Linkages between coral assemblages and coral proxies of terrestrial exposure along a cross-shelf gradient on the southern Great Barrier Reef

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Abstract Coral core records, combined with measurements of coral community structure, were used to assess the long-term impact of multiple environmental stressors on reef assemblages along an environmental gradient. Multiple proxies (luminescent lines, Ba/Ca, $\delta^{15}\text{N}$) that reflect different environmental conditions (freshwater discharge, sediment delivery to the nearshore, nutrient availability and transformations) were measured in *Porites* coral cores collected from nearshore reefs at increasing distance from the intensively agricultural region of Mackay (Queensland, Australia). The corals provide a record (1968–2002) of the frequency and intensity of exposure to terrestrial runoff and fertilizer-derived nitrogen and were used to assess how the present-day coral community composition may have been influenced by flood-related disturbance. Reefs closest to the mainland (5–32 km offshore) were characterized by low

hard coral cover ($\leq 10\%$), with no significant differences among locations. Distinct annual luminescent lines and elevated Ba/Ca values ($4.98 \pm 0.63 \mu\text{mol mol}^{-1}$; mean $\pm$ SD) in the most inshore corals (Round Top Island; 5 km offshore) indicated chronic, sub-annual exposure to freshwater and resuspended terrestrial sediment that may have historically prevented reef formation. By contrast, corals from Keswick Island (32 km offshore) indicated episodic, high-magnitude exposure to Pioneer River discharge during extreme flood events (e.g., 1974, 1991), with strongly luminescent lines and substantially enriched coral skeletal $\delta^{15}\text{N}$ (12–14‰). The reef assemblages at Keswick and St. Bees islands were categorically different from all other locations, with high fleshy macroalgal cover ($80.1 \pm 7.2\%$ and $62.7 \pm 7.1\%$, respective mean $\pm$ SE) overgrowing dead reef matrix. Coral records from Scawfell Island (51 km offshore) indicated little exposure to Pioneer catchment influence: all locations from Scawfell and further offshore had total hard and soft coral cover comparable to largely undisturbed nearshore to middle shelf reefs of the southern Great Barrier Reef.

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Introduction

There is growing concern that rapid rates of global environmental change are increasing the frequency and severity of disturbance (e.g., tropical cyclones, bleaching) to coral reefs (Nystrom et al. 2000; Hoegh-Guldberg et al. 2007). While intermediate levels of disturbance maintain high diversity on coral reefs (Connell 1978), high levels of

disturbance can cause community changes through the removal of local species (DeVantier et al. 2006) or via shifts to alternate states (Hughes 1994). Nearshore reefs adjacent to highly modified catchments may be particularly vulnerable to ecological shifts of this nature if chronically degraded water quality acts to reduce resilience to extreme disturbances (McCook 1999).

Long-term coral reef monitoring records can distinguish coral community responses to both natural and anthropogenic disturbance. For example, Done et al. (2007) used >20 years of photography and videography to study community dynamics at the chronically disturbed, turbid and nearshore Pandora Reef on the central Great Barrier Reef (GBR). They found that while recovery trajectories from tropical cyclone, flood, and heat wave disturbances varied by reef zone, the main limits to recovery of coral populations were reduced supply of coral brood stock and increased frequency of climate-related disturbances (Done et al. 2007). Despite their usefulness, long-term data sets like these are rare, particularly at high enough temporal resolution to capture rapid transitions in direct response to specific disturbances (Ostrander et al. 2000).

In the absence of long-term monitoring data, several different methods have been employed in separate regions of the GBR to assess whether nearshore reefs have experienced recent degradation. When Fabricius et al. (2005) compared community characteristics from nearshore reefs adjacent to the highly agricultural Wet Tropics catchments and the less modified Princess Charlotte Bay catchments, they found three response variables (macroalgal cover, octocoral richness, abundance of sensitive hard coral species) that were significantly correlated with a water quality index constructed from twelve water quality variables sampled repeatedly at each reef. The study shows a strong link between present day ecological community structure and recent water quality, supported by modeling studies which indicate long-term increases in sediment and nutrient delivery to the Wet Tropics region (Neil et al. 2002; Wooldridge et al. 2006).

A different approach is to determine whether a mismatch exists between present reef-building capacity and Holocene reef framework along a distance gradient from a river source (van Woesik et al. 1999). van Woesik et al. (1999) suggested that the limited reef-building at Calf and Pine islands in the Whitsunday Group of the southern GBR was associated with recent increases in suspended particulate matter and nutrients delivered to Repulse Bay by the Proserpine and O'Connell rivers. This hypothesis is likely given the rapid agricultural expansion in the Proserpine and O'Connell catchments during the past 150 years (Pulsford 1996) and measured high levels of chlorophyll *a* and sediment nitrogen at reefs closest to river sources (van Woesik et al. 1999). However, changes on longer temporal scales,

such as the closure of the Holocene high-energy window which reduced flushing from Repulse Bay, may have also contributed to reduce carbonate accretion (Hopley 1984).

In this study, a novel approach to assess broad differences in community structure is presented which links present-day coral assemblages with disturbance histories inferred from biogeochemical signatures measured from coral cores collected along a distance gradient adjacent to a highly agricultural region of the southern GBR. Three types of proxy records were derived from massive *Porites* coral colonies and were used to investigate the frequency and intensity of exposure to terrestrial discharge and fertilizer-derived nitrogen. Firstly, luminescent lines from nearshore corals on the GBR are strongly related to river discharge events (Isdale 1984; Lough et al. 2002). Secondly, peaks in barium to calcium ratios (Ba/Ca) coincide with episodic release of sediments discharged to the nearshore environment by flood events from large, dry catchments (McCulloch et al. 2003). The last proxy, coral skeletal $\delta^{15}\text{N}$, provides time-integrated measurements of relative nutrient availability bearing a signature that can be traced back to anthropogenic nitrogen sources within the catchment (Marion et al. 2005; Marion 2007). These records are combined with data on regional climate perturbations to assess recurrence intervals of disturbance since the late 1970s at three nearshore reefs. Because long-lived massive *Porites* are less susceptible to mortality from bleaching, mechanical injury and predation by COTS than faster growing species, such as acroporids (De'ath and Moran 1998; Marshall and Baird 2000), strong responses recorded in *Porites* skeletons can be indicators of large-scale disturbances that could affect survivorship of less robust corals.

The two primary objectives in this study were to: (1) describe the present-day coral community composition along a cross-shelf gradient on the southern GBR; and (2) assess the frequency and intensity with which the nearshore reefs are exposed to terrestrial runoff that might inhibit coral recovery from large-scale disturbance.

Materials and methods

Study region

The study focused on a transect of reefs fringing continental islands (Round Top: 5 km offshore, Keswick: 32 km, St Bees: 32 km, Scawfell: 51 km, and Derwent: 61 km) or carbonate platforms (Big Kindemar: 127 km and Little Kindemar: 123–134 km) along a distance gradient from the Pioneer River drainage and city of Mackay in the Mackay Whitsunday region of the southern GBR (Fig. 1). Although the catchments of the Mackay Whitsunday

region (Proserpine, O'Connell, Pioneer and Plane) represent only a small proportion (2.1%) of the 423,070 km² terrestrial area draining into the GBR World Heritage

Fig. 1 Locations of coral coring and ecological survey locations within the Mackay region of the southern Great Barrier Reef. RT, Round Top Island; KI, Kewick Island; SB, St. Bees Island; SC, Scawfell Island; DR, Derwent Island; LK, Little Kindemar Reef; BK, Big Kindemar Reef. Yellow regions are catchments of the Mackay Whitsunday management area overlaid with three major drainages. Map is displayed on a subset of a MODIS Terra satellite image (courtesy of NASA/GSFC—<http://ladsweb.nascom.nasa.gov/data/>), captured 28 January 2005 following a minor flooding event. The inset depicts the location of the study region within Australia on the central Queensland coast

Area, ~79% of the region is occupied by intensive agriculture or grazing (Rayment and Neil 1997).

Regional precipitation and river flow in northeast Queensland are strongly influenced by El Niño–Southern Oscillation (ENSO) events (Lough 1994). Mackay's tropical, humid climate exhibits seasonal wet/dry variability, with ~75% of rain falling between the austral summer months of October and March. As a consequence, Pioneer River flow is highly episodic: floods accounted for $89 \pm 8\%$ of freshwater discharged annually (mean $\pm$ SD for composite record spanning 1916 to 2003 from Queensland Department of Natural Resources and Water stations 125001A and 125007A). Strong prevailing southeasterly winds, such as observed at Mackay, produce longshore movement of inner shelf waters that typically cause northward spreading of flood plumes (King et al. 2001). Since 1968, there were 9 years with distinct, high-magnitude Pioneer River discharge events, eight tropical cyclones within the vicinity of Mackay, and three periods of high or prolonged positive sea surface temperature (SST) anomalies associated with known ENSO events (Fig. 2).

Ecological surveys

During March 2006, photoquadrat surveys were undertaken along 20 transects at shallow depths (1–5 m below Lowest Astronomical Tide (LAT)), parallel to the reef flat to assess coral family assemblages and benthic cover at each of the reefs. A minimum of two sites were surveyed at each reef,

Fig. 2 Records of regional climatic perturbations (tropical cyclones, sea surface temperature (SST) anomalies) and Pioneer River discharge. SST anomalies were calculated using weekly means from IGOSS regional 1° gridded weekly SST records, November 1981–December 2004. Cyclones are listed with closest proximity date to Mackay and maximum associated wind speed at Mackay, Australian Bureau of Meteorology station 33119. Dashed vertical lines show elevated discharge associated with cyclones. Solid vertical lines show periods of sustained, positive SST anomalies associated with known ENSO events

though transects were pooled to reef level due to the low overall numbers. Because high levels of turbidity in 2006 precluded photographic assessment of cover at Round Top Island, adjacent to the Pioneer River mouth, photoquadrats were used from surveys in September 2003. Preliminary analysis showed that the percent cover in 2003 for the most dominant classes (substratum, live hard coral, and macroalgal cover) were within the mean and standard deviation from line intercept data collected in March 2006, therefore conditions were unlikely to have substantially changed between monitoring periods. Quadrats of 0.5 m × 0.5 m were placed along a 50 m measuring tape and photographed at 2 m intervals ($n = 25$ photographs per transect). Photographs, taken with a Nikon e5000 camera, were analyzed with the CPCe random point count method (Kohler and Gill 2006) using 50 points per quadrat. Community structure was categorized by quantifying total cover of: live hard coral, soft coral, fleshy macroalgae, frondose calcareous algae (e.g., *Halimeda* sp.), bioeroding sponge (e.g., *Cliona orientalis*), substratum (divided into dead intact coral, coral rubble, reef matrix, and sand), and other (dominated by the giant clam, *Tridacna* sp., anemones, large mollusks, hydroids and ascidians). To assess variability in coral assemblages at a coarse taxonomic level, coral cover was categorized into dominant families (Acroporidae, Pocilliporidae, Poritidae, Faviidae, and Others). Morphology of the dominant family, Acroporidae, was further separated into arborescent, caespitose, cuneiform, digitate, tabular, plating, and encrusting forms. Differences in live hard coral cover were assessed with a single factor ANOVA, followed by Tukey's HSD post-hoc test to identify significant pair-wise differences using

Statistica 8.0 software. Data were arcsine square-root transformed to meet the assumptions of normality and homogeneity of variance.

All community structure data were analyzed using the multivariate software PRIMER version 6.1.5. Community structure data (including coral families and growth form) were square-root transformed and similarities were calculated using the Bray–Curtis similarity measure (Bray and Curtis 1957). Multidimensional scaling (MDS) was used to ordinate transects, and hierarchical cluster analysis (group-average linkage) was performed to detect percent similarity levels. SIMilarities PERcentages (SIMPER) analysis was used to determine community structure categories that contributed to similarities among transects within each reef location and dissimilarities between locations (Clarke and Warwick 2001). Categories with less than 90% contribution to average dissimilarity between locations were excluded.

Coral core collection

In April 2004, December 2004, and March 2006, 10 cores were drilled from massive *Porites* colonies from Round Top, Keswick, and Scawfell Islands (Table 1). All cores were collected using SCUBA at bottom depths of 3–5 m below LAT using a pneumatic, hand-held underwater drill attached to a stainless steel coring barrel. Cores were slabbed (~7 mm thick), cleaned ultrasonically in 18 MΩ water, and X-radiographed to visualize annual density bands to aid sampling for isotope analysis and chronology assignment.

Table 1 Specifications for *Porites* coral cores, including collection date, location, depth, total length of core, growth rate and type of analyses

Core	Collection date	Lat S	Lon E	Collection depth (m)	Total length (cm)	Growth rate (mm yr ⁻¹)	Analyses
Round Top Island							
RTC	4 April 2004	21.1755	149.2630	5	41	7.6 ± 1.9	L, T, N
RTF	8 December 2004	21.1708	149.2644	4	61	8.3 ± 1.8	T, N
RTH	6 March 2006	21.1720	149.2639	4	186	8.7 ± 2.4	L, T, N
RTI	6 March 2006	21.1717	149.2634	4	86	8.7 ± 1.7	L
Keswick Island							
KIB	1 April 2004	20.9177	149.4178	3	42	15.7 ± 2.4	L
KIC	1 April 2004	20.9177	149.4178	3	56	15.9 ± 2.4	L, N
KIE	13 March 2006	20.9319	14.4267	N/A	59	9.3 ± 2.1	L, T
Scawfell Island							
SCA	1 April 2004	20.8552	149.6021	4	79	15.1 ± 3.7	L
SCB	1 April 2004	20.8552	149.6021	4	55	13.7 ± 2.8	L
SCC	1 April 2004	20.8552	149.6021	4	170	14.8 ± 2.3	L, T, N

L, luminometer measurements of luminescence intensity; T, LA-ICP-MS measurements of trace elements; N, bulk annual measurements of skeletal insoluble organic $\delta^{15}\text{N}$

Coral luminescence analysis

Coral luminescence (excitation λ (nm)/emission λ (nm) = 390/490) was measured at 0.25 mm increments along the length of whole skeletal slabs using a fully automated, custom assembled optical luminometry device at the Australian Institute of Marine Science following the protocol of Barnes et al. (2003). To correct for drift within and between sample runs, luminescence and reflectance were measured from background (black “delrin” plastic disk) and calcium carbonate (*Tridacna maxima* shell) standards at the start and end of each run. Relative luminescence for all measurements along each coral slice was then calculated by the following equation (Barnes et al. 2003):

Relative luminescence

$$= \frac{(\text{lumin}_{\text{coral}} - \text{lumin}_{\text{bkgd}})}{(\text{lumin}_{\text{std}} - \text{lumin}_{\text{bkgd}})} \bigg/ \frac{(\text{reflect}_{\text{coral}} - \text{reflect}_{\text{bkgd}})}{(\text{reflect}_{\text{std}} - \text{reflect}_{\text{bkgd}})}$$

Measurements of skeletal density (g cm^{-3}) were made at the same time as luminescence measurements along the same track of each coral slice. Density was measured by the attenuation of a beam of gamma photons, centered 37.34 mm ahead of the center of the light beam used to measure luminescence. Chronologies were constructed by assuming minimum density deposition occurred during minimum winter SSTs (first week of August, based on IGOSS regional 1° gridded weekly SST records, November 1981–December 2004, <http://www.irdl.ideo.columbia.edu/SOURCES/IGOSS/nmc/>). Because the strength of relationships with climatic variables varies among different corals and, in some cases, over time within a single record, a master record was created from each location using the average of three replicate cores with overlapping data between February 1978 and August 2002 (Lough 2004). Data were excluded from the top years of the cores (>2003) due to the patchy, elevated luminescence associated with oxidized organic material from the residual tissue of coral polyps, algal symbionts, and endolithic algae (Barnes et al. 2003).

To assess the influence of Pioneer River discharge on coral luminescence, annual peak luminescence was correlated with total annual discharge (October–September). Nonparametric Spearman Rank Correlation tests were used because the peak luminescence values from the master coral records were non-normally distributed. To assess whether the influence of river floods was visible over background variability (i.e., seasonal luminescent bands; Barnes et al. 2003) at each location, two-way ANOVA tests were used to assess differences between annual maximum – mean luminescence values for 4 of the wettest years (annual Pioneer discharge >1,000,000 MI: 1979, 1989, 1990, 1991 or

1988) versus the four driest years (annual Pioneer discharge <80,000 MI: 1987, 1992, 1995, 1996) between 1978 and 2002 at each location. Data conformed to assumptions of normality (Shapiro-Wilk’s W test) and homogeneity of variance (Levene’s tests). The effect size of each factor (core, discharge level, core*discharge level) is reported with the eta squared (η^2) statistic (Cohen 1973). All analyses were performed with Statistica 8.0 software. 1991 was excluded from the Round Top analysis because the RTI colony experienced partial mortality from the event: the residual organic matter in the flood band resulted in an outlier value of highly elevated luminescence. 1988 was excluded from the Keswick and Scawfell analyses due to data gaps in KIE and SCB where the slabs were fractured.

Coral trace element analysis

Trace element concentrations of ^{43}Ca , ^{84}Sr , and ^{138}Ba in five of the coral cores (RTC, RTF, RTH, KIE, SCC) were analyzed by laser ablation inductively coupled mass spectrometry (LA-ICPMS) with an ArF excimer laser (193 nm wavelength) attached to either a modified VG Elemental PQ2⁺ or Varian 820 ICP-MS. Specifications for the laser system, data collection, and protocol for instrumental drift correction were identical to that described by Sinclair et al. (1998), except that the laser spot size was changed to $40 \mu\text{m} \times 400 \mu\text{m}$, yielding a sampling resolution of 20 nm operated at 5 Hz. All isotopic concentrations were normalized to ^{43}Ca (0.13% Ca) to account for variations due to changes in coral surface architecture and density (Fallon et al. 1999). Data were smoothed using a 10-point running median to remove outliers, followed by a 10-point mean to reduce data volume. Time series of the corals were calibrated by matching Sr/Ca maximum and minimum values to IGOSS 1° gridded weekly SST records (Beck et al. 1992). For data before 1981, the average week of SST summer maxima and winter minima was used. To assess the influence of Pioneer River discharge on coral Ba/Ca values across the nearshore spatial gradient, nonparametric Spearman Rank correlations were used to evaluate relationships between annual peak Ba/Ca ($\mu\text{mol/mol}$) with total annual discharge (October–September), while parametric Pearson product–moment correlations were used to compare weekly Ba/Ca ($\mu\text{mol mol}^{-1}$) with weekly log-transformed discharge. Ba/Ca records (1968–2003) from Round Top Island cores (RTC, RTF, RTH) were averaged prior to correlation analysis.

Coral skeletal $\delta^{15}\text{N}$ analysis

The $\delta^{15}\text{N}$ composition of acid-insoluble coral skeletal nitrogen was analyzed from cores RTC, RTF, RTH, KIC, and SCC using protocols established by Marion (2007). The

insoluble fraction represents 51% of total skeletal nitrogen and compositionally is closely related to sources and transformations of nitrogen in the water column (Marion 2007). Prior to sample preparation, an ultra-fine (<1 mm thick) layer was cut from each slab to remove superficial contamination. Annual density bands were mapped from X-radiographs onto core slices to aid in drilling annual coral carbonate samples (1.5–2.8 g). Samples were ground to a powder, decalcified in H_3PO_4 , filtered (Whatman GF/F, 0.7 μm pore size) to retain the acid-insoluble organic fraction, dried for 24 h at 60°C, and loaded in 9×10 mm tin capsules into a 31-run multi-sampler carousel. Samples were analyzed using a Carlo Erba NA1500 elemental analyzer (EA) coupled to a Finnigan MAT Delta + mass spectrometer via a ConFlo II open split interface (Stanford University Stable Isotope Laboratory). Six isotopic (IAEA-N1, USGS-24) and seven elemental (acetanilide) standards were analyzed with each set of 40 C/N samples, yielding instrument standard deviations of 0.07‰ ($\delta^{15}\text{N}$).

A 3-core composite time series (1970–2004) was developed for Round Top Island by averaging the annual $\delta^{15}\text{N}$ values for RTC, RTF, and RTH. Nonparametric Spearman Rank correlations were used to assess relationships between annual $\delta^{15}\text{N}$ and total annual river discharge (October–September). The frequency with which coral $\delta^{15}\text{N}$ exceeded 9‰ is also reported, indicating significant enrichment of particulate organic matter (POM) discharged by the Pioneer River resulting from elevated anthropogenic inputs of biologically available (fertilizer-derived) dissolved inorganic nitrogen and subsequent microbial transformations (Marion 2007). The 9‰ value represents the mean of POM filtered from water samples collected from stagnant pools adjacent to weirs on the lower Pioneer River, which were enriched by approximately 6‰ over upper Pioneer River POM measurements. Coupled nutrient analysis of water samples from the lower Pioneer pools showed elevated particulate nitrogen (PN) and dissolved organic nitrogen (DON) and low ammonium and nitrate concentrations (Marion 2007). The elevated particulate nitrogen and DON concentrations likely reflect high microbial biomass and remineralization, while the low nitrate and ammonium concentrations, both of which are reactants in denitrification (Middleburg and Nieuwenhuize 2001), suggest rapid attenuation rates produced the heavy, signature $\delta^{15}\text{N}$ values of the lower Pioneer waters that are flushed into the nearshore during flood events.

Results

Coral community assemblages

High, significant cross-shelf variability in live hard coral cover was observed ($F_{6,37} = 11.305$, $P < 0.001$; Table 2).

Values ranged from $3.3 \pm 3.2\%$ (mean $\pm$ SE) at Keswick Island (KI, 32 km from Pioneer River mouth) to peak cover of $28.9 \pm 2.1\%$ at Big Kindemar (BK, ~ 130 km from the Pioneer mouth and ~ 70 km perpendicular distance from the outer shelf of the Pompey Complex). The reefs closest to the mainland (Round Top [RT], KI, and St. Bees [SB]) were all characterized by low live coral cover: percent cover at the innermost location (RT: $7.3 \pm 2.4\%$) was slightly higher than at KI, though differences among all three locations were not significant.

Reef structure and composition, however, varied substantially between the most inshore locations. Rubble, reef matrix, and sand were the dominant benthic cover at RT ($90.5 \pm 3.1\%$; Table 2), with low densities of massive *Porites* sp. adjacent to the transects, low abundances of juvenile acroporids and sparse, small colonies of mainly encrusting *Montipora* and foliaceous *Turbinaria* settled on rock or rubble and covered in turf algae and thick sediment. Only small amounts of fleshy macroalgae were observed at this location ($1.7 \pm 0.5\%$). By contrast, tall stands of fleshy brown algae, particularly *Sargassum* sp. and *Padina* sp., dominated benthic cover at KI and SB ($80.1 \pm 7.2\%$ and $62.7 \pm 7.1\%$, respectively), overgrowing dead reef framework and rubble substrate. Very few fleshy macroalgae were observed at any other reef. At SC (the next island offshore), the shallow, often turbid reefs were dominated by soft corals ($31.3 \pm 4.6\%$). The middle-shelf reef at Derwent (DR) had a high cover of crustose coralline algae binding a well-developed reef flat that dropped steeply to rubble and pavement at ~ 10 m. The eastern, more exposed side of the reef flat had high occurrences of boring sponge (*Cliona orientalis*), which was not observed in high abundance at any other reef. The two outer reefs (BK and LK), both broad reef platforms about 9 to 13.5 km across, also had well-consolidated reef matrix, low fleshy macroalgae, and higher soft coral cover (BK: $8.8 \pm 4.0\%$; LK: $8.8 \pm 3.0\%$), such that the totals of live hard coral and soft coral were very similar to that observed at DR.

Cluster analysis identified four main groups from the community structure data from 20 transects, which are illustrated in an MDS plot (Fig. 3). Group 4 (outer middle-shelf transects: DR, LK, BK) and Group 3 (SC transects) clustered at 58.8% similarity. Together, Groups 3 and 4 were only 44.1% similar to Group 1 transects (RT) and 36.9% similar to Group 2 transects (KI and SB). The SIMPER analysis identified the benthic categories that contributed most to the similarities within groups and the differences between groups (Fig. 4). KI and SB were categorically different from all other reefs due to the high cover of fleshy macroalgae (Fig. 4b), though it was recognized that the thick algal canopy may have obscured the presence of an epilithic algal understory, juvenile corals, and consolidated reef matrix. The dissimilarity

Table 2 Mean percent cover $\pm$ SE for benthic habitat categories scored from photoquadrats and used as input for multivariate analyses

	Round Top	Keswick	St. Bees	Scawfell	Derwent	Little Kindemar	Big Kindemar
<i>Coral composition</i>							
Acroporidae	3.0 $\pm$ 0.8	2.8 $\pm$ 0.4	9.2 $\pm$ 0.7	14.4 $\pm$ 1.2	16.5 $\pm$ 0.9	12.8 $\pm$ 0.7	19.1 $\pm$ 1.8
Arborescent	0.9 $\pm$ 0.4	2.1 $\pm$ 2.0	3.2 $\pm$ 1.4	4.3 $\pm$ 2.2	0.4 $\pm$ 0.3	1.7 $\pm$ 0.9	2.4 $\pm$ 2.0
Caespitose	–	–	1.4 $\pm$ 0.7	2.5 $\pm$ 1.7	0.4 $\pm$ 0.2	3.8 $\pm$ 0.7	4.5 $\pm$ 2.1
Cueniform	–	–	0.5 $\pm$ 0.3	0.7 $\pm$ 0.4	2.1 $\pm$ 0.1	1.4 $\pm$ 0.8	4.2 $\pm$ 3.8
Digitate	0.2 $\pm$ 0.2	–	1.0 $\pm$ 0.8	3.4 $\pm$ 2.1	11.0 $\pm$ 5.1	1.3 $\pm$ 0.4	3.2 $\pm$ 2.5
Tabular	–	–	0.5 $\pm$ 0.3	–	1.2 $\pm$ 0.7	0.1 $\pm$ 0.1	0.5 $\pm$ 0.5
Plating	–	0.6 $\pm$ 0.6	2.2 $\pm$ 1.8	1.5 $\pm$ 1.4	0.1 $\pm$ 0.1	1.1 $\pm$ 0.6	1.8 $\pm$ 1.7
Encrusting	1.9 $\pm$ 0.5	0.1 $\pm$ 0.1	0.36 $\pm$ 0.2	2.1 $\pm$ 2.0	0.3 $\pm$ 0.2	1.5 $\pm$ 0.9	0.9 $\pm$ 0.4
Other	–	–	–	–	1.2 $\pm$ 0.7	0.1 $\pm$ 0.1	0.5 $\pm$ 0.5
Pocilloporiidae	0.3 $\pm$ 0.2	–	–	0.7 $\pm$ 0.2	0.8 $\pm$ 0.4	1.9 $\pm$ 0.4	2.8 $\pm$ 1.0
Faviidae	1.2 $\pm$ 0.9	–	–	0.3 $\pm$ 0.3	5.2 $\pm$ 1.0	0.9 $\pm$ 0.2	0.7 $\pm$ 0.6
Poritidae	0.3 $\pm$ 0.3	–	0.2 $\pm$ 0.2	0.7 $\pm$ 0.5	0.1 $\pm$ 0.1	1.3 $\pm$ 0.8	0.8 $\pm$ 0.7
Other coral	2.5 $\pm$ 0.9	0.4 $\pm$ 0.4	0.7 $\pm$ 0.2	1.6 $\pm$ 0.7	0.5 $\pm$ 0.2	7.6 $\pm$ 2.4	5.7 $\pm$ 0.9
<i>Community structure</i>							
Total coral	7.3 $\pm$ 2.4	3.3 $\pm$ 3.2	10.1 $\pm$ 2.7	17.7 $\pm$ 3.0	23.3 $\pm$ 6.6	24.4 $\pm$ 2.2	28.9 $\pm$ 2.1
Halimeda	–	0.1 $\pm$ 0.1	0.1 $\pm$ 0.1	0.1 $\pm$ 0.0	–	3.4 $\pm$ 2.6	8.7 $\pm$ 8.4
Macroalgae	1.7 $\pm$ 0.5	80.1 $\pm$ 7.2	62.7 $\pm$ 7.1	0.3 $\pm$ 0.2	–	0.2 $\pm$ 0.2	–
Soft coral	0.5 $\pm$ 0.2	0.1 $\pm$ 0.1	0.1 $\pm$ 0.0	31.3 $\pm$ 4.6	10.6 $\pm$ 3.8	8.8 $\pm$ 3.0	8.8 $\pm$ 4.0
Bioeroding sponge	–	1.0 $\pm$ 0.1	1.0 $\pm$ 0.5	0.2 $\pm$ 0.2	9.7 $\pm$ 6.2	0.6 $\pm$ 0.1	–
Other	–	–	0.1 $\pm$ 0.0	0.1 $\pm$ 0.0	0.4 $\pm$ 0.1	0.9 $\pm$ 0.1	0.5 $\pm$ 0.5
Substrate	90.5 $\pm$ 3.1	15.4 $\pm$ 3.7	26.1 $\pm$ 7.1	50.4 $\pm$ 3.9	56.1 $\pm$ 3.6	61.8 $\pm$ 6.0	53.1 $\pm$ 14.0
Dead coral intact	0.3 $\pm$ 0.1	2.1 $\pm$ 0.5	–	14.8 $\pm$ 3.5	1.7 $\pm$ 0.2	4.5 $\pm$ 0.8	1.6 $\pm$ 0.2
Coral rubble	41.4 $\pm$ 10.1	1.1 $\pm$ 1.1	3.8 $\pm$ 3.8	0.9 $\pm$ 0.9	0.3 $\pm$ 0.3	3.7 $\pm$ 1.9	2.2 $\pm$ 1.9
Reef matrix	15.7 $\pm$ 2.4	8.8 $\pm$ 2.2	13.8 $\pm$ 1.0	34.3 $\pm$ 3.2	52.9 $\pm$ 3.6	47.5 $\pm$ 6.1	46.5 $\pm$ 11.9
Sand	32.9 $\pm$ 6.4	3.4 $\pm$ 2.7	8.5 $\pm$ 4.1	0.4 $\pm$ 0.4	1.2 $\pm$ 0.3	6.2 $\pm$ 2.7	2.7 $\pm$ 0.4

Fig. 3 Multidimensional scaling (MDS) plot of coral community data from Round Top Island (RT), Keswick Island (KI), St. Bees Island (SB), Scawfell Island (SC), Derwent Island (DR), Little Kindemar Reef (LK) and Big Kindemar Reef (BK). Circles around clusters of transect data points represent minimum % similarity between groups

a	Round Top	Keswick	St. Bees	Scawfell	Derwent	Little Kindemar	Big Kindemar
	87.1%	82.9%	85.0%	89.3%	84.4%	82.0%	73.3%
	Reef Matrix Acroporidae Other Coral	Macroalgae Reef Matrix Acroporidae	Macroalgae Reef Matrix	Reef Matrix Soft Coral Acroporidae	Reef Matrix Soft Coral Acroporidae Faviidae	Reef Matrix Soft Coral Acroporidae Other Coral Faviidae	Reef Matrix Soft Coral Acroporidae Other Coral

b	Round Top					
	Keswick	St. Bees	Scawfell	Derwent	Little Kindemar	Big Kindemar
Keswick	58.4%					
	Macroalgae Reef Matrix Other Coral Acroporidae Faviidae					
St. Bees		18.6%				
	Macroalgae Reef Matrix Other Coral Faviidae Acroporidae Soft Coral	Acroporidae Reef Matrix Macroalgae Faviidae Poritidae Soft Coral				
Scawfell			50.3%			
	Soft Coral Acroporidae Reef Matrix Faviidae Other Coral Pocilloporidae	Macroalgae Reef Matrix Soft Coral Acroporidae	Macroalgae Soft Coral Reef Matrix Faviidae Acroporidae			
Derwent				19.1%		
	Soft Coral Reef Matrix Acroporidae Faviidae Other Coral	Macroalgae Reef Matrix Soft Coral Acroporidae Faviidae	Macroalgae Reef Matrix Soft Coral Faviidae Acroporidae	Soft Coral Faviidae Reef Matrix Acroporidae Poritidae Pocilloporidae		
Little Kindemar					18.0%	
	Soft Coral Acroporidae Reef Matrix Halimeda Poritidae Pocilloporidae	Macroalgae Reef Matrix Soft Coral Acroporidae Other Coral	Macroalgae Reef Matrix Soft Coral Other Coral Faviidae Halimeda	Soft Coral Halimeda Poritidae Acroporidae Pocilloporidae	Faviidae Halimeda Acroporidae Reef Matrix	
Big Kindemar						17.5%
	Acroporidae Halimeda Soft Coral Reef Matrix Poritidae Faviidae	Macroalgae Reef Matrix Acroporidae Soft Coral Halimeda Other Coral	Macroalgae Reef Matrix Soft Coral Halimeda Acroporidae	Soft Coral Halimeda Acroporidae Poritidae Reef Matrix Other Coral	Halimeda Faviidae Acroporidae Reef Matrix Soft Coral	Halimeda Acroporidae Reef Matrix Soft Coral Poritidae

Fig. 4 Results of SIMPER analysis showing benthic cover classes that contributed most strongly to (a) similarity between transects at each survey location, and (b) differences between locations. Benthic cover classes are listed in order of their contribution to similarities

and dissimilarities. In the dissimilarity matrix, categories to the left of each cell were more abundant at the location labeled by row, while categories to the right were more abundant at the location labeled by column

between SC and the Group 4 locations (19.1–22.7%) was within range of the dissimilarity among the Group 4 locations (17.5–21.8%) and was most distinguished by the

high cover of soft corals (Fig. 4b). While acroporid corals were the dominant family at all locations, the Group 4 locations had higher proportions of other representative

families and the highest cover of carbonate reef matrix (Table 2).

Coral luminescence

Mean relative coral luminescence intensity from the master coral records at each location decreased with distance from the Pioneer River mouth (mean $\pm$ SD for RT:

0.746 ± 0.091 ; KI: 0.501 ± 0.056 ; SC: 0.379 ± 0.035 ; Fig. 5). The RT cores showed distinct annual luminescent lines even in low flow years which resulted in the lack of significant correlation ($P = 0.099$) between annual peak luminescence and Pioneer River discharge (Table 3a). The difference between maximum – mean luminescence in wet versus dry years was significant ($F_{1,18} = 12.851$, $P = 0.0021$) and explained $\sim 41\%$ of the variance among

Fig. 5 (a) Relative luminescence intensity for Round Top (black bold), Keswick (medium grey) and Scawfell (light grey) corals between 1978 and 2002. Each line represents a 3-core average. Weekly Pioneer discharge ($\text{MI} \times 10^5$) is shown below. (b)

Representative core slabs from Round Top (RTC), Keswick (KIC) and Scawfell (SCC) photographed under UV light. White lines between cores connect luminescent lines from major flood years

Table 3 Spearman Rank correlations of annual Pioneer discharge versus: (a) maximum relative luminescence intensity (1978–2002); (b) peak Ba/Ca concentrations (1968–2002); and (c) coral skeletal $\delta^{15}\text{N}$ (1970–2002)

Site	<i>n</i>	Spearman <i>R</i>	<i>t</i>	<i>P</i>
(a) Maximum luminescence vs. Total discharge (1978–2002)				
Round Top Island	25	0.338	1.721	0.099
Keswick Island	25	0.511	2.849	0.009
Scawfell Island	25	0.406	2.132	0.044
(b) Maximum Ba/Ca vs. Total discharge (1968–2002)				
Round Top Island	35	0.427	2.716	0.010
Keswick Island	35	0.228	1.344	0.188
Scawfell Island	35	−0.052	−0.301	0.765
(c) Coral skeletal $\delta^{15}\text{N}$ vs. Total discharge (1970–2002)				
Round Top Island	33	0.611	4.293	0.000
Keswick Island	33	0.382	2.304	0.028
Scawfell Island	33	−0.059	−0.330	0.744

Significant *P* values are in bold

Table 4 Two-way ANOVA of differences between maximum minus mean luminescence values in wet years (annual Pioneer discharge >1,000,000 MI) versus dry years (annual Pioneer discharge <80,000 MI) for: (a) Round Top Island; (b) Keswick Island; (c) Scawfell Island

Source of variation	df	MS	<i>F</i>	<i>P</i>	η^2
(a) Round Top Island					
Core	2	0.0002	0.200	0.8203	0.013
Discharge level	1	0.0137	12.851	0.0021	0.406
Core*Discharge level	2	0.0002	0.214	0.8092	0.014
Error	18	0.0011			
(b) Keswick Island					
Core	2	0.0006	1.929	0.1741	0.038
Discharge level	1	0.0239	76.689	0.0000	0.758
Core*Discharge level	2	0.0004	1.292	0.2989	0.026
Error	18	0.0003			
(c) Scawfell Island					
Core	2	0.004	1.297	0.2978	0.066
Discharge level	1	0.0056	18.374	0.0004	0.469
Core*Discharge level	2	0.0000	0.101	0.9041	0.005
Error	18	0.0003			

RT cores (Table 4a). At KI, peak annual luminescence in the master coral record was significantly correlated with Pioneer discharge ($P = 0.009$), and wet versus dry years explained ~76% of the total variance ($F_{1,18} = 76.689$, $P < 0.001$) in maximum – mean luminescence (Table 4b). The same pattern was observed, though weaker, at SC where peak annual luminescence in the master coral record was significantly correlated with Pioneer discharge ($P = 0.044$), and wet versus dry years explained ~47% of the variability ($F_{1,18} = 18.374$, $P = 0.004$) in

maximum – mean luminescence (Table 4c). In the RT master core record, the difference between maximum – mean luminescence exceeded 0.1 in 9 years of the 25 year record, including major flood years (1979, 1990, 1991), El Niño years (1982, 1983, 1993), and other years (1978, 1980, 1981). The difference was greater than 0.1 in 6 of the above years (1978, 1979, 1980, 1983, 1990, 1991, and 1993) in the KI master core, but only in 3 years (1983, 1989, and 1991) in the SC master core.

Coral Ba/Ca

Mean coral Ba/Ca concentration decreased with distance from the Pioneer River mouth (mean $\pm$ SD for RT master: $4.98 \pm 0.63 \mu\text{mol mol}^{-1}$; KIE: $4.20 \pm 0.52 \mu\text{mol mol}^{-1}$; SCC: $3.55 \pm 0.98 \mu\text{mol mol}^{-1}$). The master record from RT exhibited smooth annual peaks whose maximum values were significantly correlated with annual Pioneer River discharge ($P = 0.010$; Fig. 6, Table 3b). Baseline winter Ba/Ca values remained elevated during wetter periods (1974–1980, 1988–1991 and, to a lesser extent, 1998–2002). Weekly RT Ba/Ca values were also significantly related to weekly discharge ($df = 1839$, $t = 14.312$, $P < 0.001$), but only accounted for a small proportion ($r^2 = 0.10$) of the overall variance. The KI coral also had clear annual Ba/Ca peaks but the maximum values were not correlated with annual discharge ($P = 0.188$, Table 3b). Although the KIE core had moderately elevated

Fig. 6 Coral records of weekly Ba/Ca from Round Top, Keswick and Scawfell islands. The Round Top values for Ba/Ca are an average of three records. Horizontal dashed lines are mean values for each location. Weekly Pioneer discharge is plotted below

winter minima and summer peaks between 1974 and 1980, the record between 1988 and 1991 was highly variable (Fig. 6). The significant correlation between weekly Ba/Ca and weekly discharge ($df = 1839$, $t = 2.30$, $P = 0.022$) was likely an artifact of high sample size given the low correlation coefficient ($r^2 = 0.003$). The Ba/Ca record from SC was highly variable and had no significant relationship with Pioneer River discharge.

Coral skeletal $\delta^{15}\text{N}$

Mean coral skeletal $\delta^{15}\text{N}$ declined by $\sim 4.5\text{‰}$ with increasing distance offshore (mean $\pm$ SD for RT master: $8.15 \pm 1.29\text{‰}$; KIC: $5.65 \pm 2.67\text{‰}$; SCC: $3.54 \pm 2.63\text{‰}$). Annual coral $\delta^{15}\text{N}$ was positively correlated with annual Pioneer discharge at both RT ($P < 0.001$) and KI ($P = 0.028$), but not at SC ($P = 0.744$; Table 3c). The $\delta^{15}\text{N}$ values in the RT master record ranged from 6.00 to 11.13‰ and exceeded the threshold 9‰ (Pioneer catchment “source”; Marion 2007) 11 times in the 33-year record, predominantly during large flood years (1970, 1974, 1976, 1977, 1979, 1989, 1991, 2000) or in years following extreme events or multiple wet years (1975, 1978, 1992; Fig. 7). At KI, $\delta^{15}\text{N}$ values ranged from 2.50 to 13.62‰, exceeding 9‰ only in 1974 and 1991, coincident with two of the three largest flood years in the record. Isotopic data from SC were generally more

depleted and consistently below the 9‰ threshold, ranging from -3.82 to 7.50‰ .

Discussion

The position of a reef across the continental shelf and its relative proximity to highly modified terrestrial catchments will affect its exposure to terrestrial discharge and, therefore, the frequency of major disturbances. Given the perceived role of disturbance history in shaping present-day coral communities (Hughes 1989), it is highly likely that disturbance events and/or chronic stressors may have influenced the community structure of reefs in the Mackay region. Here, the disturbance regime for this region is reconstructed, using biogeochemical coral proxies of the frequency and intensity with which the nearshore locations are exposed to acute flood events and chronic turbidity plus nutrient enrichment. The magnitude and frequency of terrestrial exposure are discussed in relation to coral assemblage data to assess likelihood of direct and indirect effects on coral community composition (Fabricius 2005).

Group 1: Chronic, high-magnitude exposure

Nearshore reefs located adjacent to river drainages have particularly high rates of disturbance. In addition to the main categories of disturbance that affect offshore reefs ecosystems worldwide (e.g., bleaching, tropical cyclone damage, predation, overfishing), nearshore reefs are also subject to both acute and chronic disturbance from terrestrial discharge that can affect reef development and persistence. Due to an evident lack of accreted carbonate framework, the coral assemblages at Round Top resemble an “incipient reef” (*sensu* Hopley et al. 1989), which has not formed a true reef flat and consists mainly of thin carbonate veneers and isolated coral colonies at under 10% cover. Given the historically recent and severe land modification of the Pioneer catchment (Jupiter and Marion 2008), the key question is whether an antecedent submerged reef at Round Top “turned off” and became buried by heavy sedimentation or whether reef development never “turned on” due to chronically adverse conditions (Budemeier and Hopley 1988).

As observed in prior studies (Alibert et al. 2003; McCulloch et al. 2003), coral Ba/Ca was significantly related to river discharge (Table 3b), which is the main source of Ba to the nearshore (Hanor and Chan 1977). Ba transported by rivers rapidly desorbs from fine-grained terrestrial sediment within the low salinity (0–5 ppt) zone and advects with the flood plumes into nearshore waters, where it is incorporated into coral aragonite in close proportion to its local abundance (McCulloch et al. 2003).

Fig. 7 Coral records of annual $\delta^{15}\text{N}$ from Round Top, Keswick and Scawfell islands. The Round Top values for $\delta^{15}\text{N}$ are an average of three records. Horizontal dashed lines indicate source value from lower Pioneer River reservoirs (9‰) that is discharged into nearshore waters during flood events. Annual Pioneer discharge is plotted below

Although Hacker (1988) estimated a two- to fourfold increase in sediment yield from the Pioneer catchment since European arrival, the majority of eroded terrestrial sediment may never reach coral reef communities: due to its unusual macrotidal configuration, much of the sediment is retained within the Pioneer River Estuary or along the adjoining foreshore. Ba may continue to desorb from sediment buried in the estuary and nearshore and be flushed seaward with flood tides (Carroll et al. 1993; Alibert et al. 2003). This process likely contributes to the elevated Ba/Ca values that continue for several months following flood events (Fig. 6). The round shape of the Round Top Ba/Ca peaks contrasts strongly with the sharp Ba/Ca peaks observed from inshore corals influenced by the Burdekin River (Sinclair and McCulloch 2004), which passes through virtually no estuary and discharges sediment directly into the marine environment (Hacker 1988).

While some fine sediment may still be transported with Pioneer flood plumes and have consequent effects on reef organisms (Fabricius 2005), Larcombe and Woolfe (1999) argue that turbidity is largely governed by local hydrodynamics and resuspension as opposed to sediment supply. Limited inner reef development between Mackay and Broad Sound (Fig. 1) has been previously attributed to elevated turbidity caused by high current speeds (up to 3 m s^{-1}) associated with large (up to 10 m) tidal ranges (Kleypas 1996). Frequent high tidal velocities create chronic turbidity from sediment resuspension, thus limiting maximum reef depth, while low mean water levels restrict upward reef growth (Kleypas 1996; Cooper et al. 2007). With a 6.4-m tidal range, Round Top Island would experience similar levels of sediment resuspension and a compressed zone for reef development, with bottom depths only $\sim 5\text{--}10 \text{ m}$ below LAT. Like the reefs around the Northumberland Islands adjacent to Broad Sound described in Kleypas (1996) and van Woesik and Done (1997), the coral community at Round Top had greater numbers of turbidity tolerant species, such as encrusting *Montipora* spp. and foliaceous *Turbinaria* spp., with reduced overall dominance of more sensitive branching *Acropora* spp. The high turbidity may have additionally contributed to the lack of macroalgae as heavy sedimentation can maintain algal communities in arrested succession through negative effects on recruitment, survival, and growth of fleshy species (Umar et al. 1998). Similarly, Done et al. (2007) noted absence of macroalgae and *Acropora* at backreef location at Pandora Reef with high sedimentation rates and a high proportion of fine ($<63 \mu\text{m}$) particles.

North of Broad Sound, which receives minimal river inputs, nearshore reef development may have also been limited by freshwater exposure. The coral luminescence records suggest that Round Top is chronically exposed to pulses of freshwater. Although there were significant

differences in maximum – mean luminescence intensity in wet versus dry years, there was no significant relationship between peak luminescence and annual Pioneer River discharge. This is because, at only 5 km from the Pioneer River mouth, Round Top corals are influenced by strong tidal flux and show intense annual luminescent lines, even in years of low to moderate discharge. The combined luminescence and Ba/Ca records therefore suggest that long-term, chronic (sub-annual) disturbance from both freshwater and elevated turbidity may have prevented historic reef development at Round Top by creating adverse conditions for major reef builders. The small colonies present had little cementation to the reef matrix and are therefore susceptible to mechanical damage which prevents reef accretion (van Woesik and Done 1997).

Group 2: Episodic, high-magnitude exposure

In contrast to the coral core records from Round Top Island that indicate a long-term, chronically stressful environment, both the Keswick Island luminescence and $\delta^{15}\text{N}$ time series show discrete, episodic exposure to terrestrial discharge. Of all three locations, Keswick corals showed the most significant difference in peak luminescence height (relative to mean luminescence intensity) in wet versus dry years. The longest core from Keswick Island (KIC: 1968–2004) had particularly bright luminescent lines in every major flood year during the record (1971, 1974, 1976, 1989, 1990, and 1991), with elevated peaks that sharply contrasted with luminescence resulting from seasonal differences in skeletal density (Fig. 5b).

In addition, Keswick coral skeletal nitrogen from two of the most extreme flood years (1974 and 1991) had elevated $\delta^{15}\text{N}$ values (12.24‰ and 13.62‰, respectively). These values are highly enriched over background seawater particulate organic matter (POM) $\delta^{15}\text{N}$. Wastewater from septic systems and untreated sewage, with $\delta^{15}\text{N}$ of dissolved inorganic nitrogen (DIN) typically above 10‰ (Heaton 1986), have been shown to enrich the $\delta^{15}\text{N}$ values in coral skeletons and other reef organisms (Risk and Erdmann 2000; Marion et al. 2005). However, Mackay has a secondary sewage treatment facility and mean $\delta^{15}\text{N}$ of POM sampled from the outflow was $3.0 \pm 0.2\text{‰}$ (Marion 2007). Therefore, enrichment in flood years in the KI corals is more likely to reflect discharge of ^{15}N -enriched lower Pioneer River nitrogen sources ($\sim 9\text{‰}$) combined with further fractionation ($+1\text{--}7\text{‰}$) associated with planktonic uptake of land-derived nitrogen and microbial remineralization of senescent plankton detrital matter (Waser et al. 1998; Marion 2007).

Extreme flood events have previously been related to large-scale death of coral assemblages in the southern GBR. The combination of massive flooding coinciding

with peak spring tides in January 1918 is believed to have resulted in near total mortality of the innermost fringing reefs of the Whitsunday group (Rainford 1925). In the Keppel Islands following Cyclone Joy in late 1990, floodwaters from the Fitzroy River damaged corals to 1.3 m depth, causing epidermal cell death and bleaching predominantly in corals from the families Acroporidae and Pocilloporidae (van Woessik et al. 1995). In such cases, recovery of coral cover can be slow: DeVantier et al. (2006) reported low coral cover and species richness from reefs in the Northumberland Group and Keppel Islands surveyed in 1997 that were considered legacies from the 1990 death event.

During extreme, acute events, nearshore reefs adjacent to agricultural centers or waste disposal sources can be inundated with anthropogenic nutrients that may have direct and indirect effects on coral reef organisms (Fabricius 2005), with possible dramatic effects on coral community composition. For example, pulses of terrestrial nutrients are rapidly transformed into phytoplankton biomass that is advected offshore with the flood plumes (Furnas et al. 2005). Elevated nutrient concentrations are known to contribute to biologically mediated flocculation of sediments and organic matter (derived from phytoplankton blooms) into large, sticky aggregates (Fabricius and Wolanski 2000). As small coral reef organisms (e.g., coral recruits) are highly susceptible to smothering and consequent mortality from marine snow (Fabricius et al. 2003), acute exposure to flocculated particulate matter can skew population demographics and impede coral recovery by removing whole cohorts (Fabricius 2005). A recent modeling study concluded that the nutrient-enriching impact of rivers draining agricultural catchment of the GBR has extended 20–30 km further offshore since European arrival (Wooldridge et al. 2006). In the Mackay region, long-term coral $\delta^{15}\text{N}$ data show isotopic enrichment associated with flood years that has increased at a rate significantly correlated with regional increases in fertilizer consumption since the 1950s (Marion 2007). This change, in concert with repeat disturbance causing coral mortality, may have had a strong, recent effect on the current coral community composition.

High cover of fleshy macroalgae was observed at all Keswick and St. Bees transect locations and appears to persist through time and seasons (S. Jupiter, pers. obs.). There is still considerable debate, however, regarding the significance of large stands of macroalgae on nearshore GBR reefs (DeVantier et al. 1998). Although fleshy macroalgae have been suggested to be indicators of eutrophication and subsequent reef degradation (Bell and Elmetri 1995), their presence is often a natural successional stage following disturbance that damages or kills coral tissue (Diaz-Pulido and McCook 2002). When recurrence

intervals of disturbance are low, rapid radial extension ($>10 \text{ cm yr}^{-1}$) of fast-growing coral genera such as *Montipora* and *Acropora* enable the colonies to overgrow algal holdfasts during senescent periods and recover dominance within the community (Done 1992). Macroalgal persistence, however, is likely due to complex, synergistic effects of increased disturbance frequency, increased nutrients and reduced herbivore abundance that will vary in importance by location (McCook 1999).

Because no data currently exist on herbivore abundance at Group 2, it is uncertain whether the initial cause of macroalgal dominance resulted from reduced herbivory (e.g., McManus et al. 2000), high frequency disturbance coupled with enhanced nutrient availability or a combination of the above. The disproportionate representation of acroporids and near absence of more robust taxa such as faviids and poritids appears to suggest that repeated disturbance caused major mortality at the site, while the coral core data indicate that the reefs have recently (within the past 16 years) been exposed to high volumes of freshwater carrying terrestrial nitrogen that did not historically reach the island (Marion 2007). In theory, 16 years should be ample time for coral recovery if there is adequate adult stock of fast growing acroporids (Done et al. 2007) and the reef suffers no further acute or chronic disturbance. Yet current numbers of acroporids may be too low to repopulate the reef, and the islands are geographically isolated (by both distance and prevailing currents) from their neighbors. The ability to recover may be further reduced if established fleshy macroalgal stands limit settlement of coral larvae (Kuffner et al. 2006) and exposure to nutrient-rich runoff reduces survivorship. Fabricius et al. (2005) suggested that declining water quality may have similarly slowed coral recovery at Russell and Normanby reefs, two inshore locations within the Wet Tropics region that had reduced coral cover since 1990 due to bleaching, crown-of-thorns (COTS), and a cyclone. In both locations, coral cover has either remained static or continued to decline even in the absence of further severe disturbance.

Group 3: Episodic, low-magnitude exposure

In contrast to the Group 2 reefs, the coral core records suggest that exposure to terrestrial discharge is highly attenuated and infrequent by 51 km offshore at Scawfell Island (Group 3). Although peak coral luminescence was correlated with Pioneer River discharge, the amplitude of the peaks was very low, suggesting the freshwater was considerably diluted during the flood years (1989, 1991) when plumes may have reached the reef. Alternatively, it is possible that the luminescent lines resulted from localized island runoff draining into Refuge Bay, produced by the same precipitation events causing runoff for the Pioneer

River. A third bright luminescent line in 1983 is unlikely to be a response to freshwater runoff due to the low discharge volume from the Pioneer River. As anomalous luminescent lines have previously been associated with thin, high-density stress bands in corals distant from terrestrial sources (Smithers and Woodroffe 2001), the intense line (visible in 1983 for all the cores analyzed in this study) may represent a regional response to El Niño-induced climate perturbations (Jupiter 2006).

The characteristics of Ba/Ca and $\delta^{15}\text{N}$ records from Group 3 corals do not indicate strong exposure to Pioneer catchment sources. The generally low, but variable Ba/Ca values (mean = 3.55 $\mu\text{mol/mol}$) were similar to Ba/Ca values from Davies Reef, approximately 70 km NNE from Townsville and out of reach of most river plumes (Alibert et al. 2003). Although there were large peaks in the record, they have no regular frequency and likely reflect heterogeneity within coral skeletal elements or incorporated organic material rather than a stronger, over-riding environmental signal (Allison 1996). Mean skeletal $\delta^{15}\text{N}$ values (3.5‰) were similar to measurements of marine POM (Marion 2007) and *Porites lobata* tissue $\delta^{15}\text{N}$ (3.8‰) measured from corals 40–50 km offshore from Townsville (Sammarco et al. 1999). Natural marine $\delta^{15}\text{N}$ values typically fall between ~4 and 6‰ (Owens 1987), with localized variability depending on relative contributions of: N-fixation, which depletes the $\delta^{15}\text{N}$ of the particulate nitrogen pool; remineralization by phytoplankton, resulting in $\delta^{15}\text{N}$ enrichment; and upwelling of deep-water nitrate, also resulting in $\delta^{15}\text{N}$ enrichment (Altabet 2006).

When evaluated together, the coral records support the conclusion that Scawfell Island is relatively free from the influence of the Pioneer catchment. It is therefore expected that Scawfell hard and soft coral abundance fluctuates in response to their relative susceptibility to bleaching, mechanical disturbance, predation, and disease. Mean live hard coral cover ($17.7 \pm 3.0\%$) was slightly lower than observed by van Woessik and Done (1997) on Cockermouth and Scawfell Islands' reefs (26.9%), while dominance of acroporid corals was higher, possibly because the sampling was not as extensive as in the prior study. The below-average value compared with the average (33%) of AIMS nearshore monitoring sites (Sweatman et al. 2007) may be due to competition for space with soft coral assemblages ($31.3 \pm 4.6\%$), which had the highest cover recorded from all locations. Episodic disturbance that causes hard coral decline can release octocorals from competition and increase their abundance (Fabricius 1998). For example, following massive bleaching and coral mortality in 1998 at Aldabra Atoll, Seychelles, soft corals of the genus *Rhytisma* opportunistically colonized newly available space (Stobart et al. 2005). While disturbance from tropical cyclones (eight over the record period noted in Fig. 2),

bleaching (potentially in 1983 or 1998 during large SST anomalies), predation, or disease could have initiated a release of soft corals at Scawfell Island, it is unlikely to have been triggered by a flood-related event.

Group 4: Relatively unexposed

To date, there appear to be no prior surveys of reef condition or community structure at the three outermost reefs. Mean live hard coral cover at Derwent Island and the Kindemar reefs (23–29%) was within the range of the highly variable values (~10–70% median cover) observed by the Australian Institute of Marine Science's long-term monitoring surveys (1986–2005) of middle shelf reefs in the Pompey Sector (Sweatman et al. 2005). Even though the reef geomorphology varied among survey sites at each reef, the reefs clustered together largely due to similar high abundances of crustose coralline algae, which can indicate high wave energy conditions (Done 1982). All the middle-shelf reefs in this region are likely to encounter high energy conditions from waves propagating through the Capricorn Channel (Kleypas and Hopley 1992).

Although there is no luminescence or geochemical data from corals at Group 4 reefs, it is unlikely that flood plumes from the Pioneer or adjacent rivers would travel this far across the shelf: Lough et al. (2002) found no visible luminescent lines from Credlin Reef (~50 km NNE of Derwent). However, variable effects of tropical cyclones, COTS outbreaks, and bleaching have been noted at nearby reefs in the Pompey sector (Sweatman et al. 2005). For example, Sweatman et al. (2005) noted declines in hard coral at Credlin Reef both following Cyclone Justin in 1997 and after the 2002 bleaching event, while significant coral mortality was associated with high numbers of COTS observed in 2001 on Southampton reef (~40 km N of Little Kindemar). Yet without temporal monitoring data, long-term coral records or surveys of scarring on massive *Porites* to assess the timing of prior COTS outbreaks (DeVantier and Done 2007), we can say little about disturbance frequency or which particular disturbances may have affected community composition at Derwent on the Kindemar Reefs.

In summary, coral core records can provide insights into long-term environmental changes, in particular providing constraints on the frequency and intensity to which nearshore reefs are exposed to terrestrial runoff. By measuring multiple proxies that reflect different environmental parameters, logical links can be made between the structure of present day coral communities and how they may have responded to prior acute or chronic disturbance. The results from this study conducted along an inshore to offshore gradient of environmental change suggest several classes of response. Not surprisingly, reefs historically exposed to high levels of

runoff and chronic turbidity may never have been capable of reef development. Intermediate locations that are episodically disturbed by pulses of river runoff enriched in anthropogenic nutrients may have reduced ability to recover, which can affect reef persistence if corals are replaced by macroalgae and if destructive processes (e.g., erosion) outweigh carbonate accretion (Done 1999). Finally, more distal reefs that are minimally exposed to terrestrial discharge likely have strong capacity for recovery from other types of documented disturbance (e.g., tropical cyclones, bleaching, COTS), given the current abundance of coral, however, this may be affected in the near future by global climate change. Given that multi-decadal environmental monitoring is non-existent for most coral reef regions, long-lived coral records, as archives of environmental change, fill an important gap in assessing how modern reef assemblages were shaped by historical disturbance.

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