Coral Reefs
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REPORT

The impacts of flooding on the high-latitude, terrigenoclastic influenced coral reefs of Hervey Bay, Queensland, Australia

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Abstract This study examines the impacts of an acute flooding event on the marginal, high-latitude, terrigenoclastic influenced coral reefs of Hervey Bay in southeast Queensland, Australia. In January 2011, the Mary River near Hervey Bay experienced its eleventh highest flood on record. The Mary River catchment has been highly modified since European colonisation, and, as a result of heavy rain and flooding, Hervey Bay was exposed to reduced salinity and elevated levels of turbidity and nutrients for approximately 14 weeks. Through the use of photograph transects and point intercept analysis, per cent cover of coral reef benthic communities was measured prior to and just after the flooding event. Sites were located between 250 m and 5 km from the mainland and from 18 to 85 km away from the mouth of the Mary River. Overall, there was a ~40 % reduction in coral cover post-flood, including significant mortality up to 89 % at four of six reefs. Mortality did not vary with distance along the coast from the Mary River, but mortality was found to be highest closer to the mainland, where turbidity and nutrients levels were also the highest. Despite the decades of input of highly turbid and nutrient laden waters from the Mary River, recovery has occurred in the past, and, given the persistence of similar conditions, would be expected to take place again. Climate change predicts increased frequency of severe storms and flooding, and this, combined with elevated sedimentation and nutrients from the highly modified catchment, may reduce these recovery periods, resulting in the deterioration of Hervey Bay reef communities.

Keywords Marginal · Turbid · High-latitude · Flood · Australia · Coral

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Introduction

Coral reefs worldwide have always been subject to large-scale natural disturbances such as runoff and flooding. When unaffected by anthropogenic factors, coral reef communities often persist and recover from natural disturbances (Pandolfi et al. 2006). Anthropogenic changes to the environment, however, can lead to reduced capacity by coral reef communities to overcome disturbance (Pandolfi et al. 2003; Hughes et al. 2010). Changing land use, catchment degradation, pollution and terrestrial runoff adversely affect a coral reef's resistance and resilience, and this may result in increasing degradation, morbidity and mortality (Fabricius 2005; Kroon et al. 2011; Schaffelke et al. 2011). At least 25 % of coral reefs worldwide are threatened by runoff and flooding (Burke et al. 2011). In Australia, only 5 % of reefs are identified as being threatened by terrestrial runoff (Burke et al. 2011). However, given the large amounts of nutrient runoff from rivers along the east coast of Australia (Kroon et al. 2011) and the likely resulting impacts on Great Barrier

Reef coral communities through, for example, crown-of-thorns starfish outbreaks (De'ath et al. 2012), the percentage of reefs around Australia impacted by runoff and flooding is likely to increase substantially. Furthermore, coral communities extend into high latitudes along the coast of Australia, and these high-latitude communities are also subject to runoff and flooding. Climate change predicts that flooding will become more severe in eastern Australia (IPCC 2007; CSIRO and BOM 2012), and the future of coral reefs affected by such flooding is uncertain.

At latitude 25° south, the coral reefs of Hervey Bay are at the southern margin of scleractinian coral reef formation along the Australian east coast (Zann 2012). These reefs are subject to terrestrial runoff and sedimentation from the nearby Mary River, which has been highly modified since European colonisation (Johnson 1996). Flooding is a common occurrence in the Mary River with thirty-seven "minor" (5 m+) or larger floods identified for Maryborough in the 150-year record up to January 2011, an average of one flood every 4 years (BOM 2011). Average annual output of suspended solids and nutrients (total nitrogen and phosphorus) is currently estimated at 8.1–13.0 times that prior to European colonisation (Kroon et al. 2011). Reef communities of Hervey Bay are dominated by the coral genera *Turbinaria, Goniopora* and *Favia* (Zann 2012), known to be tolerant of elevated sediment and turbidity (Sofonia and Anthony 2008). However, the sensitivity to large floods of these high-latitude coral communities, already subject to reduced calcification, photosynthesis and energetics as a result of colder temperatures and decreased light (Harriott and Banks 2002), is not yet established.

In December 2010 and January 2011, after decades of drought conditions (Gräwe et al. 2010), Queensland, Australia experienced intense and persistent rainfall (Giles 2012) which caused severe flooding along the coast, including the Mary River. From the 6 December 2010 until 16 January 2011, parts of the Mary River catchment received 1,000 mm of rain (BOM 2012) resulting in elevated flows and then flooding from 8 to 16 January (BOM 2011). Fortunately, this extreme rainfall was not consistent over the whole of the catchment and the Mary River at Maryborough, 30 km from the mouth, only registered what was classified as a moderate, one in twenty year flood (BOM 2011; MRCCC 2011). Although the flood level fell below the record of 12.27 m from 1893, it registered 8.20 m and was the eleventh highest flood on record (BOM 2011). The subsequent downstream transport of sediment and freshwater resulted in a flood plume that travelled 50 km away from the mainland into Hervey Bay and 95 km north (e-atlas.org 2011), where it then merged with the flood plume from the adjacent Burnett river system.

Here, we examine the effects of this acute flooding event of January 2011 on coral communities of the marginal, high-latitude, terrigeno-clastic influenced reefs in Hervey Bay through changes in hard and soft coral abundance and community structure. Water quality data from before (since 1994), during and after the flood plume are examined to assess the water quality of the flood waters in relation to historical water quality conditions. Finally, since flood plumes have spatio-temporal variation in concentrations of sediment and salinity within them (Devlin and Schaffelke 2009), and it has been found that Mary River plumes can be concentrated within 10 km of the mainland by prevailing winds and water circulation in the bay (Gräwe et al. 2010), we also determine whether the impacts vary according to the distance of the coral community from the mouth of the river and how distant the community is located away from the mainland. Our study provides increased understanding of the impacts on six Hervey Bay coral reefs of acute flooding from the highly anthropogenically modified Mary River catchment, and how high-latitude coral communities may respond to future flooding during predicted climate change.

Materials and methods

The study area

Hervey Bay (25.00°S, 152.85°E) is situated at the northern end of the Great Sandy Straits on the southern coast of Queensland, Australia (Fig. 1). It has an area of approximately 4,000 km^2 and is 80 km across the north facing opening. The waters of Hervey Bay are relatively shallow with an estimated mean depth of 15 m (Gräwe et al. 2010) and a maximum tidal range of 4 m. Fraser Island, a 124-km long sand island, protects the bay from oceanic swell and the predominantly south-easterly winds (Fig. 1).

The Mary River is approximately 300 km long with a catchment of around 10,000 km^2 (Prange and Duke 2004). Its mouth opens into Great Sandy Strait 15 km to the south of Hervey Bay. The Mary River catchment has been modified extensively since European colonisation around 1840 and large parts of the catchment are subject to high levels of land clearance, grazing and farming with only 1 % currently remaining in a natural state (Johnson 1996; Campbell and McKenzie 2004; Prange and Duke 2004). In 1996, erosion was observed along an estimated 85 % of the catchment (Johnson 1996). A series of barrages maintain water in the river during drier periods when there is little or no flow. Rainfall in the Mary River catchment occurs year round with higher rainfall and flooding occurring in the summer months from December to March (BOM 2012). Average annual rainfall for Hervey Bay is 1,090 mm, though rainfall is typically 50 % greater in some of the more elevated parts of the catchment (BOM 2012). Typical

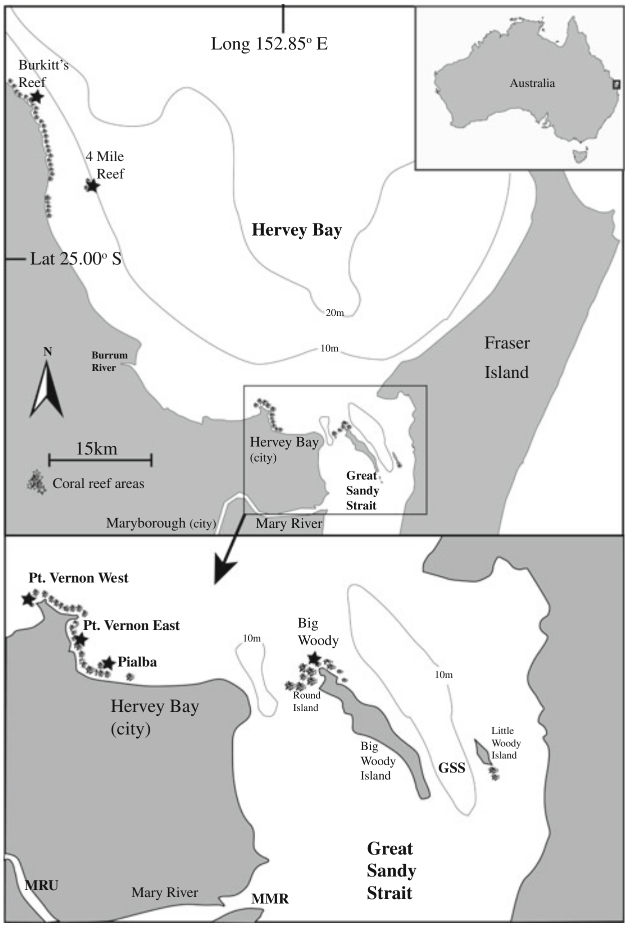


Fig. 1 Location of Mary River, coral reef study sites and water quality sites near Hervey Bay, Queensland, Australia. Water quality sites: Great Sandy Strait (GSS), Mary River upstream (MRU) and mouth of Mary River (MMR). With the exception of the map of Australia, all of the *mapped areas* are within Great Sandy Marine Park

combined rainfall for December/January in Hervey Bay is around 240 mm and around 350 mm in wetter areas of the catchment (BOM 2012).

Six coral reef sites were examined for this study (Fig. 1): 4 Mile Reef, Burkitt's Reef, Pt. Vernon West, Pt. Vernon East, Pialba and Big Woody. With the exception of 4 Mile reef, the survey sites are part of an intermittent fringing reef that stretches from Great Sandy Strait north through Hervey Bay and northward along the coast (Fig. 1). Almost all the reefs of this study occur in less than 5 m depth at high tide and are variously located up to 85 km from the mouth of the Mary River and 5 km from the mainland (Table 1). These reefs are all protected from prevailing oceanic swell by the presence of Fraser Island, though Burkitt's and 4 Mile reefs are more exposed to wave action due to the longer fetch (70 km) (Fig. 1). Up to 54 hermatypic coral species have been documented on these reefs with coral cover typically between 20 and 50 % at the reef scale (DeVantier 2010; Alquezar et al. 2011; Zann 2012).

Table 1 Size, depth range, distance to mainland and distance to mouth of the Mary River of the reef survey sites

Reef	Area (m^2)	Depth range (m)	Distance mainland (km)	Distance mouth Mary River (km)
Burkitt's Reef	Fringing	3–8	0.5	85
4 Mile Reef	20,000	5–12	5.0	70
Pt. Vernon West	Fringing	3–5	0.4	30
Pt. Vernon East	Fringing	3–5	0.25	26
Pialba	Fringing	3–5	0.7	24
Big Woody	Fringing	3–5	4.0	18

Flood plume and ambient water quality data

Mary River flood plume and historical water quality data for the Hervey Bay area were obtained from the Queensland government's Department of Science, Information Technology, Innovation and the Arts (DSITIA). Since 1994, monthly data have been collected by DSITIA in the Great Sandy Strait (site GSS, Fig. 1) and the Mary River 22.45 km (Site MRU, Fig. 1) just south of Maryborough. In January 2011, water quality in the flood plume was measured by DSITIA on several occasions at four locations adjacent to reefs in this study: Burkitt's Reef, 4 Mile, Point Vernon West and Pt. Vernon East (Table 2). Mean salinity, turbidity, total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP) and dissolved oxygen saturation (DO_{sat}) were calculated from the monthly measurements and used as a basis for comparison to conditions in the plume. These parameters were specifically examined because they were available in the historical data set, are consistent with previous water quality studies and are listed as trigger nutrients by the National Australian and New Zealand Environment Conservation Council (ANZECC) guidelines (ANZECC 2000), the National Oceanic and Atmospheric Administration (NOAA) Screening Quick Reference Tables (Buchman 2008) and DSITIA water quality objectives (DERM 2010) for the Mary River and Great Sandy Strait. DSITIA also measured 23 different dissolved metals in plume waters at the mouth of the Mary River (Site MMR, Fig. 1) and 14 different pesticides in plume waters at MMR and at Pt. Vernon West, but only those exceeding DSITIA, NOAA or ANZECC trigger levels are discussed further.

Sampling methods

Photographic belt transect methods with photo-software analysis (Leujak and Ormond 2007) were used to measure

Table 2 Water quality data collected Jan–Feb 2011 from plume water near reef study sites in Hervey Bay, Queensland, Australia

Parameter	Reef Site							
	Burkitt's Reef		4 Mile Reef		Pt. Vernon W		Pt. Vernon E	
Sample date	18-Jan-11	6-Feb-11	18-Jan-11	6-Feb-11	19-Jan-11	31-Jan-11	19-Jan-11	31-Jan-11
Salinity range (ppt)	31.2–33.7	na	31.2–34.3	na	29.4–31.2	32.3	29.8–30.1	32.1
Turbidity range (NTU)	9.0–13.6	na	<1	na	3.6–16.9	9.9–12.6	7.4–23.4	7.5–9.9
TSS (mg l^{-1})	79	35	12	14	18	35	24	34
TP (mg l^{-1})	0.025	0.014	0.008	0.006	0.012	0.020	0.022	0.015
TN (mg l^{-1})	0.230	0.180	0.130	0.110	0.180	0.190	0.280	0.180
DO_{sat}	86.8–91.1	na	101.5–115.4	na	97.7–105.8	91.4–93.8	104.7–106.7	94.6–100.3
Temperature (°C)	26.73–26.84	na	26.76–26.98	na	27.46–28.12	26.45–26.46	27.79–28.29	26.35–26.46

Data for table provided by: © State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2012

TSS total suspended solids, *TP* total phosphorus, *TN* total nitrogen, DO_{sat} dissolved oxygen saturation, *na* no sample available

per cent cover of the benthic coral communities on the reef slopes. Pre-flood photographs were taken 6 months prior to the floods in July 2010 and covered 5 of our 6 study sites: Burkitt's Reef, 4-Mile Reef, Pt. Vernon West, Big Woody Island and Pialba Reef. At each of these reef sites, photographs covering ~60 cm × 70 cm of substrate were taken every metre along five haphazardly placed 30-m transects. Pre-flood photograph transects were also taken at a sixth site, Pt. Vernon East, in July/August 2006 (Zann 2012). In this case, a GPS was used to track photographs taken along two transects (150 and 200 m), which stretched from the inshore to the seaward edge of the reef. A total of one hundred and twenty ~60 cm × 70 cm photographs were taken at this reef site (Zann 2012). Post-flood photographs were taken 5–7 months after the flooding, from June to August 2011, using the same reef locations identified by GPS coordinates and using methods consistent with pre-flood surveys, including the GPS tracks used by Zann (2012) at Pt. Vernon East.

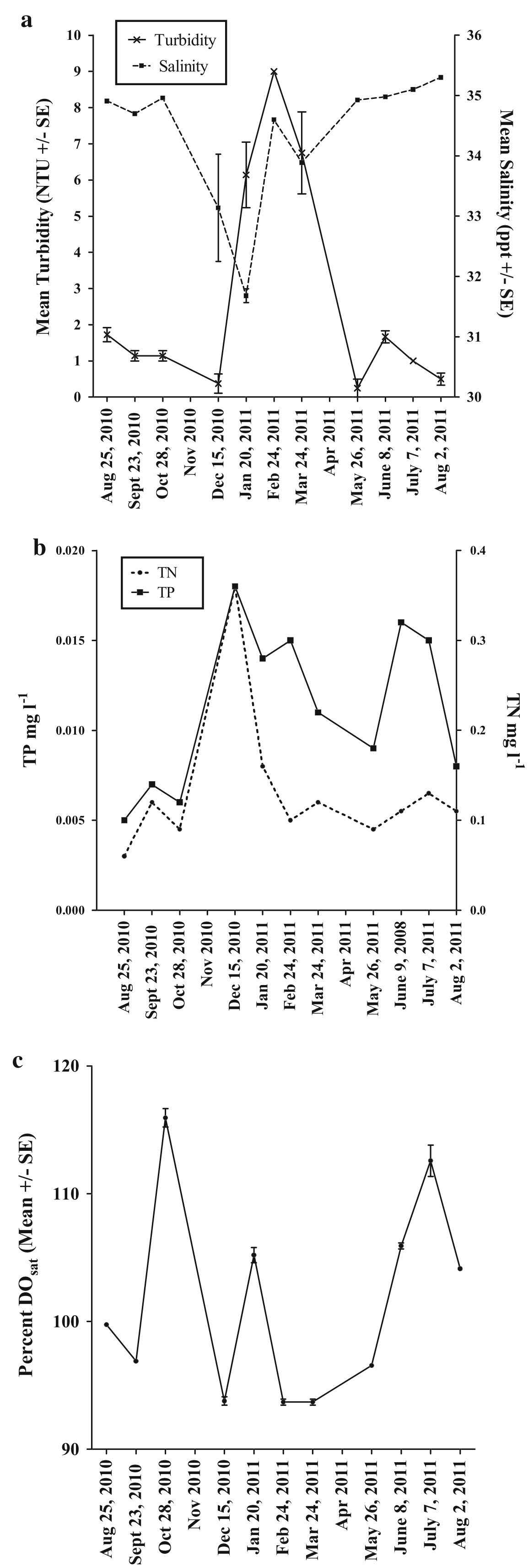
Over 1,800 pre- and post-flood photographs were analysed using the software Coral Point Count with Excel extensions (CPCE) (Kohler and Gill 2006). Each image had 15 points randomly overlaid, and the taxon for each point was identified to species and placed into the following categories: hard corals, octocorals, macroalgae, other invertebrates, seagrasses and substrata. Substrate was often composed of mixtures of sand, mud, dead coral, rubble and turf within epilithic algal matrix, and these were combined under the "Substrata" category. Per cent cover estimates were calculated for all taxa and categories. Due to difficulties with identification to species level on photographs in turbid conditions, *Goniopora* species were grouped to genus and bushy branching soft corals (other than nephtheid and xeniid corals) were grouped to *Cladiella*.

Data analyses

Statistical analyses were conducted using the software PRIMER v6 (Clarke 1993) and the add-on package PERMANOVA (Anderson et al. 2008). Two permutational analysis of variance (PERMANOVA) models were created to examine changes post-flood—a univariate model to examine changes in absolute abundance of hard and soft corals and a multivariate model to examine changes in coral relative abundance and community structure. The models included distance of the reef from the mouth of the Mary River and distance from the high tide level on the mainland as continuous predictors (covariates) and flood as a categorical fixed factor with two levels (pre- and post-flood). Type I sum of squares were calculated to ensure that any overall effect of time is independent of the effects of the covariates. Prior to creation of the models, the square root transformed univariate and multivariate data were subject to PERMDISP analyses to assess the homogeneity in the dispersion of the data between pre- and post-flood data sets. Where lack of homogeneity of dispersion (PERMDISP $p < 0.05$) was found in the data set, a more conservative significance level of $p = 0.01$ was used. To determine changes in total abundance and community structure post-flood, full models with interactions were generated using PERMANOVA on either univariate Euclidean or multivariate Bray-Curtis matrices using the distances as covariates. Non-significant factors were sequentially removed to create the simplest model. As a result of the modified methods and the difference in the timing of the baseline photography at Pt. Vernon East, analyses were carried out with and without that site see if results varied.

Non-metric multidimensional scaling (NMDS) plots were prepared to visually display the relative similarity of

Fig. 2 Turbidity, Salinity, total phosphorus (TP), total nitrogen (TN) ▶ and dissolved oxygen saturation (DO_{sat}) in Great Sandy Strait (site GSS) illustrating passage of the Mary River flood plume from 25 August 2010 to 2 August 2011. **a** Mean turbidity and salinity from all depths, **b** TN and TP from 0.2 m. **c** Dissolved oxygen saturation from all depths. Data for figure provided by: © State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2012



the reefs in terms of coral community structure before and after the flood. SIMPER analyses were undertaken to investigate the contribution by particular species to differences found in community structure pre- versus post-flood. Finally, species richness was compared pre- and post-flood using paired *t* tests.

Results

Water quality in the flood plume

The alteration of water quality in Hervey Bay began in early December, soon after flows were elevated in the Mary River by the initial persistent heavy rainfall in the catchment (BOM 2012) and finished approximately 14 weeks later, between March and May (Fig. 2a, b, c). Although the flooding of the Mary River officially occurred from 8 to 16 January 2011, the impacts on Hervey Bay coral reefs would have begun the month before when the initial flow of freshwater and nutrients (Fig. 2a, b) entered Great Sandy Strait (water quality site GSS, Fig. 1) and Hervey Bay. The subsequent flood plume in January transported an even greater amount of freshwater and nutrients, but also sediment as evident by the slightly delayed occurrence of elevated turbidity (Fig. 2a). Salinity dropped from 35 to 31.5 ppt (Fig. 2a), and nutrient (TN and TP) levels were elevated to 2–3 times their historical average (Fig. 2b; Table 3). Salinity was generally found to be lower at the reef sites and turbidity and nutrients elevated (Table 2) relative to Great Sandy Strait (Fig. 2a, b). 4 Mile reef was the exception to this, measurements indicating reduced exposure to the plume. TSS levels at reef sites varied from 12 to 79 mg l^{-1}. Dissolved oxygen saturation (DO_{sat}) was variable over the course of the flood plume (Fig. 2c) and showed no deviation from average historical conditions (Table 3). DO_{sat} at the reef locations was quite variable but perhaps slightly reduced in comparison (Table 2). Temperatures at the different reef locations were variable (Table 3) but generally within 1 °C of historical average temperature (27.03 °C) for this time of year in Great Sandy Strait.

No pesticides/herbicides were detected in the flood waters at any locations. Of the metals analysed at MMR,

Table 3 Historical mean (1994–2012) total nitrogen (TN), total phosphorus (TP), salinity, turbidity and dissolved oxygen saturation (DO_{sat}) for Great Sandy Strait (site GSS) and for the Mary River (site MRU), along with Environmental Protection Objectives for that location (DERM 2010)

Parameter	Mean for GSS	WQ objective for GSS	Mean for MRU	WQ objective for MRU
TN mg l^{-1} (SE)	0.140 (0.007)	0.115	0.710 (0.016)	0.300
TP mg l^{-1} (SE)	0.009 (0.0004)	0.010	0.082 (0.003)	0.025
Salinity ppt (SE)	35.6 (0.03)	na	na	na
Turbidity NTU (SE)	1.14 (0.1)	2	119.06 (4)	8
DO_{sat} % (SE)	98.1 (0.4)	95	83.1 (0.7)	95

Data for table provided by: © State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2012

na not applicable

copper (0.003 mg l^{-1}) and cobalt (0.0007 mg l^{-1}) exceeded the 99 % protection levels stipulated by the ANZECC guidelines (ANZECC 2000) but did not exceed the trigger levels in the NOAA Screening Quick Reference Table for acute conditions (Buchman 2008).

Pre- and post-flood abundance of hard and soft corals

Mean total coral community benthos cover at the study sites varied between 40 and 60 % pre-flood and between 5 and 60 % post-flood (Fig. 3a). The coral communities were dominated by hard and soft corals, which typically comprised >90 % of benthic cover (Fig. 3b). As a result, only hard and soft coral abundance data were analysed statistically.

The primary factors of interest for the univariate model describing absolute coral cover (Table 4) are those containing the pre- versus post-flood elements. The dispersion of the data pre- versus post-flood was non-homogeneous (PERMDISP, $p = 0.008$), and therefore, a conservative significance level of $p = 0.01$ was used to remove factors from the model. The final simplified model (Table 4) contains the “Flood” factor, indicating significant changes in total coral abundance post-flood. For all reefs combined, there was ~40 % reduction in total coral abundance from 48.1 % (SE = 2.5 %) to 29.7 % (SE = 3.3 %), but flood impacts were not consistent among the reefs. They varied from no significant change in post-flood abundance (Big Woody reef and 4 Mile reef) up to an 89 % reduction in total coral abundance at Pt. Vernon East (Figs. 4, 5a, b). Pt. Vernon East was surveyed 4 years prior to the flooding rather than just prior to the flooding, so it is possible that

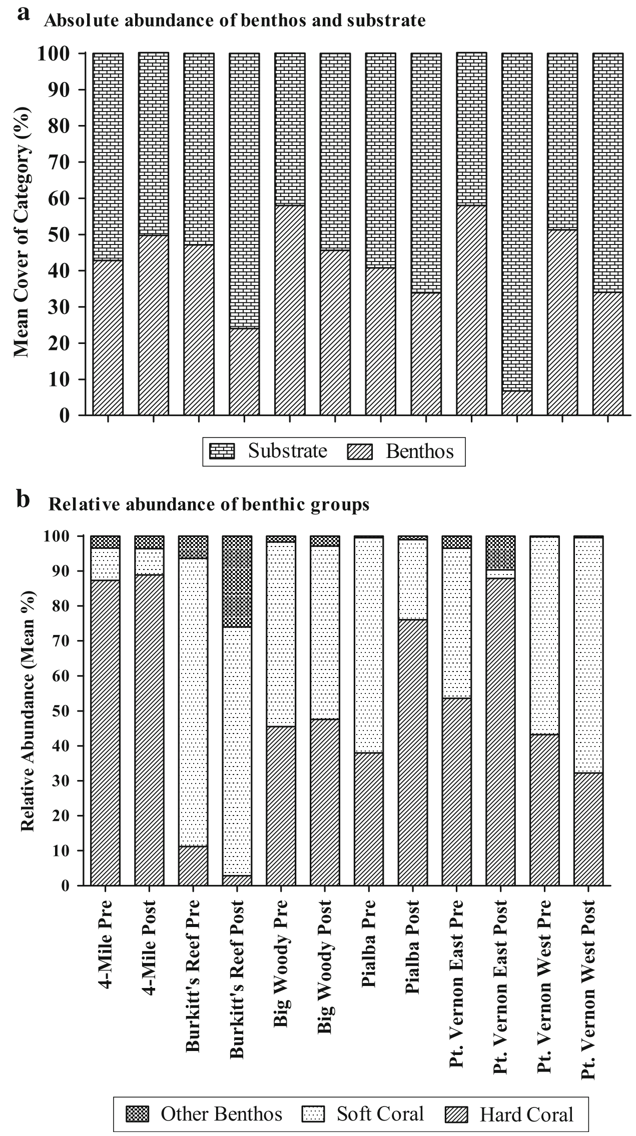


Fig. 3 Pre- and post-flood abundance of benthos and substrate on Hervey Bay reefs; **a** Absolute abundance of benthos and substrate (“Benthos” = all living organisms); **b** Relative abundance of benthic groups (“Other Benthos” = macroalgae, sponges, echinoderms, crustaceans, other non-coral coelenterates, ascidians, polychaetes and bryozoans)

some of the mortality may not have been flood related (e.g. disease). However, this site was visited frequently by one author in 2008–2010 as part of a community coral bleaching monitoring programme and was considered to be a healthy reef location (see pre-flood photograph, Fig. 5a) with coral cover comparable or better than the other surveyed sites, though this was not systematically measured.

Variation in mortality from flood impacts was significantly correlated with distance from the mainland (“Distance mainland × flood” in Table 4). Flood impacts decreased with increasing distance from the mainland, with no significant reduction in mortality beyond 700 m

Table 4 Permutational analysis of variance (PERMANOVA) with distance covariates for changes in absolute cover of total (hard and soft) coral on the reefs of Hervey Bay, Queensland, Australia pre- and post-flood, January 2011

Source of variation	*df*	MS	Pseudo-F	*p*
Distance mainland	1	119.539	11.703	0.003
Distance mouth	1	1.910	1.144	ns
Distance mainland × distance mouth	1	1.398	0.837	ns
Flood	1	48.275	28.914	0.001
Distance mainland × flood	1	22.596	13.534	0.001
Distance mouth × flood	–	–	–	ns
Distance mainland × distance mouth × flood	–	–	–	ns
Error	58	1.670	–	–

ns not significant ($p > 0.01$)

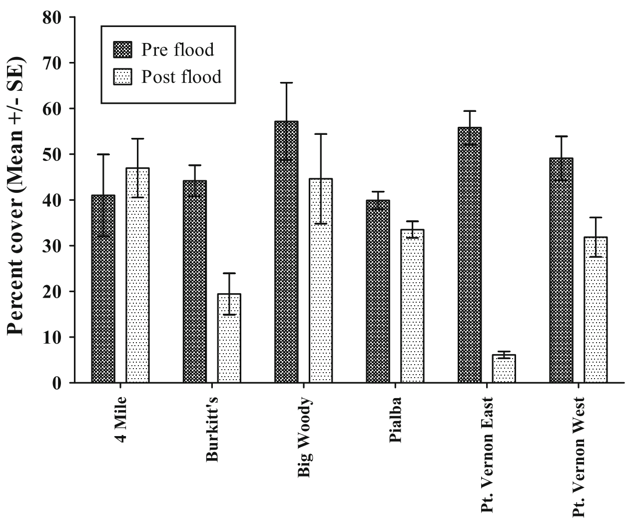


Fig. 4 Pre- and post-flood absolute abundance of total (hard and soft) live coral on six reefs from Hervey Bay, Queensland Australia

(Fig. 6a; Table 4). Surprisingly, no correlation was found between flood-related mortality and distance from the mouth of the Mary River (= distance travelled by the plume) (Fig. 6b; Table 4), so this factor was removed from the model. The three-way interaction factor "distance mouth × distance mainland × flood" was also non-significant and removed from the model (Table 4). The analysis carried out without Pt. Vernon East resulted in an identical model with slightly elevated *p* values, so all reefs were included for the final model.

Impacts on community structure

Thirty-two hard coral taxa (genus or species level) were identified (Table 5) in this study out of the 54 that have been previously recorded (DeVantier 2010; Alquezar et al. 2011; Zann 2012). *Goniopora* and *Cladiella* were relatively abundant across virtually all the sampled reef locations pre-flood, with average absolute cover per transect of 7.9 and 22.2 %, respectively. The NMDS plot shows that, with the exception of Pialba and Pt. Vernon East reefs, the pre- and post-flood communities at each reef are similar to each other, but distinct from those of the other reefs (Fig. 7). This can also be seen by the differences in relative abundance of genera among the reefs (Fig. 8a–f). SIMPER analyses (Table 6) at the genus level pre-flood indicate *Goniopora* and *Cladiella* were abundant at most reefs but

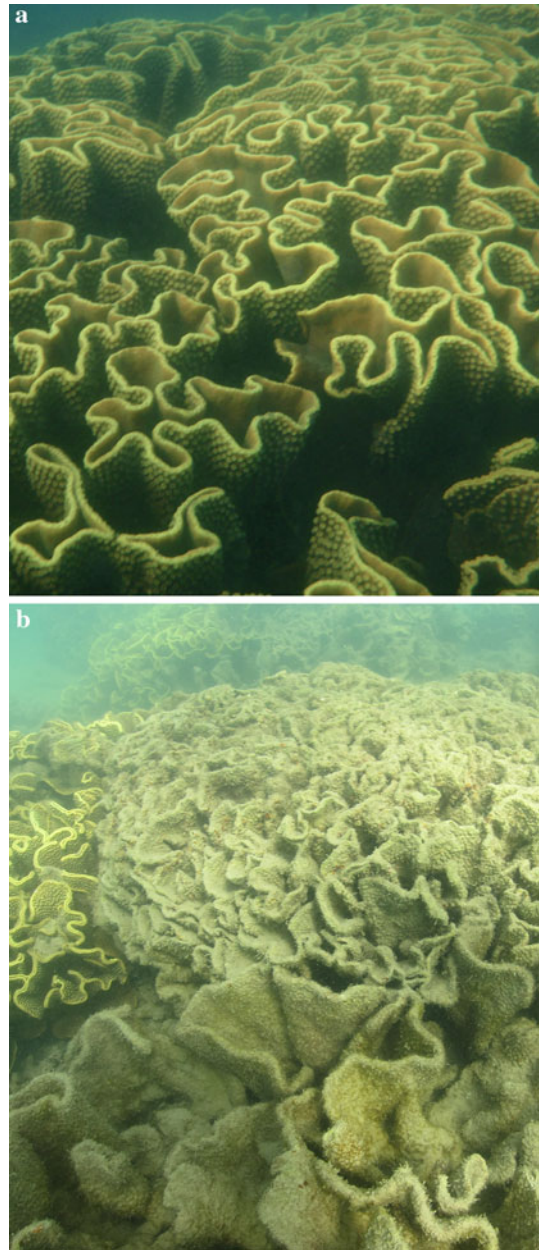


Fig. 5 Photographs of *Turbinaria mesenterina* at Pt. Vernon East: **a** pre-flood in August 2009 and **b** post-flood July 2011

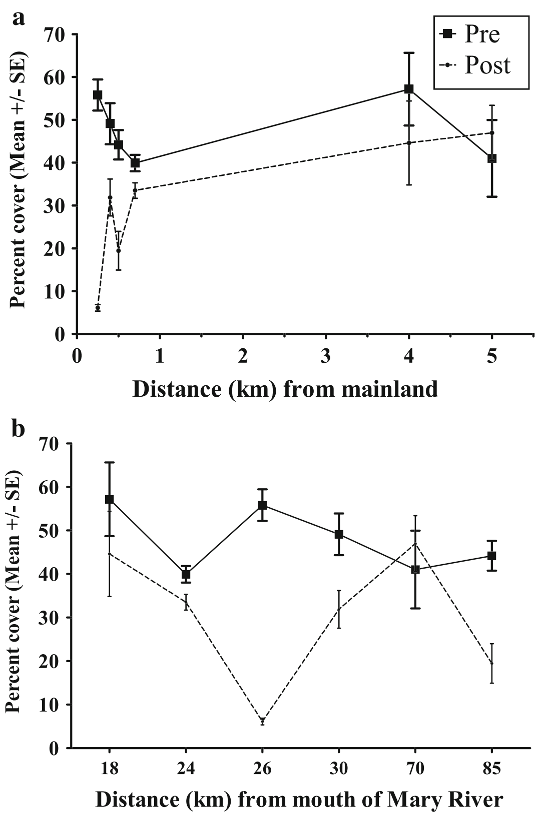


Fig. 6 Pre- and post-flood abundance of total (hard and soft) live coral on 6 reefs from Hervey Bay, Queensland, Australia; **a** relative to distance from the mainland; **b** relative to distance from the mouth of the Mary River

that Pialba and Pt. Vernon East reefs were largely distinguished from other reefs by the greater abundance of *Turbinaria*. 4 Mile reef was distinguished by abundant *Pocillopora* and *Montipora*, and Big Woody by the presence of *Acropora*. Burkitt's Reef and Pt. Vernon West had high abundance of the less common species ("Other species"—Fig. 8a, f).

Genus level data were used for the multivariate PERMANOVA model since it yielded the same simplified model as the species level data. The use of genus level data also increased the homogeneity of the dispersion (PERMDISP, $p = 0.052$) which allowed the significance threshold for removal of factors from the model to remain at $p = 0.05$. As with the univariate model, the primary factors of interest in the multivariate PERMANOVA model are those assessing the pre- versus post-flood component (Table 7). Despite the underlying significant variation in community structure with distance from mainland and distance from river mouth (i.e. factor = "distance mainland," "distance mouth" and "distance mainland × distance mouth"), significant changes in community structure were also detected between pre- and post-flood surveys ("Flood" factor, Table 7). However, neither distance from the mouth nor distance from mainland correlated with flood-related coral mortality, and these factors were removed from the simplified model, as was the three-way interaction factor "distance mouth × distance mainland × flood" (Table 7). The analysis carried out without Pt. Vernon East resulted in an identical model with slightly elevated p values, so all reefs were included for the final model.

Species richness was variable among reefs and pre- and post-flood (Table 5). Despite the significant changes in community structure, paired t tests indicated that there were no overall significant reductions in species richness on the reefs. Thus, even though significant differences in mortality were found among species, no species were lost to flood mortality. *Goniopora* (−67 % absolute abundance) and *Cladiella* (−55 % absolute abundance) suffered high mortality and this also resulted in reduced relative abundance (especially *Goniopora*) after the flood on Pt. Vernon, Pialba Burkitt's and Pt. Vernon West reefs (Fig. 8a–d) overall (Fig. 8g). Although *Turbinaria* also suffered mortality (Fig. 5b), this genera generally showed increased relative abundance across all of the flood affected reefs (Fig. 8a–d), as well as overall (Fig. 8g). Collectively, the changes in abundances of *Cladiella*, *Goniopora* and *Turbinaria* accounted for 64.78 % of the dissimilarity between pre- and post-flood coral assemblages (Table 8). Although *Pocillopora*, *Montipora* and *Acropora* also showed increased relative abundance overall (Fig. 8g), these genera were generally of low abundance and restricted to 4 Mile and Big Woody reefs, which were not significantly flood impacted.

Discussion

Flooding impacts on coral abundance

Flooding is a natural occurrence and represents a natural threat to coral reefs that are adjacent to areas of terrestrial runoff, such as rivers. Flooding can reduce salinity and increase nutrient levels, sedimentation and turbidity, which can detrimentally impact coral reef communities. Reduced salinity causes physiological effects through osmotic stress (Fabricius 2005; Berkelmans et al. 2012), high nutrient levels affect physiology and community structure (Walsh 2011), while high sedimentation causes physical damage through abrasion, reduced recruitment through burial of suitable settlement locations and physiological stress and reduced photosynthesis through burial and shading (Fabricius 2005; Perry 2011). The degree of impact by these factors is largely determined by the degree and length of exposure. For example, salinities of less than 30 ppt may cause mortality given exposure anywhere from 1 day to a

Table 5 Pre- and post-flood coral community composition (presence/absence) and total species richness on the reefs of Hervey Bay, Queensland, Australia

Taxa	4 Mile Reef		Burkitt's Reef		Big Woody Reef		Pialba		Pt. Vernon East		Pt. Vernon West	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Acanthastrea lordhowensis	–	–	–	–	–	–	–	–	–	–	+	–
Acropora bushyensis	+	–	–	–	–	–	+	–	–	–	–	–
Acropora digitifera	–	–	–	–	+	+	–	–	–	–	–	–
Acropora glauca	+	+	+	+	–	–	–	–	–	–	–	–
Acropora spp.	+	–	+	–	–	–	–	–	–	–	–	–
Favia favus	–	–	–	–	–	+	–	–	–	–	–	–
Favia maritima	–	–	–	+	+	+	–	–	+	+	+	+
Favia veroni	–	–	–	+	–	–	–	–	–	–	–	+
Favites chinensis	–	–	–	–	+	+	–	–	–	–	–	–
Favites flexuosa	–	–	–	–	–	–	–	–	–	–	+	–
Favites pentagona	–	–	–	–	–	+	+	–	–	–	–	–
Favites spp.	–	–	–	–	–	–	–	–	–	–	–	+
Goniastrea australensis	–	–	–	–	–	–	–	–	–	–	+	+
Goniopora	–	–	+	+	+	+	+	+	+	+	+	+
Montastrea curta	–	–	–	–	–	–	–	–	–	–	+	–
Montipora mollis	–	–	–	–	+	+	–	–	–	–	–	–
Montipora spongodes	+	+	–	–	–	–	–	–	–	–	–	–
Montipora spp.	–	+	–	–	–	–	–	–	–	–	–	–
Montipora turtlensis	–	+	–	–	–	–	–	–	–	–	–	–
Plesiastrea versipora	–	–	–	–	–	+	–	–	+	+	–	–
Pocillopora damicornis	+	+	+	+	+	+	–	+	+	+	+	+
Psammocora superficialis	–	–	–	–	–	–	–	–	+	–	–	+
Psammoroca spp.	–	–	–	–	–	–	+	–	–	–	–	–
Turbinaria bifrons	–	–	–	–	–	–	+	–	–	–	–	–
Turbinaria frondens	–	–	–	–	–	+	–	+	+	+	–	–
Turbinaria mesenterina	–	–	–	+	–	–	+	+	+	+	–	–
Turbinaria patula	–	–	–	–	–	–	–	–	–	–	+	–
Turbinaria peltata	–	–	–	+	+	+	+	+	+	+	+	+
Turbinaria radicalis	–	–	+	–	–	+	–	+	+	+	+	+
Turbinaria reniformis	–	–	–	–	–	–	+	–	–	+	+	–
Turbinaria spp.	–	–	–	–	–	–	+	–	–	+	+	–
Turbinaria stellulata	–	–	+	–	–	+	–	–	+	–	+	+
Cladiella group	+	+	+	+	+	+	+	+	+	+	+	+
Gorgonian	–	–	+	+	–	+	–	–	–	–	–	–
Lobophytum spp.	+	–	+	+	+	–	+	+	+	–	+	+
Sarcophyton spp.	–	–	+	+	+	+	+	+	+	–	+	+
Soft coral (Mostly *Xenia* spp.)	–	+	+	+	–	+	+	–	–	–	+	+
Total species	7	7	11	12	10	17	13	9	13	11	17	14

few weeks (Berkelmans et al. 2012), while reduced light as a result of high turbidity (30 NTU) and sedimentation can affect coral physiology in weeks (Fabricius 2005; Weber et al. 2012). The input of nutrients can exacerbate the impacts of sedimentation to where coral tissue necrosis could occur in as little as a day (Weber et al. 2012). In high-latitude areas such as Hervey Bay, the impacts of flooding may be greater due to the typically reduced energetics associated with limited light and colder temperatures (Harriott and Banks 2002). While coral communities adjacent to areas prone to flooding and sedimentation may develop a resilience to natural levels of terrestrial runoff (Browne et al. 2012), when a catchment is anthropogenically modified by urbanisation and

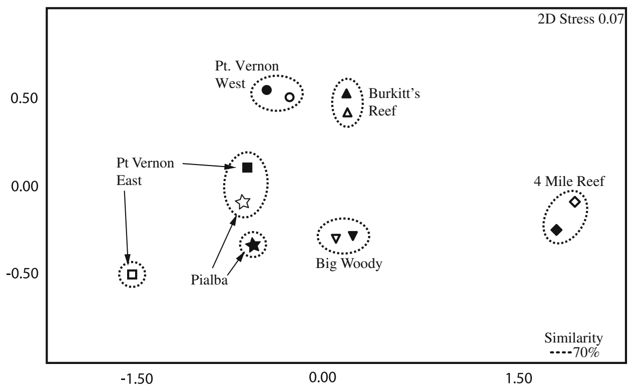


Fig. 7 Non-metric multidimensional scaling (NMDS) plot of total (hard and soft) coral community structure on 6 reefs from Hervey Bay, Queensland, Australia, pre- and post-flood. (*Symbols* pre-flood filled and post-flood not filled)

agricultural use, as occurs in the Mary River catchment, floods transport unnaturally large amounts of freshwater, sediments and nutrients and these may amplify the impacts on coral communities.

The 2010–2011 heavy flows and eventual flooding of the Mary River severely impacted water quality and caused significant mortality to the corals of Hervey Bay. It is not possible to identify any one primary cause of mortality because the reefs were subject to highly variable combinations of lowered salinity and elevated sedimentation, turbidity and nutrients all at the same time. At the levels measured, any one of these factors could have resulted in significant impacts on the coral communities (Fabricius 2005; Berkelmans et al. 2012; Browne et al. 2012); however, the presence of these factors combined for 14 weeks would have likely exacerbated these impacts.

It was possible to exclude certain factors as significant contributors to the mortality found in this flood. Pesticides/herbicides from terrestrial runoff have been identified as a significant threat to Hervey Bay (McMahon et al. 2005), but were not detected in this flood plume. Thermal stress was also unlikely to be a major factor given the relatively normal temperatures found at that time (Table 2). While it is possible that the elevated copper and cobalt measured in the floodwaters may have contributed to coral mortality, it seems unlikely to be significant in this acute event given the low levels measured. The continued chronic input of such heavy metals, which through bioaccumulation can cause many adverse impacts (Bastidas et al. 1999; Reichelt-Brushett and Michalek-Wagner 2005), could have impacts on recovery and persistence of coral communities.

Variability in flood impacts among reefs

Impacts of flooding on coral reef communities vary based on: salinity, sediment/silt content, nutrient levels, pollutant levels, the duration of the flood and other factors such as tides, currents and winds which direct the flood plume (Van Woesik et al. 1995; Devlin and Schaffelke 2009). In the case of the Mary River flood, all sampled reefs were well inside the extent of the visible plume for at least a month (Fig. 9) and yet mortality varied significantly among them. In this study, mortality was found to be greatest on the reefs closer to the mainland. Satellite imagery indicates that this plume was pushed shoreward and northward (e-atlas.org 2011) (Fig. 9). South-easterly winds were predominant for Hervey Bay in January 2011, with 71 % of winds during the time of the flood plume from this direction, including 90 % of all the winds greater than 10 km h^{-1} (Bureau of Meteorology Wind Data, January 2011). These prevailing winds (Fig. 9) combined with general coriolis effect (Furnas 2011) would have driven the plume waters northerly towards the mainland which would have increased the exposure of the reefs there. Modelling carried out by Gräwe et al. (2010) for the 1992 and 1999 floods showed similar prevailing winds and shoreward patterns of travel, and in these floods, the lower salinity plume waters were pushed into a 10 km wide band along the mainland. The flood plume resulting from the January 2011 flood, which was slightly smaller than the 1992 and 1999 floods, appears to be more concentrated in a narrower band adjacent to the shore. Water quality measurement of the plume at the reefs near the mainland (Pt. Vernon West, Pt. Vernon East and Burkitt's Reef) indicates that these reefs were exposed to much higher levels of turbidity, TSS and nutrients and reduced DO_{sat} compared with 4 Mile Reef, located 5 km from the mainland (Table 2).

Other factors may have contributed substantially to the variable mortality among reefs. For example, hydrodynamics vary among the reefs in Hervey Bay. The Big Woody reef site is exposed to relatively high tidal water movement that squeezes past Big Woody in the Great Sandy Strait and such high water flow areas are known to reduce the impacts of sedimentation through removal of sediment (Larcombe et al. 2001). In contrast, the Pt. Vernon area has very slow tidal currents and is considered an area of high sediment accumulation and frequent resuspension (BPA 1989; Zann 2012). Wind driven resuspension is likely to be increased at nearshore locations such as Pt. Vernon East and Burkitt's Reef (the two most impacted reefs), which are subject to the dominant south-easterly winds. Other sources of freshwater, sediment and nutrients may also have contributed to the variable mortality. Stormwater drains (from the adjacent city of Hervey Bay) and creeks along the shores of Hervey Bay would have contributed freshwater, sediment and nutrients to the more inshore areas. High mortality to coral reefs as a result of rainfall along shore (at low tide) has been indicated in other locations (GBRMPA 2007) and may have occurred here

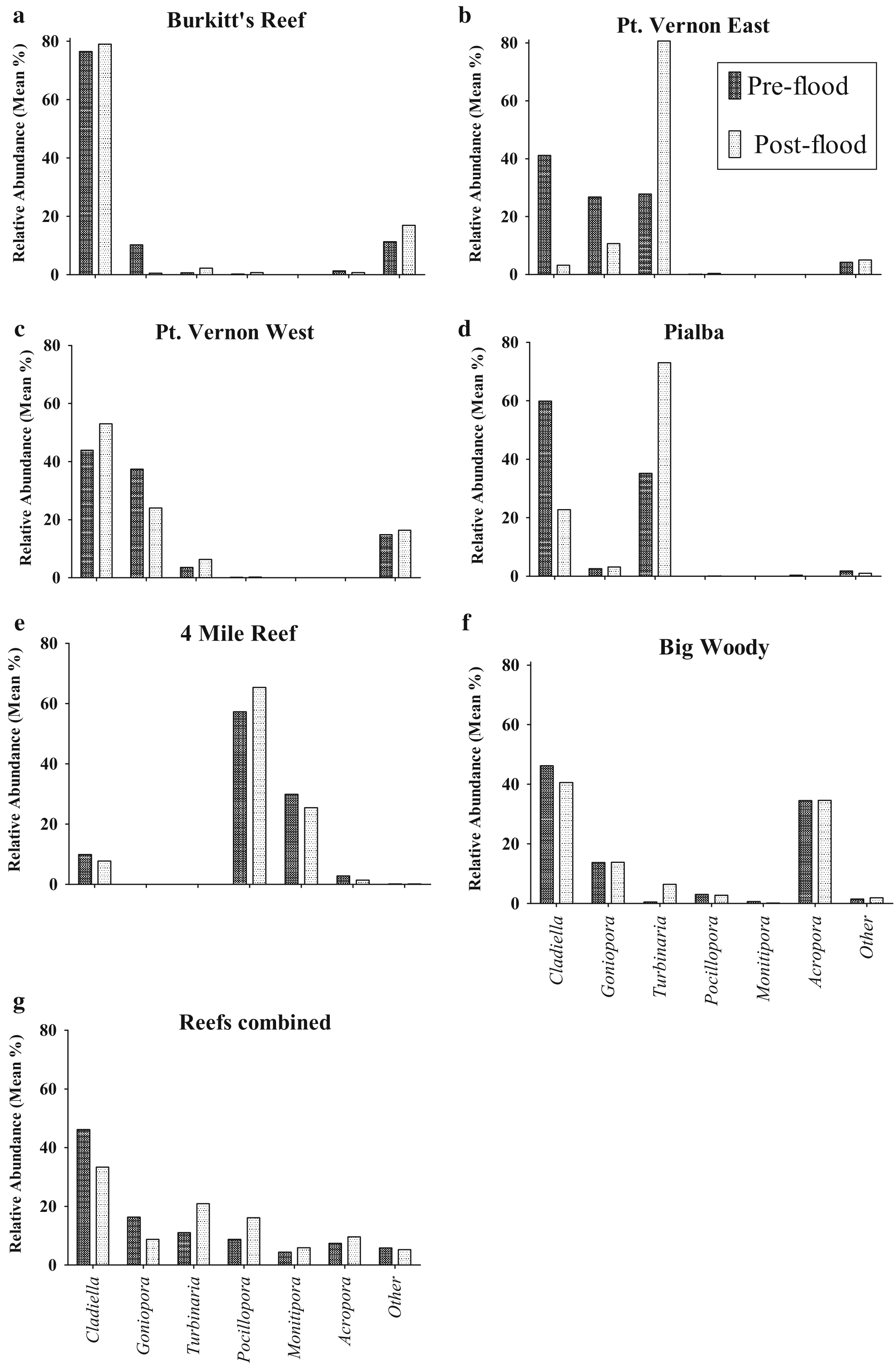


Fig. 8 Pre- and post-flood relative abundances of coral genera for 6 reefs from Hervey Bay, Queensland, Australia; (six most abundant genera are shown) **a** Burkitt's Reef, **b** Pt. Vernon East, **c** Pt. Vernon West, **d** Pialba, **e** 4 Mile Reef, **f** Big Woody and **g** Reefs combined

undetected by water quality sampling (Table 3). Finally, the smaller Burrum River (catchment area of 2,368 km^2), which also flooded, is located south of Burkitt's reef (Fig. 1) and would have contributed somewhat to the plume's load of freshwater, sediment and nutrients to that reef.

Changes in community structure

The most abundant hard and soft coral species on Hervey Bay reefs (e.g. *Goniopora, Turbinaria and Cladiella*) are tolerant of turbid, sediment rich conditions (Schleyer and Celliers 2003; Sofonia and Anthony 2008; Zann 2012).

Table 6 SIMPER analysis of pre-flood coral communities on the reefs of Hervey Bay, Queensland, Australia

Reef	Genus	Mean abundance (% cover)	Contribution to similarity (%)	Cumulative (%)
4 Mile Reef	*Pocillopora*	23.49	51.45	51.45
	Montipora	12.25	41.19	92.64
Burkitt's Reef	*Cladiella*	33.78	83.69	83.69
	Goniopora	4.48	9.01	92.70
Big Woody	*Cladiella*	26.17	83.40	83.40
	Acropora	19.54	6.55	89.95
Pialba	*Cladiella*	23.92	68.12	68.12
	Turbinaria	14.04	29.57	97.70
Pt. Vernon East	*Cladiella*	22.92	52.95	52.95
	Turbinaria	15.50	26.14	79.09
	Goniopora	14.95	18.38	97.47
Pt. Vernon West	*Cladiella*	22.42	54.98	54.98
	Goniopora	19.09	33.20	88.18

Per cent contribution based on Bray-Curtis similarity of abundance of genera in transects within a reef (cutoff set to minimum 5 % contribution)

Table 7 Permutational analysis of variance (PERMANOVA) with distance covariates for changes in coral community structure at genus level on the reefs of Hervey Bay, Queensland, Australia pre- and post-flood, January 2011

Source of variation	*df*	MS	Pseudo-F	*p*
Distance mainland	1	35,344	15.140	0.001
Distance mouth	1	15,348	34.866	0.001
Distance mainland × distance mouth	1	14,438	14.242	0.001
Flood	1	6,702.7	6.612	0.001
Distance mainland × flood	–	–	–	ns
Distance mouth × flood	–	–	–	ns
Distance mainland × distance mouth × flood	–	–	–	ns
Error	58	1,013.7	–	–

ns not significant ($p > 0.05$)

These species have combinations of large polyps, morphology conducive to passive removal of sediment, facultative heterotrophy and low light tolerance (Stafford-Smith and Ormond 1992; Anthony and Hoegh-Guldberg 2003; Sofonia and Anthony 2008). Despite these adaptations, these species, especially *Goniopora* and *Cladiella,* suffered severe mortality. *Turbinaria* showed reduced mortality relative to other species, and this variable mortality resulted in altered community structure, especially at Pialba and Pt. Vernon East reefs, where *Turbinaria* became the dominant species (Fig. 8a, b). Should flooding become a

Table 8 SIMPER analysis of pre- versus post-flood coral communities on the reefs of Hervey Bay, Queensland, Australia

Genus	Mean abundance pre-flood (% cover)	Mean abundance post-flood (% cover)	Contribution to dissimilarity (%)	Cumulative (%)
Cladiella	22.21	9.91	33.72	33.72
Turbinaria	5.32	6.21	16.12	49.84
Goniopora	7.88	2.61	14.93	64.78
Pocillopora	4.24	4.77	13.77	78.54
Acropora	3.57	2.83	7.70	86.25
Montipora	2.10	1.76	6.71	92.95

Per cent contribution based on Bray-Curtis dissimilarity of abundance of genera (cutoff set to minimum 5 % contribution)

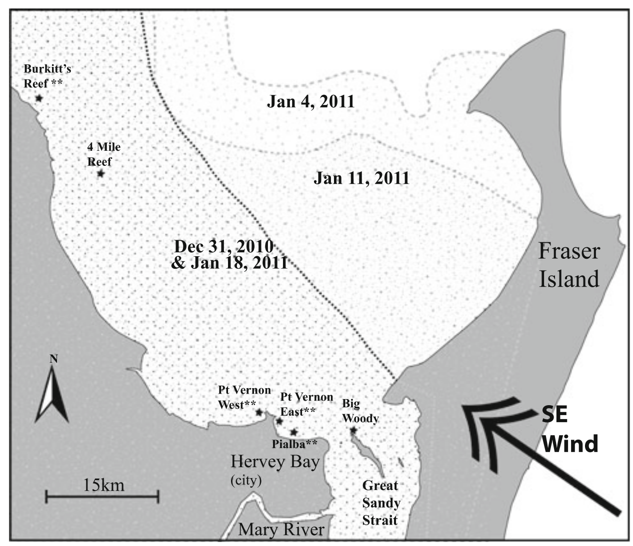


Fig. 9 Extent and subsequent contraction of Mary River flood plume during January 2011 flooding of Hervey Bay, Queensland, Australia. Dominant wind direction is from the south-east. (Satellite defined extents of plume obtained from e-Atlas.org, JCU)(e-atlas.org 2011). ** Indicates reef with significant coral mortality

more chronic occurrence in Hervey Bay, further shifts towards communities prevalent with flood resistant coral species would be expected (Browne et al. 2012).

Prospects for recovery

Coral reefs are more likely to recover from acute disturbance, such as flooding, as compared to more chronic types of disturbance such as ongoing pollution (Connell 1997; Wakeford et al. 2008; Graham et al. 2011). Hervey Bay coral reefs have recovered from an even larger flood in the past. In 1992, the Mary River experienced its seventh largest flood on record (BOM 2011), which was subsequently followed by wind and waves from a passing cyclone (Preen et al. 1995). Coral abundance estimates carried out before and after the flood on Big Woody reefs indicate that there were changes in absolute coral cover from around 50 % pre-flood to less than 15 % post-flood (FRC 1993). In our study, coral cover at the Big Woody reef site had pre-flood coral cover of around 57 %, indicating successful recovery of absolute coral cover during that 18-year period.

The rate of recovery of coral reefs from disturbance is dependent on many factors such as reef management, proximity to land, geographic region, water quality and scale of disturbance (Graham et al. 2011). All the reefs we studied are within the Great Sandy Marine Park. Burkitt's Reef has Marine National Park status which strictly regulates commercial and public access and use. The other reefs are Conservation Park Zone which primarily regulates commercial use of the reef (QPWS 2009) but allows relatively unrestricted access and use by the public. Such access may delay recovery through boat anchor damage, trampling and fishing. Rates of recovery of coral reefs at high latitude, as opposed to more tropical waters, are poorly understood but might be expected to be reduced as a result of the effects of cooler temperatures and reduced light on physiology and growth (Harriott and Banks 2002). However, the recovery from the 1992 flood is comparable with recovery seen on tropical reefs (Graham et al. 2011) suggesting that this may not be the case for Hervey Bay reefs. It is not clear how great a role water quality will play in determining recovery from the 2010/2011 flood. The Mary River and its catchment have for years been identified as a source of sediment and pollution to downstream riverine, estuarine and marine communities (Preen et al. 1995; Johnson 1996; McKenzie et al. 2003; McMahon et al. 2005; Kroon et al. 2011). Average levels of turbidity, TN and TP levels are all high relative to Environmental Protection water quality objectives for mid-estuary waters, while DO_{sat} at 83.09 % is around 12 % below the objective for mid-estuary waters (Table 3). Despite this input, historical mean turbidity, TP, TN and DO_{sat} in Great Sandy Strait remain near to or below Environmental Protection objectives (Table 3) indicating that significant dispersion/dilution is taking place. Therefore, the coral communities of Hervey Bay, though experiencing occasional acute episodes of elevated turbidity and nutrients, are not continually subject to them. Overall, assuming that these same environmental conditions continue into the future, it is expected that recovery will occur from this flood in a similar or shorter time frame to that of the larger 1992 disturbance. Further monitoring of these sites over the coming years will be necessary to see if and how quickly recovery takes place.

Implications of flood impacts to Great Sandy Marine Park management

Flooding from the Mary River is a common disturbance and, given its potentially severe impacts on marine communities, is a factor that should be incorporated into any management strategy for Great Sandy Marine Park. It has been suggested that in areas with frequent disturbance, the protection of lower risk communities may provide better outcomes for overall recovery, provided that the protected areas contain representative species and habitat diversity (Game et al. 2008). The results from this study indicate that the likelihood of flood impacts in Hervey Bay is reduced the further the reef is from the mainland and that species such as *Goniopora* and *Cladiella* are more susceptible to mortality. Therefore, it may be useful for managers of Great Sandy Marine Park to consider additional protection to those lower risk coral reefs that are relatively distant from the mainland and which contain communities with high diversity and abundance of species (e.g. Big Woody, 4 Mile Reef). Furthermore, in order to maximise recovery potential, it may be useful to provide further protection to higher risk inshore reefs with relatively high abundance of *Goniopora* and *Cladiella* but which also have high diversity (e.g. Burkitt's Reef and Pt. Vernon West).

Climate change and catchment management

Under a high emissions scenario, predictions for the Wide Bay-Burnett area, including Hervey Bay, are for a 2.9 °C increase in average annual atmospheric temperature by 2,070 with 140 % more cyclones (DERM 2009). Rainfall is expected to drop by 10 % but is predicted to occur in high intensity rainfall events separated by severe droughts (IPCC 2007; CSIRO and BOM 2012). These, combined with increasing sea level, are predicted to result in increased frequency of severe flooding, and these floods will likely contain higher sediment loads (McCulloch et al. 2003). Under this future scenario, given the already high levels of sediment and nutrients transported to the coral reefs from the Mary River catchment, the coral reef communities of Hervey Bay are likely to suffer more chronic, higher frequency episodes of mortality with shorter intervals of recovery. Successive reductions in coral cover render recovery of coral communities increasingly difficult (Graham et al. 2011). Examples of improvements to catchments to the point where coral communities show noticeable improvements are rare, but they do exist (Hunter and Evans 1995). If changes can be made to improve the Mary River catchment to reduce the runoff of sediments, nutrients and pollutants, the recovery and persistence of coral reefs of Hervey Bay will be enhanced.

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