blocks have been thrown up from the reef front (Fig. 3B). however, we note that no storm rubble ridge was produced at this locality. Most of the numerous *Porites* microatolls also remain undamaged and alive, although some have been fractured *in situ* and/or are partly tilted (Fig. 3C). However *Acropora*, *Montipora* and *Echinopora* colonies that were previously abundant and provided an expansive veneer of living coral between the *Porites* microatolls experienced high mortality – total live coral cover along the seaward reef flat declined from ~35% to <10% (Fig. 3D). Some of these colonies are broken but most remain intact and appear to have died *in situ*, and are now covered with filamentous and turf algae (Fig. 3E). In the absence of evidence indicating physical destruction, sediment burial or abrasion, we infer that the widespread mortality of these corals was probably driven by freshwater inundation either by direct rainfall during the event or by flood discharges immediately after: the extent of post-Yasi flood plumes being evident in available satellite imagery (see http://e-atlas.org.au/content/cyclone-yasi-satellite-images). Over the longer term, and of interest in terms of how reef framework fabrics accumulate in these environments, it is perhaps most likely that these colonies will breakdown to form *in situ* death assemblages. However, we also note that even only 6 months after TC Yasi there is clear evidence of colony re-growth occurring, with small branched corals re-appearing from within the dead *in situ* framework (Fig. 3F), a process rather analogous to that described following coral bleaching induced mortality by Diaz-Pulido et al. (2009). In deeper water (2-4 m) along the reef front most coral colonies seemed to have survived, even large plate-like forms, with only local minor breakage and localised fragmentation of branched *Acropora* observed in our brief assessment of these environments.

4.1.2 Lugger Shoal

Lugger Shoal is a small, roughly 'L-shaped' reef, with both the limbs ~450 m long and ~150 m wide (Perry et al., 2009). The reef is located within a headland embayment that is fringed by a narrow zone of mangroves to the south and by a siliciclastic-dominated beach to the west (Fig. 4A). The reef itself is located around 400 m offshore from the high tide mark of the beach. Coring and radiometric dating indicates the reef initiated ~800 cal yBP and reached sea-level in the last ~100-150 years (Perry et al., 2009). It is thus in a late 'mature' stage of its development (sensu Hopley et al., 2007). The reef flat at Lugger Shoal is at an elevation of ~0.3 m above LAT and deepens slightly towards its leeward side. In its pre-Yasi state, large *Porites* sp. bommies (up to ~1.5 m in height and to ~2 m in diameter) dominated the reef flat (Fig. 4B) and many of these colonies were clearly constrained in their upward growth by present sea level and adopted a microatoll morphology. Coring investigations have indicated that these bommies extend through the entire reef sequence (Perry et al., 2009), and provide an important structural component to the reef, between which a mixed clast- to matrix-supported coral rubble facies has accumulated. Prior to Cyclone Yasi, the inter-bommie deposits were either covered with fine sands and muds, or colonised by living corals (Fig. 4B). Live coral cover across the reef flat was ~ 35% in 2007 with *Porites* sp. being the dominant coral (comprising ~70 % of the modern coral assemblage; Perry et al., 2009). Other common corals recorded include branched and tabular colonies of *Acropora* sp. (mainly along the seaward areas of the reef flat), *Turbinaria frondens*, *Goniastrea aspera*, *Favia* sp., *Favites* sp., *Galaxea* *fascicularis* and *Platygyra* sp.. Macroalgal and turf algal cover on the reef flat was ~ 3 % and 28 % respectively, and crustose coralline algal cover ~15%. Unconsolidated sands and muds comprised ~15% of the reef flat surface.

TC Yasi caused only limited geomorphological and ecological change at Lugger Shoal. The large *Porites* colonies were mostly intact, although a few large bommies, especially towards the rear of the reef flat, were either partially fractured or toppled (Fig. 5A), although the living tissue cover of these colonies appeared complete. There was also no obvious change in the topographic relief on the reef flat in terms of the depth to substrate surface in the intra-bommie areas. Colonies of *Goniastrea* and *Galaxea* that previously colonised the inter-bommie substrates seem largely undamaged (Fig. 5B), with limited evidence of fracturing or toppling, and there is little or no evidence of coral rubble deposition. However, colonies constructed by some taxa that were abundant prior to Yasi, such as *Turbinaria frondens,* were noticeably absent and are assumed to have been removed during the cyclone. It is interesting to note that along the adjacent shoreline, both the fringing mangroves along the northern side of Tam O'Shanter point, and trees on the mainland coast, had been badly damaged, with trees almost completely defoliated and some uprooting evident.

4.1.3 Dunk Island (Resort Reef)

At Dunk Island our investigations focused on a fringing reef developed within an embayment on the north-west corner of the island, which we have previously termed 'Resort Reef' (Perry and Smithers, 2010) (Fig. 6A). Two elevationally distinct areas of reef flat development are recognised, one in the NE corner of the embayment, and one extending from the SW end of the bay seawards, to the rear of which a steep, coarse-grained siliciclastic beach is developed. Previous coring and dating reveal that this reef was emplaced over two temporally discrete periods. The first reef-building phase occurred during the late stages of the post-glacial marine transgression-early sea-level highstand in this region, between ~6.9–4.5k cal yBP, the second followed the late Holocene sea-level regression and stillstand (~1.6k cal yBP to present) (Perry and Smithers, 2010). The NE reef flat is at ~ 0.8 – 1.0 m above present LAT level and is clearly relict. In its pre-Yasi state (based on data collected in 2008 and 2009), its surface was covered in siliciclastic intertidal sands/muds and lithic clasts, and no living corals occurred (although the tops of numerous dead *Porites* microatolls were visible; Fig. 6B). The reef flat across the SW area of the bay is geomorphologically distinct and is lower (~0.4–0.5 m above LAT). This reef flat is exposed over a larger area than the NE reef flat, but is also clearly relict – it is partially veneered by muddy-sands and dead *in situ Porites* microatolls (relief of 0.1–0.15 m above the surrounding substrate) are exposed. Pre-Yasi, numerous small (<0.3 m diameter), living *Goniastrea aspera* colonised this surface, whilst along much of its seaward reef flat edge there was widespread colonisation by corals of the genera *Acropora* sp., *Montipora* sp., *Galaxea* sp. and *Favia* sp., and a discontinuous zone of large *Porites* 'bommies' occurred along the reef front (Fig. 6C). We interpret these corals as a recent patchy living community growing upon the underlying reef framework rather than a continuous extension of it. Despite the age differences, both reef flats are examples of reefs in 'senile' evolutionary states (sensu Hopley et al., 2007).

Dunk Island suffered major damage from TC Yasi, with rainforest trees extensively defoliated and broken, and resort infrastructure, including the buildings and boat jetty destroyed beyond use (Fig. 7A). The beach at the back of the reef flat and in front of the resort was severely eroded, with the toe-of-beach migrating landward by up to ~10 m and sediment stripped from the beach face deposited onshore (Fig. 7B). The remnant beach is thus much narrower and more of the underlying mid-Holocene reef flat exhumed by Yasi is now exposed (compare Figs. 7C and D). In contrast to these substantial changes there is little visible evidence of change to the basic geomorphic structure of the reef flats (Fig. 7E); we identified no evidence for major reef flat erosion and only localised evidence of coral rubble deposition likely to be associated with the event. We could detect no major changes to the geomorphology of the mid-Holocene age (high elevation) reef flat, but abundant trees/logs have been washed onto the reef flat surface and a few isolated coral blocks (to ~0.5 m diam.) were deposited. Similarly, no major geomorphic changes are evident on the lower late Holocene age reef flat. However, some ecological changes clearly occurred to the relatively depauperate pre-Yasi coral community. Most notably, localised over-turning/toppling of live corals, the deposition of a few large colonies or reef blocks (Fig. 7F), and some evidence of breakage/toppling of *Acropora*/*Montipora* colonies were observed along the seaward edge of the reef flat. However, across the main reef flat itself, the numerous small *Goniastrea* colonies that were present pre-Yasi appear to have survived, and many smaller colonies of *Turbinaria*, *Acropora* and *Montipora* whose size suggest were growing prior to TC Yasi, were also undamaged (Fig. 7G). Also notable is the abundance of very small juvenile recruits of *Acropora* and *Turbinaria* on exposed intertidal reef rock. In the shallow reef front areas the fields of large *Porites* bommies that were present pre-Yasi also survived without physical damage, but many have suffered either partial or complete mortality on their uppermost surfaces (Fig. 7H) (tissue cover is better on their flanks) and these upper surfaces now have turf algal cover. As at King Reef this seems most likely a function of freshwater-induced bleaching.

4.1.4 Paluma Shoals (Southern Shoal)

Paluma Shoals is located ~150 km south of the mainland landfall track of TC Yasi and is comprised of a series of reef platforms developed along an erosional shoreline in central Halifax Bay. The reef can be divided into two main areas; 1) a Southern Shoal; and 2) a series of connected reef flats, collective described as the North Shoal (Smithers and Larcombe, 2003; Palmer et al., 2010) (Fig. 8A). The focus of our post-Yasi investigations was the South Shoal, which is located ~500 m seaward of the main shoreline, and which extends ~750 m alongshore and has a reef flat ~300 m wide. The reef flat is elevated ~0.1 m above LAT level and is presently detached from the wide intertidal sandflats that characterise this section of coast by a narrow (~30 m wide), shallow, muddy subtidal channel. Coring and radiometric dating indicates the South Shoal initiated growth ~1,200 cal yBP and reached sea level in the last 100-200 years (Perry et al., 2008). Data collected pre-Yasi in 2006 (and which subsequent visits confirmed was typical of the pre-Yasi state right up until just before that event) confirm that the seaward reef flat coral community on the South Shoal was dominated by colonies of *Galaxea fascicularis* and *G. aspera* microatolls (up to ~ 2 m diameter). These microatolls stood ~0.5 m above LAT and exhibited a strongly heliotropic growth form (Smithers & Larcombe, 2003) and were a very distinctive feature of the reef flats (Fig. 8B). Inter-microatoll substrates were dominated by large stands of *Acropora pulchra* (Fig. 8B) and*Turbinaria*. Along the landward edge of the reef flat *Porites rus* microatolls were abundant. Live coral cover was measured at ~50-60% across the reef flat (but up to ~80 % in central to seaward areas) (Palmer et al., 2010).

Cyclone Yasi had variable impacts and left a different signature of its passage on different areas of the South Shoal at Paluma. In general, the basic *Goniastrea*-dominated make up of the reef flat was unaffected (Fig. 9A) with only localised colony fracturing and/or toppling (Figs. 9A, B), and live coral cover remaining relatively high (25-30%) along the seaward reef flat. In addition to *Goniastrea*, expansive stands of *Galaxea* are still present and, less commonly, *Turbinaria* and *Platygyra*. The most obvious impact of Yasi along seaward reef flat margin was the localised deposition of a rubble/shingle ridge, which forms a low elevation sheet-like deposit of mainly *Acropora* shingle as well as *Turbinaria* plates and blocks of *Galaxea* (Figs. 9C, D). These deposits are ~20-30 cm thick and thin landwards over a distance of ~20-30 m and are sourced, we assume, at least in part from the reef front. Across the central and landward areas of the reef flat, the large *Goniastrea* bommies again remain *in situ* and generally undamaged, although occasional examples of toppled/overturned corals were observed. The substrate between these bommies comprises sand and rubble with small *Goniastrea* colonies present, and a high turf and macroalgal cover.

The major change observed across the central and landward areas of the reef flat at Paluma Shoals was loss of the previously extensive *A. pulchra* stands. In some cases patches of relatively fresh looking *Acropora* shingle have been deposited around *Goniastrea* heads, perhaps suggesting that they were deposited more or less in place through colonies collapsing in on themselves, but in other cases this branched *Acropora* shingle forms sheet-like deposits up to 30-40 cm thick, again deposited in/around large *Goniastrea* bommies (Fig. 9E), and may have been transported short distances. *Porites rus* remain abundant in the landward reef flat zone (mostly in-place and undamaged albeit with some localised toppling/tilting; Fig. 9F), and colonies of *Pocillopora*, *Platygyra* and *Turbinaria* also remain mostly intact. There is no evidence for major sediment erosion or deposition in the immediate vicinity of Paluma Shoals, although extensive onshore studies were not conducted.

4.2 Impacts on intertidal and shallow subtidal sedimentary environments

In addition to observations made of the main geomorphic and ecological changes that occurred following TC Yasi, surficial sedimentary data were also collected from sites across and around two of the reefs, at Lugger Shoal and Dunk Island, to allow comparisons with pre-event data. These are described below and provide an insight into the transport and deposition of nearshore sediments that occurred during and immediately after the event. These post-Yasi data were collected about 6 months post event and so we must assume that some sediment reworking had occurred between TC Yasi and sampling.

4.2.1 Lugger Shoal

Across Lugger Shoal, pre-event surficial sedimentary data were available from along 3 cross-reef, shore normal transects (Fig. 10). Analysis of pre-Yasi sediment samples indicate that surface sediments on the main area of the reef were dominated by medium to coarse-grained sands with ~ 10-15 weight % fine content, whilst off-reef subtidal sediments to seaward of the reef flat were slightly finer-grained (mainly medium-grained sands with ~15-30 weight % fines content) (Figs. 10 B, C). Pockets of high mud deposition (>30 weight % fines) occurred in the back-reef areas, and these shallow sub-tidal/intertidal substrates were dominated by fine to very fine-grained sands (Fig. 10B). Post-Yasi samples from these same sites show a changed pattern of sediment distribution, consistent with the removal and flushing of the finest-grained sediments. The abundance of the finest grain size fractions is reduced in samples both across the reef flat and from the back-reef and seaward areas (compare Figs. 10C and E) and is reflected by an increase in sediment mean grain size. Given that there is no evidence of any onshore sediment accumulation our interpretation is that these finer-grained sediments have been flushed offshore into deeper water.

4.2.2 Dunk Island

Pre-event surficial sedimentary data were available from 50 spot sample points covering the full extent of the embayment at Resort Reef at Dunk Island, including both the reef flats, the upper beach and the immediate shallow sub-tidal areas (Fig. 11). These samples were collected in 2009 and reveal that the carbonate content and weight % fines content of sediments around the embayment were spatially heterogeneous. Highest carbonate content values (> 80 weight %) occur in sediments recovered from points in the immediate vicinity of the exposed reef flats and decrease both to seaward and landward (Fig. 10A). High intertidal and beach sediments are dominated by siliciclastic sediments (mainly quartz) and have carbonate contents of <20 %. Weight % fines content (Fig. 10C) of surface sediments also varies markedly, with relatively low values (<10 %) in sediment collected from the exposed reef flats, and much higher values (>40 %) in the shallow reef front and back-reef areas. Mud content in the well-sorted beach sediments is also very low (< 5%). Analysis of surficial samples from the same sample points collected post-Yasi indicate a general reduction in the weight % carbonate content of the sediments across the whole embayment (Figs. 10A, B), whilst there is a general trend for an increase in the mud content of the same samples (Figs. 10C, D), at least in areas away from the reef flat. Based on field observations during sample collection, when the reef flat was subaerially exposed, our interpretation is that these changes reflect the deposition of a fine mud drape on the surface of the reworked reef flat (rather than stripping of carbonates). In fact shallow core samples (described elsewhere) confirm that the main sediment impact across these sites has been a stripping/flushing of muds in the upper ~10 cm of the sediment column, and that these muds are now re-accumulating as a surficial drape on the reef flat surface.

5. Discussion

Although TC Yasi was one of the most powerful recorded cyclones to have crossed the Queensland coast of Australia, the observed impacts on nearshore reefs examined in the central-northern section of the Great Barrier Reef were highly site specific and variable in character. Geomorphic changes to the reef were generally limited, we observed no major erosion of the reef framework structures across the reef flats at any of the reefs examined, and ecological impacts, although significant at some sites, were similarly localised and site specific. In general therefore, the degree of damage was less than might have been envisaged for a storm of this magnitude, and it is most pertinent to note, especially given the generally poorly lithified, sediment-dominated fabrics that are typical of these nearshore reefs, that the basic geomorphology of the reef flats across the reefs examined remained essentially unchanged.

In terms of coral mortality across the sites examined, the type and magnitude of decline was highly variable. At some sites widespread mortality of branched coral taxa occurred as a function of high wave energy regimes e.g., Paluma Shoals. At other sites e.g., King Reef, equally high mortality occurred, but the dead coral skeletons remain *in situ*, and at this site freshwater-induced bleaching appears the most likely cause of death. At Dunk Island and Lugger Shoal, there was little change in the ecology of the reefs and limited colony mortality evident. In terms of geomorphological features associated with the event, these appear similarly variable across sites, but we note no evidence for major changes to the reef flats occurring. There is, however, clear evidence of localised rubble and sediment erosion and/or of sediment and rubble deposition at all of the sites we visited e.g., in the form of coral fracturing, rubble deposition, and sediment movement, but again these were highly site specific.

At Paluma Shoals, the clearest geomorphic evidence of TC Yasi's path is the localised deposition of a low elevation seaward storm ridge and of shingle sheet deposition across central areas of the reef flat. These shingle deposits represent localised phases of essentially instantaneous framework accumulation akin to that documented following Hurricane Allen in Jamaica (Scoffin and Hendry, 1984). Conversely, at Lugger Shoal and at Dunk Island, major erosion and deposition of coral rubble is not observed, but instead significant reworking and transport of beach, back-reef and shallow reef front sediments has occurred. At Lugger Shoal sedimentary datasets provide evidence for major offshore fine sediment flushing, whilst at Dunk Island, there is clear evidence of major onshore coarse sand deposition – evident through beach and landward reef flat sediment stripping – and subsequent (post-event) mud deposition across the reef flat. The spatial distribution of these different ecological and geomorphic changes across the study sites are summarised schematically in Fig. 12.

An obvious question arising in relation to these observed impacts (or lack thereof) is what factors have dictated the variable nature of the geomorphic processes and deposits, and ecological impacts observed? Several factors are likely to have contributed to the observed patterns, and these include: site proximity to the landfall path, reef location relative to the coastline and any coastal protection afforded, pre-event ecological conditions, and, as a contributing factor, reef evolutionary state (sensu Hopley et al., 2007). In terms of site proximity, the eye of the cyclone passed very close to three of the sites we examined, King Reef, Lugger Shoal and Dunk Island. Whilst there is some evidence for colony toppling and localised rubble generation at each of these sites, and evidence of significant back-reef and reef front sediment transport at at least two sites (Lugger Shoal and Dunk Island), the types and patterns of physical damage to the reefs was: 1) less than one might have projected; and 2) inconsistent between sites. However, as other studies have shown this is perhaps not surprising because local differences in reef orientation relative to the angle of wave approach and subtle differences in wind/wave speed can significantly influence the degree of damage (Poutenin, 2007). Such factors are thus highly likely to have had a strong influence on the degree of impact caused by TC Yasi. The eye of the storm transited a route located approximately centrally between all 3 of these sites, and thus the predominant direction of wind/wave activity would have been from the east to south east as the storm approached the shore, and then from the south to south west as the storm moved on land. As a result, some degree of protection would probably have been afforded by the headlands and embayments close to which at least two of these reefs, Lugger Shoal and Dunk Island reef, have formed. In contrast, Paluma Shoals, which is located about 150 km to the south, sits within the central areas of an open, exposed embayment (Halifax Bay), and would have received the full force of the storm-driven waves that approached, in this locality, from the north-north-east. Thus, perhaps somewhat counter-intuitively far more evidence of physically driven geomorphic and ecological change is observed at this site.

An additional contributing factor in terms of the types and amount of change that occurred will have been the pre-existing ecological condition of the reefs and, linked to this, their evolutionary state (see Perry & Smithers, 2011). For example, at Dunk Island, both the older and younger reefs are in 'senile' evolutionary states (*sensu* Hopley et al., 2007) and were already characterised by very low (<5%) live coral cover. Not surprisingly therefore, little or no change in coral cover is observed on these reef flats. Similarly, across the expansive and planar 'senile' reef flat at King Reef there was little or no change observed to what was already a relict, low live coral cover (<5%) system. Conversely, at Paluma Shoals, a reef with high (up to ~80%) pre-Yasi live coral cover, extensive destruction of branched coral taxa occurred during the event. Thus, the reef furthest from the landfall path in our study (Paluma Shoals) actually suffered the greatest ecological damage, in part because of its exposed, open water setting (as discussed above), but also because it was characterised by coral assemblages of which some components were highly susceptible to physical damage. Additionally, where major ecological changes occurred following TC Yasi, site-specific differences clearly occurred in terms of the major drivers of the observed ecological changes. For example, whilst wave action was undoubtedly responsible for most of the ecological change observed at Paluma Shoals (through branched *Acropora* destruction), along the seaward margins of the reef flat at King Reef and at Dunk Island, dead corals remain mostly *in situ* even where, in the King Reef case, these comprise communities of typically 'fragile' coral taxa (*Montipora*, *Acropora* etc). In these cases mortality can, most likely, be attributed to freshwater-induced coral bleaching. These patterns of high spatial heterogeneity and variable impacts mirror those reported at sites on the mid- and outer shelf reefs in a post-Yasi assessment conducted by the Australian Institute for Marine Sciences.

What is perhaps more surprising, given the magnitude of Yasi, is that clear cyclone related depositional features are not more common. Indeed, it is only really at Paluma Shoals that any evidence is seen for the formation of an (albeit limited) shingle ridge and for the deposition of shingle deposits across the reef. No other such features are seen at the sites. Again, this is largely linked to the availability of suitable ecological stocks of corals that can be broken and thus contribute to such landform development. Few other ‘typical’ cyclone related depositional features (see summary in Scoffin, 1993), with the exception of a very few isolated coral blocks and localised over-turning of coral colonies, are seen at any of the sites. Localised toppling and fracturing of large *Porites* and *Goniastrea* bommies and microatolls attest to the wave energy regimes that impacted these reefs, but limited abundance of rubble generating coral taxa has restricted shingle ridge development.

A concluding point that can be made in relation to the patchy and variable nature of the features observed following TC Yasi is that the preservable signature of this high magnitude event will actually be very variable within and between sites. Indeed, one can state with some confidence, that the fossil record would not provide a clear or consistent geomorphic or ecological signal of this event such as observed in some fossil reef sequences (Perry, 2001). In some localities and in some parts of individual reefs (Paluma Shoals is a good example) clear phases of more or less instantaneous rubble deposition have occurred. Given that this rubble deposition was widespread across the reef flat it is likely that high resolution dating approaches would probably detect these sequences as discrete storm packages in core or outcrop and that such depositional packages would have good preservation potential. At the other sites, however, clear geomorphic signatures of the event are patchy and would be very hard to discern in any preserved sequence. Similarly, there are few clear ecological indicators that would leave a preservable trace of the event, or at least one that could be clearly pinned to the passage of a major cyclone. Thus whilst clear evidence of multiple cyclone events, as preserved in storm ridge sequences, have been observed in some coastal settings (Hayne and Chappell, 2001; Nott and Hayne, 2001; Nott, 2011;

Nott et al., 2009), the preservable signatures of these events within nearshore reefs seem more ambiguous and site specific.

In summary, all of these reefs are examples of reefs with well developed, often relict reef flats, a factor that has to varying degrees contributed to limiting major geomorphic and ecological change. A question that arises is about the immediate ecological response and recovery of coral communities impacted by Cyclone Yasi. Our field observations suggest this is also likely to vary markedly between the two most heavily impacted sites, King Reef and Paluma Shoals. At both sites ecological change was highly taxa specific, with massive taxa relatively unaffected, but with branched and foliose colonies declining markedly in abundance. At King Reef, however, there is already evidence for on-going re-growth of branched colonies that underwent extensive (inferred) freshwater-induced bleaching, with branches of *Montipora* emerging from the otherwise dead *in situ* reef framework (see Fig. 3F). Relatively rapid recovery of these colonies is likely. Similarly, numerous juvenile corals (that survived Yasi) appear to be growing well, and new recruits were also observed on available substrate. In contrast, at Paluma Shoals, widespread physical destruction and complete mortality of branched *Acropora* occurred, and new recruitment into the site will be necessary for recovery of these previously abundant reef flat corals. However, evidence from other inshore sites on the GBR suggests that such recovery can happen relatively quickly (Done et al., 2007). More generally, the reef flats at King Reef and Lugger Shoal are both dominated by large *Porites* colonies, and at Paluma Shoals by large *Goniastrea* colonies, taxa that seemingly have a high resilience to physical disturbance. These taxa have been relatively unaffected and thus the main coral structural facets of the reef flat communities remain little changed.

6. Conclusions

TC Yasi had highly site specific and spatially highly heterogeneous impacts on the geomorphology and ecology of the turbid-zone coral reefs located within the nearshore areas of the central Great Barrier Reef. Overall impacts, given the size of the cyclone, were generally far less than anticipated, and exposure regime and pre-existing ecological reef state, were probably more important as controls on the degree of change that occurred than proximity to the immediate landfall path. Ecological impacts were highly varied, with the most significant impacts evident at King Reef (probably caused by rainfall-induced freshwater bleaching) and at Paluma Shoals, where widespread physical destruction of branched *Acropora* occurred. Clear evidence of colony regrowth was observed at King Reef, but at Paluma Shoals *Acropora* recruitment will be necessary for recovery of this component of the reef flat community. More massive taxa (*Porites* and *Goniastrea* microatolls and bommies) were relatively unaffected. Only localised geomorphic change was evident across the sites, but again the resultant landform changes were highly site specific: at Paluma Shoals, in the form of storm ridge/shingle sheet deposition; at Lugger Shoal through major offshore fine sediment flushing; and at Dunk Island, through major onshore coarse sand transport and deposition. The type and magnitude of damage was strongly influenced at the site level by differences in exposure, evolutionary state (and thus general ecological conditions), and by differences in reef flat coral taxa that vary in susceptibility to disturbance. Critically, we observe no evidence of major erosion of the framework structure of these reefs implying, and despite their sediment-dominated unlithified internal structure, a high degree of physical resilience to major physical disturbance events.

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Figure captions

Fig. 1 Location map showing: (A) general areas of study in central Queensland; (B, C) location of study sites referred to; and (D) information on Cyclone Yasi's storm track and intensity. King Reef, Dunk Island and Lugger Shoal are most immediately influenced by river run-off from the Herbert River Catchment to the south (area 9,884 km^2), the Tully Catchment (area 1,683 km^2) which comprises both the Tully and Hull Rivers, and the Johnston Catchment to the north (area 2,323 km^2) which includes Maria Creek (see Map B). Paluma Shoals is influenced by flood plumes from the Burdekin River to the south (area 130,109 km^2), the Ross River Catchment (area 1,708 km^2) and the Black River catchment (1059 km^2).

Fig. 2. King Reef prior to Cyclone Yasi. (A) View looking west across King Reef towards Kurrimine Beach; (B) View across the central reef flat showing planar, sediment filled surface and isolated living *Goniastrea* colonies (arrowed); (C,D) Seaward reef flat margin on spring low tide showing thriving coral communities, dominated by *Montipora*, *Acropora* and (arrowed in 'D') fields of *Porites* microatolls.

Fig. 3. King Reef post Cyclone Yasi. (A) View across the central reef flat areas showing little or no evident change to the planar character of this reef zone. *Goniastrea* colonies remain seemingly unaffected. (B) Isolated Porites colony deposited on the seaward reef flat margin; (C) Fractured, but still *in situ*, *Porites* microatoll to seaward of the reef flat; (D) Dead *in situ* stands of *Acropora* between *Porites* microatolls along the seaward reef flat edge. (E) View showing dead *in situ* coral colonies on the seaward reef flat margin, covered in filamentous algae; (F) View showing re-growth of surviving colonies from the surrounding dead *in situ* framework.

Fig. 4. Lugger Shoal prior to Cyclone Yasi. (A) View south across Lugger Shoal towards Tam O'Shanter Point; (B) View looking towards Dunk Island (top of photo) showing the *Porites* dominated structure of the reef flat and their colonisation by *Goniastrea* colonies.

Fig. 5. Lugger Shoal post Cyclone Yasi. (A) Top surface of tilted *Porites* microatoll along the landward margin of the reef flat; (B) Intact and in-place *Goniastrea* colony on the reef flat surface.

Fig. 6. Resort Reef at Dunk Island prior to Cyclone Yasi. (A) View looking south-west across Dunk Island. 'Resort Reef' is in the embayment in the centre of the picture; (B) View looking across the relict, planar mid-Holocene reef flat, with exposed mid-Holocene *Porites* microatolls visible in the foreground; (C) View landwards across living *Porites* microatolls along the seaward margin of the lower elevation, late Holocene reef flat.

Fig. 7 Impacts of Cyclone Yasi at Resort Reef, Dunk Island. (A) Extensive damage caused to resort infrastructure; (B) Sediments bulldozed out of the resort that were washed onshore during Yasi; Pre- (C) and post- (D) views across the landward areas of the reef flat showing exhumation of the rear reef flat by beach sediment stripping; (E) View of younger, low elevation reef flat showing no signs of major erosion or geomorphic change; (F) Isolated overturned coral on seaward margin of late Holocene reef; (G) Intact colony of *Turbinaria* on the reef flat that clearly survived Yasi; (H) Bleached and dead upper surface of *Porites* microatoll along seaward reef flat margin.

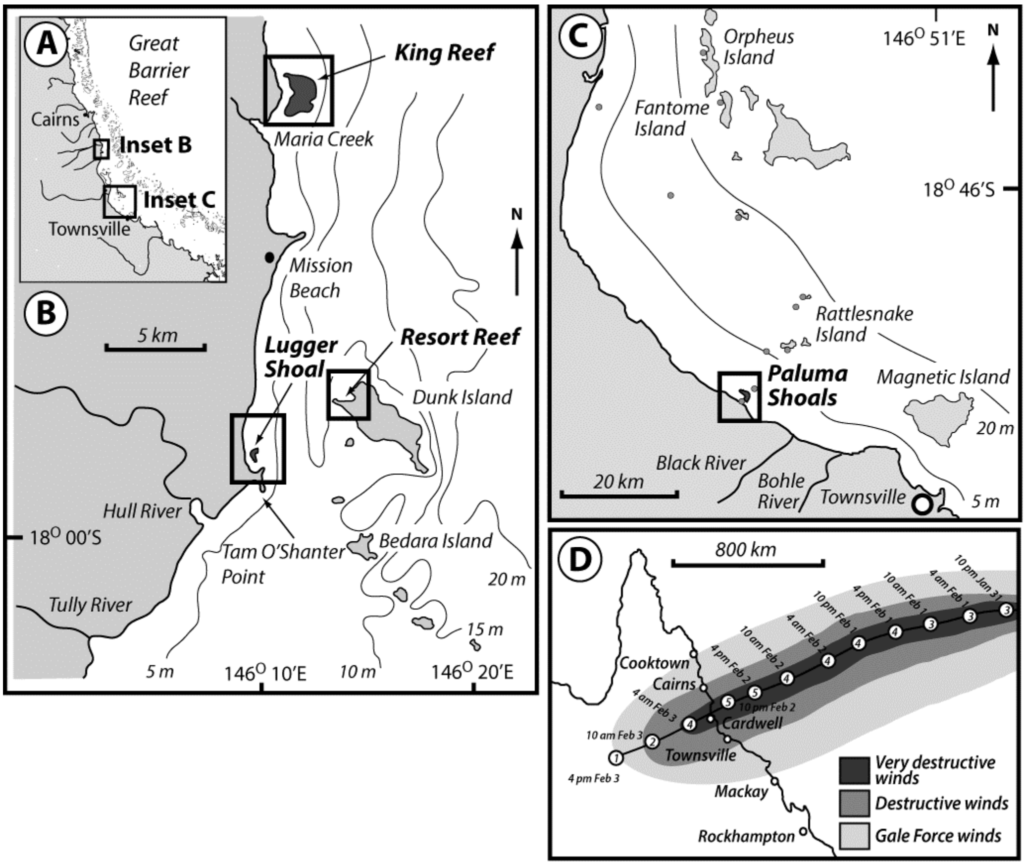
Fig. 8. Paluma Shoals prior to Cyclone Yasi. (A) View across nearshore areas of Halifax Bay. Paluma Shoals are the areas of reef exposed just below the beach line in the top of the picture; (B) View showing high live coral cover and abundance of *Goniastrea* bommies and of *Acropora* stands in the central areas of the reef flat.

Fig. 9. Impacts of cyclone Yasi at Paluma Shoals. Fractured (A) and toppled (B) *Goniastrea* bommies, but note that the basic *Goniastrea* bommie dominated character of the reef flat persists. (C) View across seaward reef flat showing localised development of a low elevation shingle ridge or sheet, which has partially covered (in D) *Goniastrea* bommies. (E) Close-up of *Acropora* shingle deposits in the central reef flat area; (F) Tilted *Porites* microatoll and colonising *Goniastrea* head along the landward margin of the reef flat.

Fig. 10. Sediment properties of the nearshore and shallow sub-tidal sediments on and around Lugger Shoal pre- (B, C) and post- (D, E) Cyclone Yasi.

Fig. 11. Sediment properties of the nearshore and shallow sub-tidal sediments in and around the Resort Reef embayment pre- (A, C) and post- (B,D) Cyclone Yasi .

Fig. 12. Schematic diagram illustrating spatial variations in both the ecological and geomorphic impacts of Cyclone Yasi across the four reef sites examined.



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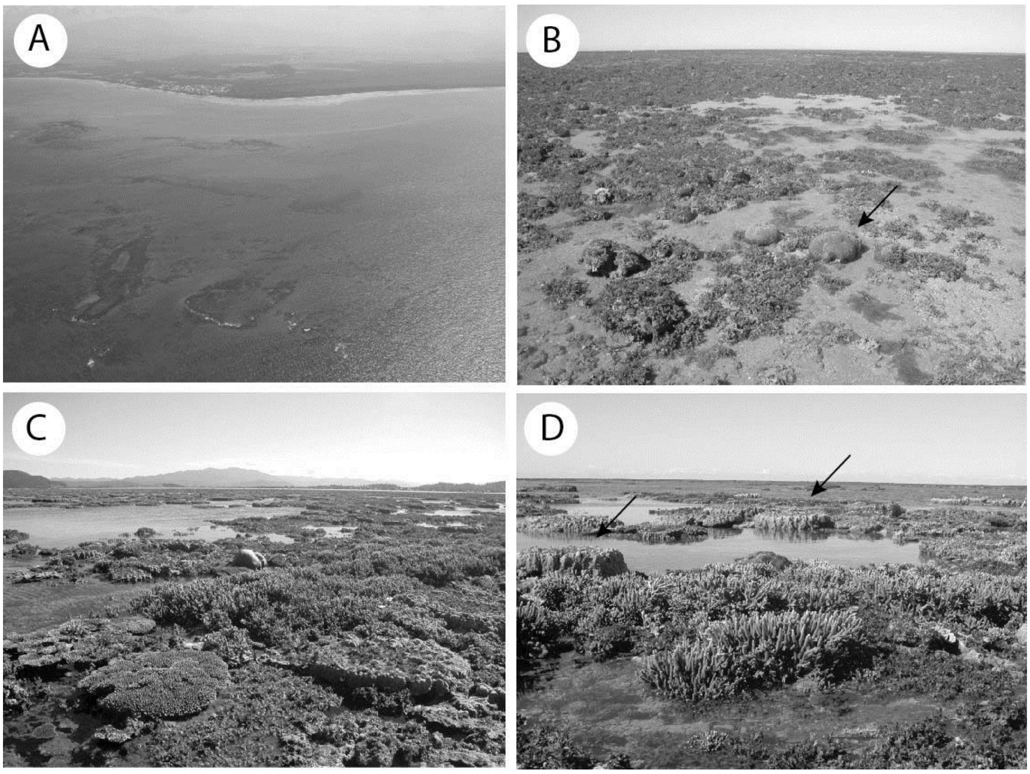

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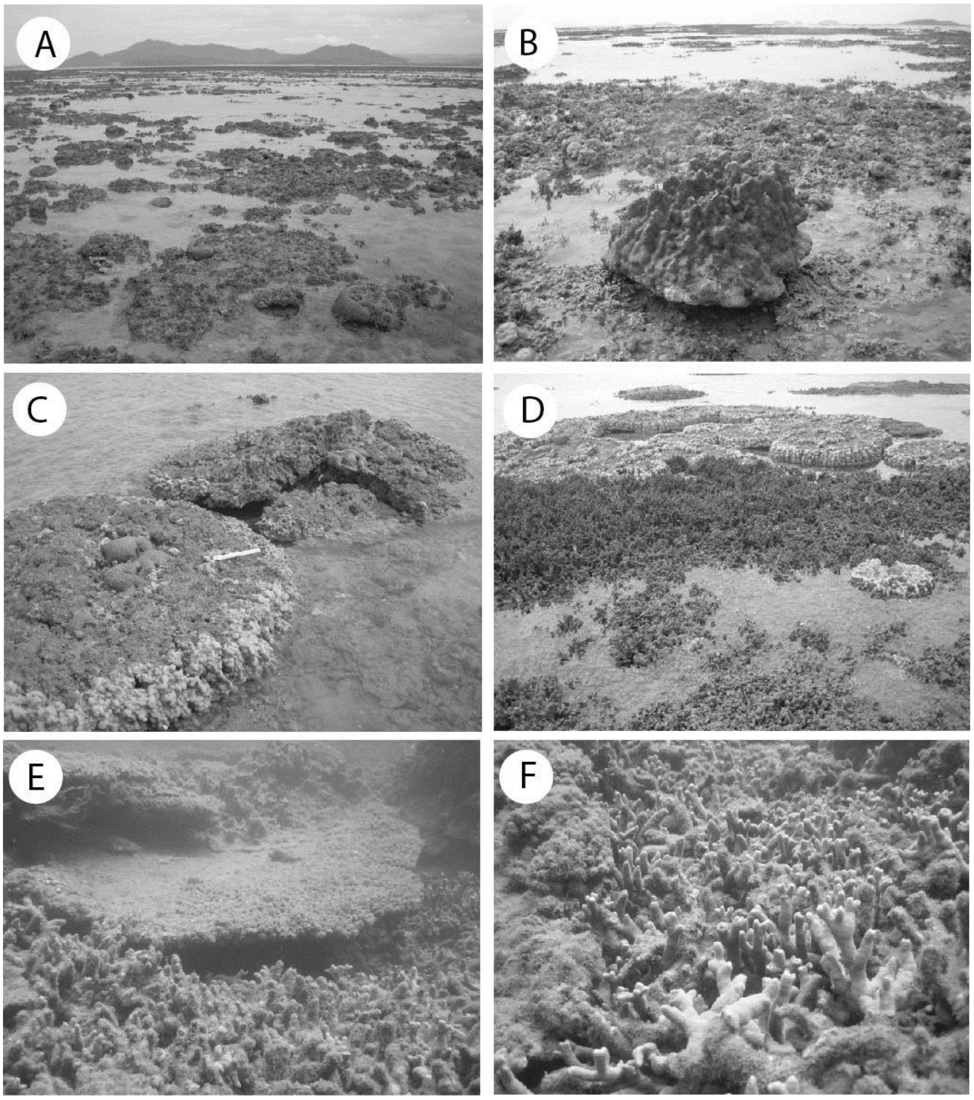
A
B
C
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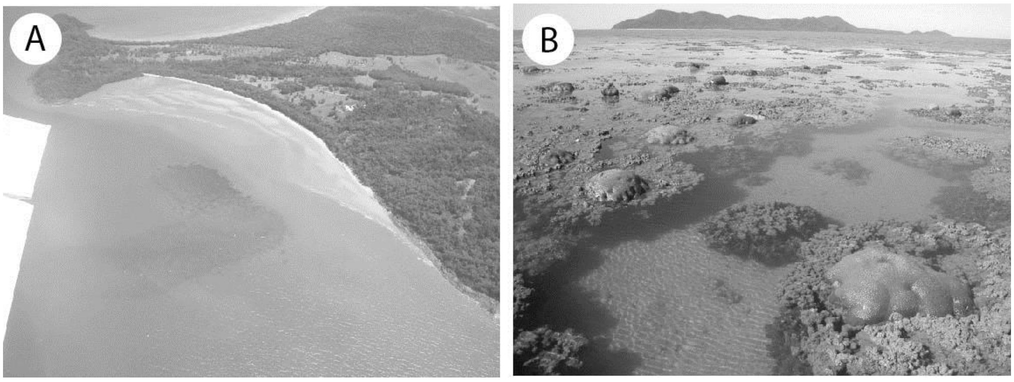
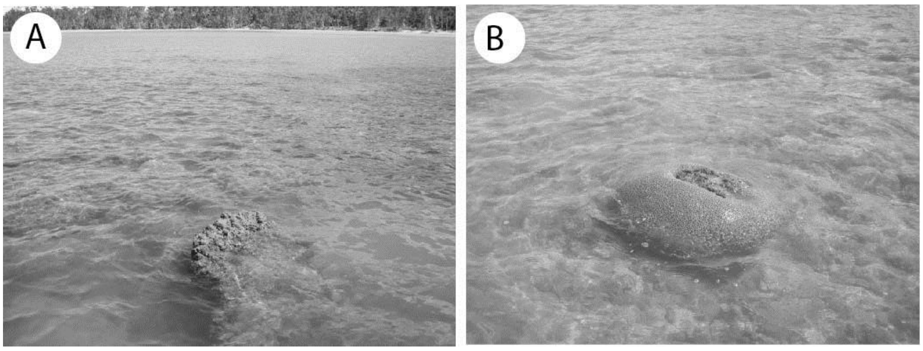
E
F


A
B


A
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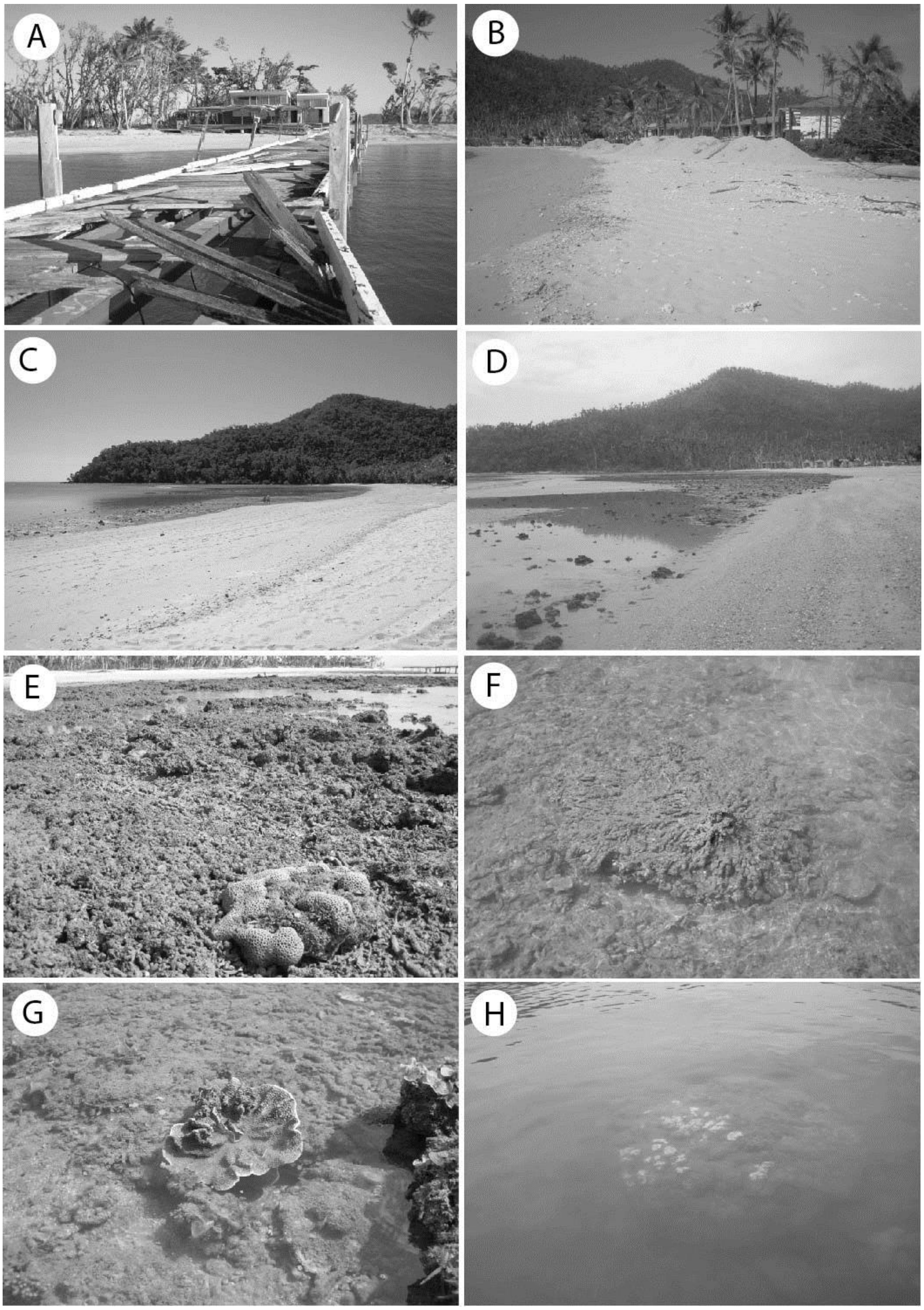
A
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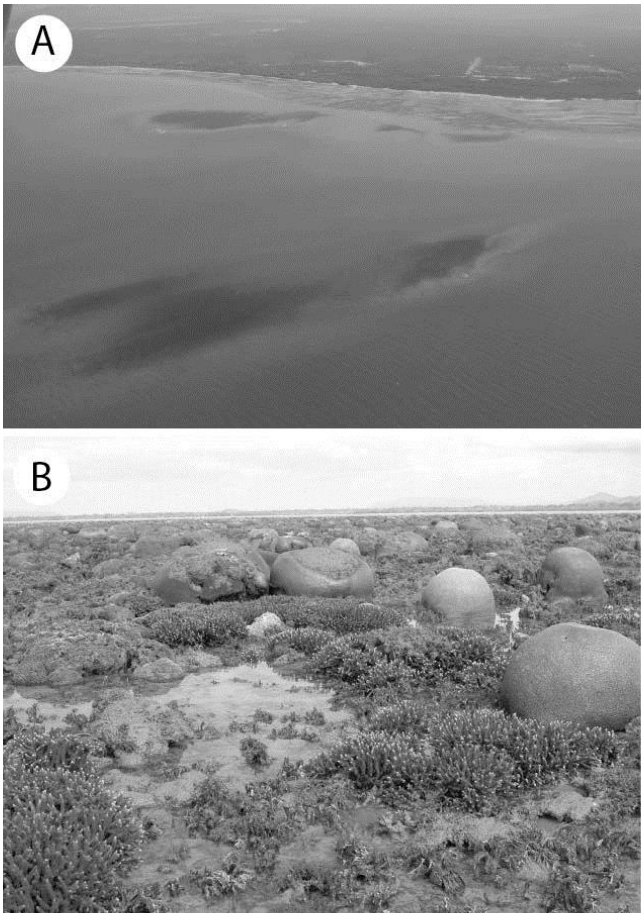
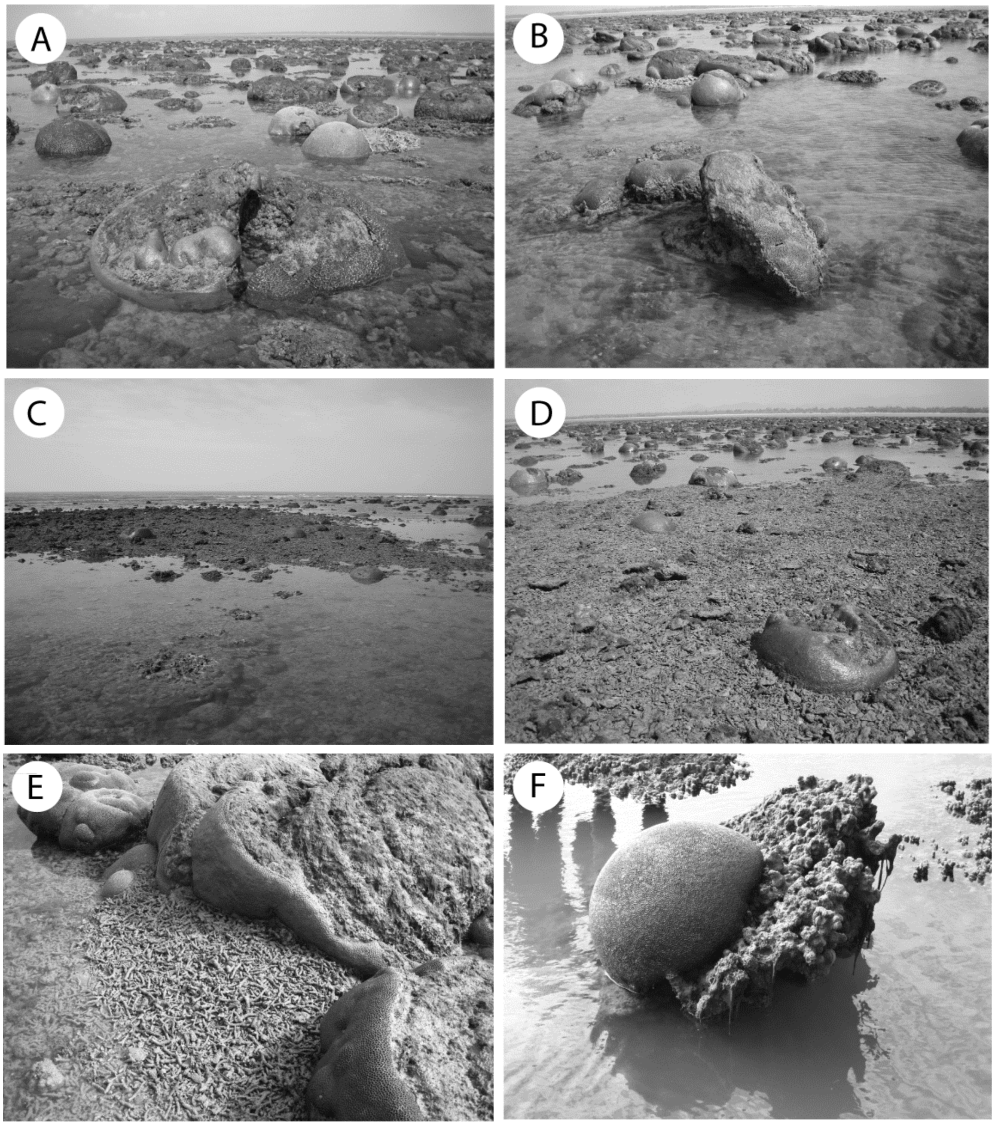

A
B


A
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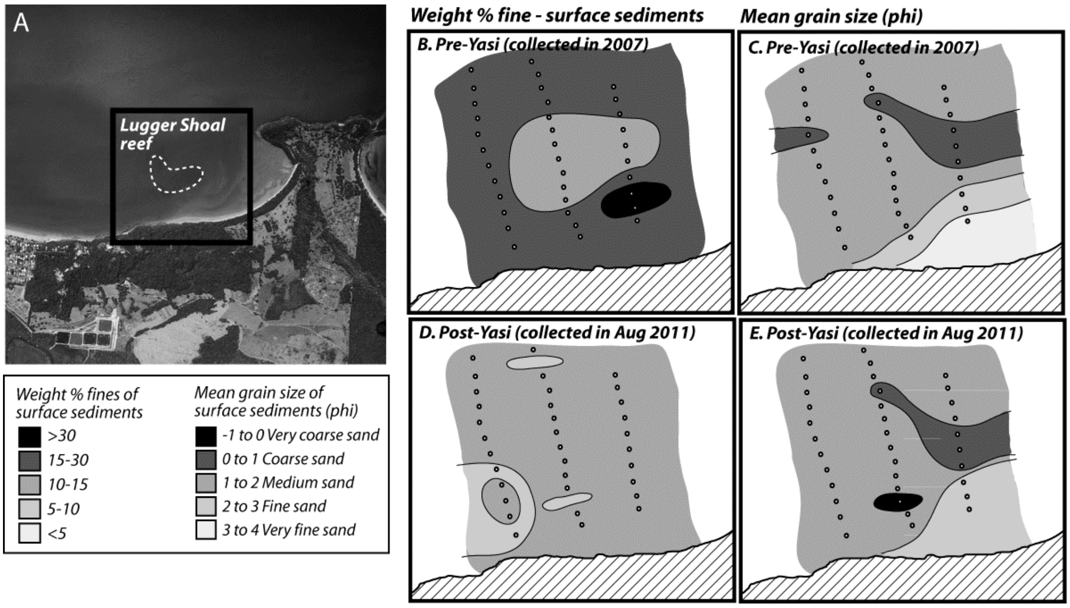
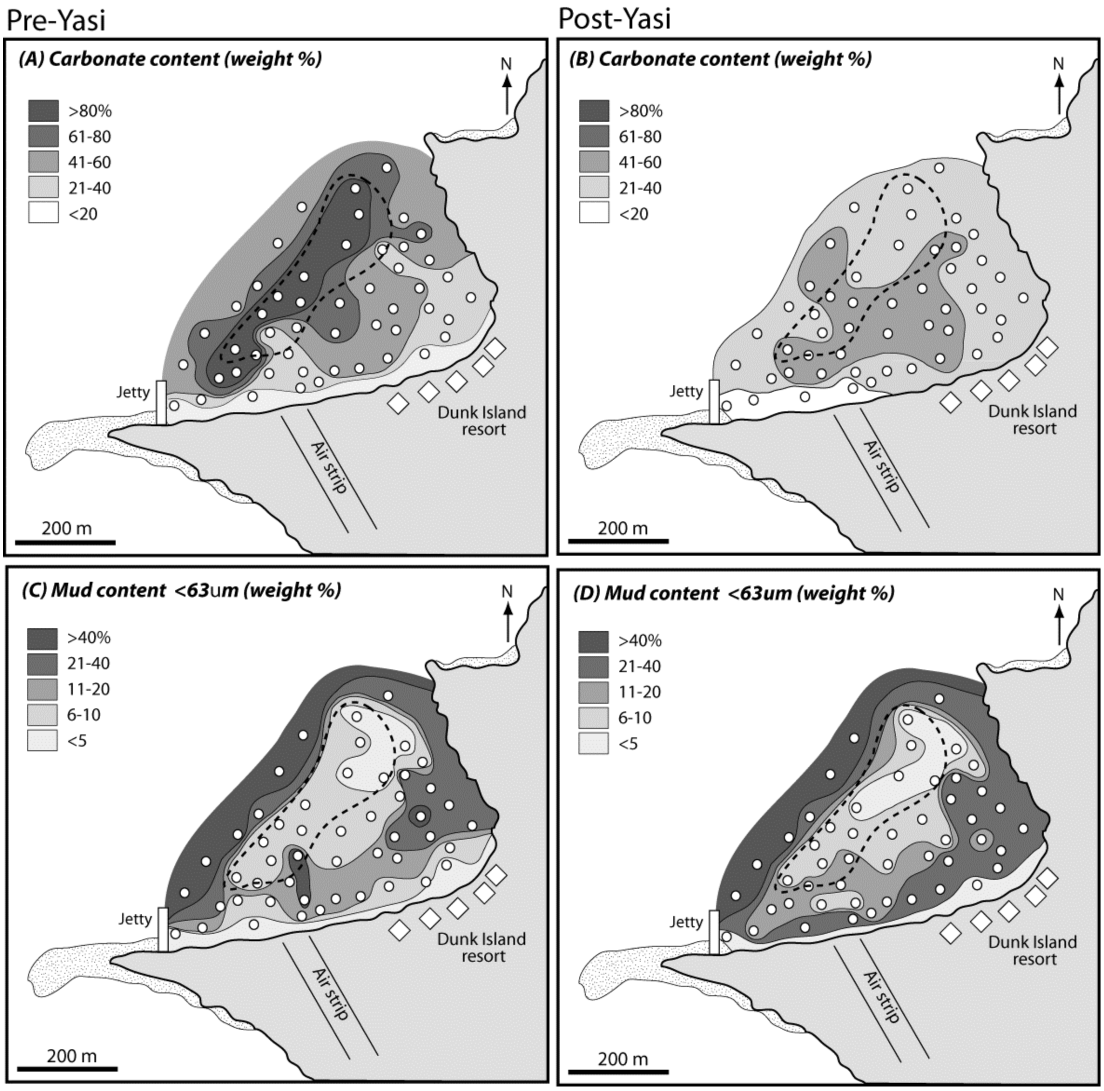
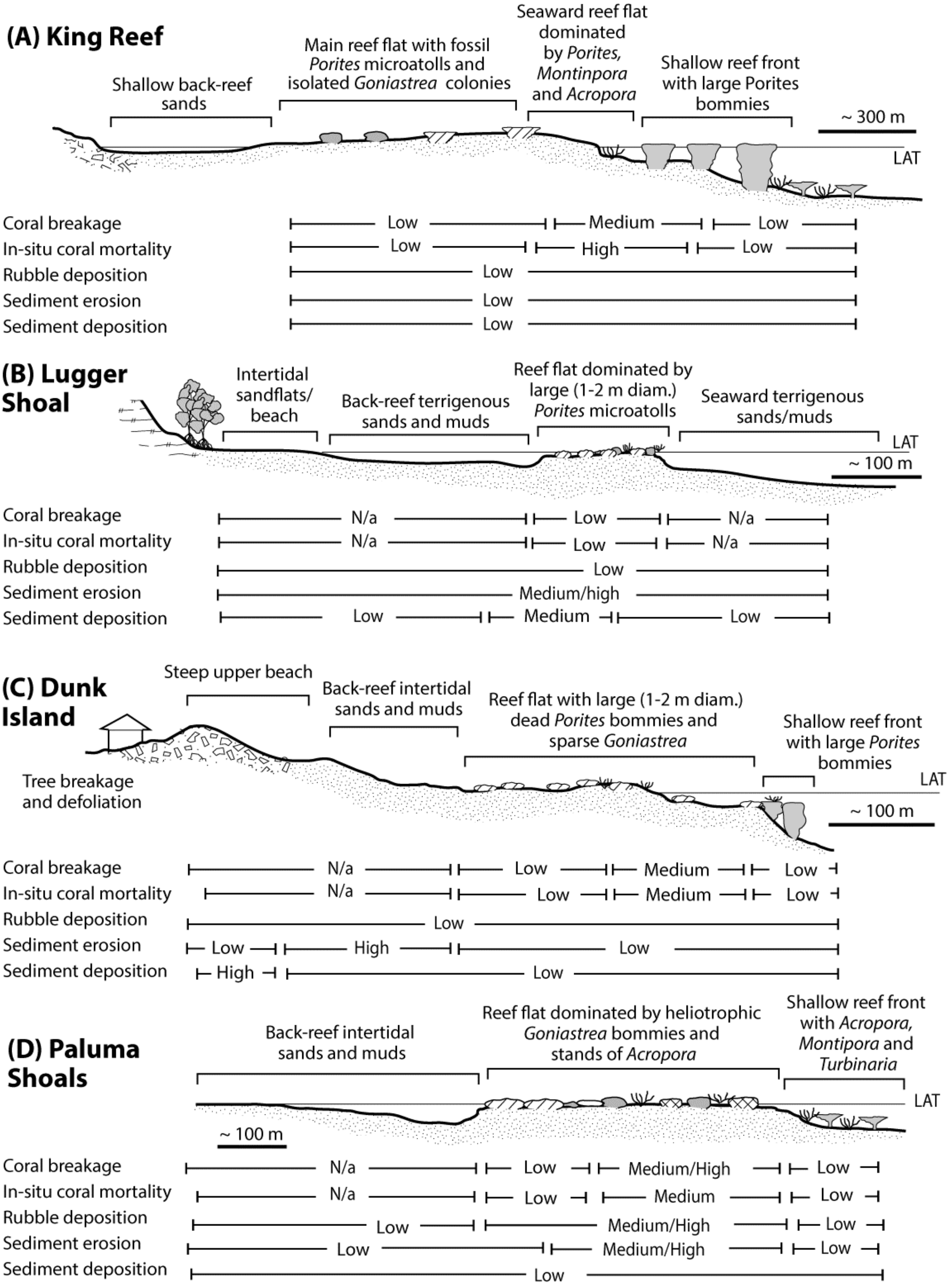

A
Lugger Shoal reef
Weight % fine - surface sediments
Mean grain size (phi)
B. Pre-Yasi (collected in 2007)
C. Pre-Yasi (collected in 2007)
D. Post-Yasi (collected in Aug 2011)
E. Post-Yasi (collected in Aug 2011)
Weight % fines of surface sediments
>30
15-30
10-15
5-10
<5
Mean grain size of surface sediments (phi)
-1 to 0 Very coarse sand
0 to 1 Coarse sand
1 to 2 Medium sand
2 to 3 Fine sand
3 to 4 Very fine sand


Pre-Yasi
Post-Yasi
(A) Carbonate content (weight %)
>80%
61-80
41-60
21-40
<20
N
Jetty
Dunk Island resort
Air strip
200 m
(B) Carbonate content (weight %)
>80%
61-80
41-60
21-40
<20
N
Jetty
Dunk Island resort
Air strip
200 m
(C) Mud content <63um (weight %)
>40%
21-40
11-20
6-10
<5
N
Jetty
Dunk Island resort
Air strip
200 m
(D) Mud content <63um (weight %)
>40%
21-40
11-20
6-10
<5
N
Jetty
Dunk Island resort
Air strip
200 m


(A) King Reef
Shallow back-reef sands
Main reef flat with fossil Porites microatolls and isolated Goniastrea colonies
Seaward reef flat dominated by Porites, Montinpora and Acropora
Shallow reef front with large Porites bommies
~ 300 m
LAT
Coral breakage: Low | Medium | Low
In-situ coral mortality: Low | High | Low
Rubble deposition: Low
Sediment erosion: Low
Sediment deposition: Low
(B) Lugger Shoal
Intertidal sandflats/ beach
Back-reef terrigenous sands and muds
Reef flat dominated by large (1-2 m diam.) Porites microatolls
Seaward terrigenous sands/muds
LAT
~ 100 m
Coral breakage: N/a | Low | N/a
In-situ coral mortality: N/a | Low | N/a
Rubble deposition: Low
Sediment erosion: Medium/high
Sediment deposition: Low | Medium | Low
(C) Dunk Island
Steep upper beach
Back-reef intertidal sands and muds
Reef flat with large (1-2 m diam.) dead Porites bommies and sparse Goniastrea
Shallow reef front with large Porites bommies
LAT
~ 100 m
Tree breakage and defoliation
Coral breakage: N/a | Low | Medium | Low
In-situ coral mortality: N/a | Low | Medium | Low
Rubble deposition: Low
Sediment erosion: Low | High | Low
Sediment deposition: High | Low
(D) Paluma Shoals
Back-reef intertidal sands and muds
Reef flat dominated by heliotrophic Goniastrea bommies and stands of Acropora
Shallow reef front with Acropora, Montipora and Turbinaria
LAT
~ 100 m
Coral breakage: N/a | Low | Medium/High | Low
In-situ coral mortality: N/a | Low | Medium | Low
Rubble deposition: Low | Medium/High | Low
Sediment erosion: Low | Medium/High | Low
Sediment deposition: Low