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Letters

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ABSTRACT

Exposure to disturbance is rarely considered in marine protected area planning. Typically, representing and replicating the habitat types present within protected areas is used to spread the risk of protecting frequently disturbed sites. This was the approach used during the 2004 re-zoning of the Great Barrier Reef Marine Park (GBRMP) via the Representative Areas Program. Over 10 years later, we examine whether the risk was spread by mapping exposure of coral reefs in the GBRMP to four disturbances that cause coral mortality: bleaching, tropical cyclones, crown-of-thorns starfish outbreaks, and freshwater inundation. Our objectives were to: (1) assess whether no-take areas include a range of disturbance regimes, and (2) identify coral reef areas with lower relative exposure. At least 13% and an average of 31% of reef locations in each of 11 exposure classes are included within no-take areas. A greater proportion of low-exposure areas are within no-take areas than high-exposure areas (34.2% vs. 28.3%). The results demonstrate the value of risk spreading when exposure data are not available while also showing that regularly assessing exposure increases capacity for adaptive, resilience-based reef management.

Introduction

A common goal of marine ecosystem management is to protect natural assets and values for current and future benefit. One of the most common approaches used to protect marine and coastal systems is spatial management, such as zoning of marine protected areas or reserves that exclude or limit human activities (Day 2002). The size and location of protected areas is a key consideration for maximizing effectiveness (Halpern 2003;

McCook *et al.* 2010; Moffitt *et al.* 2011), which is informed by marine spatial planning (MSP, Fernandes *et al.* 2009). MSP enables managers and planners to integrate multiple sources of information expected to influence management effectiveness (Ehler & Douvere 2009). These include current and predicted future patterns of use, habitat condition, representativeness, and important ecological processes (e.g., larval connectivity). Managers and MSP experts also frequently acknowledge the importance of considering ecological vulnerability in the selection and establishment of marine protected areas (Halpern *et al.* 2012).

Spatial variation in exposure to climate-driven disturbances and other environmental stressors are important determinants of the vulnerability of marine ecosystems (Turner *et al.* 2003, Johnson & Marshall 2007). This is especially the case for coral reefs, where impacts caused by climate change and other disturbances can be severe but are not spatially uniform (Osborne *et al.* 2011). Often the effects of these disturbances can exceed the impacts of human activities and the effects of marine management (Mumby & Steneck 2008). Therefore, management decisions that incorporate available knowledge of spatial patterns in exposure to disturbances may have the best chance of achieving management goals, such as supporting the natural resilience of reef systems (Game *et al.* 2008a; Mcleod *et al.* 2008). However, disturbance regimes have proven a challenging dimension to include in MSP, often due to limitations in data availability and analytical capacity.

The Great Barrier Reef (GBR) Marine Park is a global icon of marine ecosystem management. In 2004, the GBR Marine Park was rezoned to increase the proportion of the Marine Park protected within no-take areas (Day 2002; Day *et al.* 2002). An expert focus group developed biophysical operating principles for the rezoning that suggested a minimum of 20% of the Marine Park be protected within no-take areas (Fernandes *et al.* 2009). This minimum recommendation took disturbances such as cyclones, pollution events, climate change impacts, and other disturbances into consideration. 33% of the Marine Park was protected after application of an "insurance factor" (1.65 * 20%); a concept initially recommended within Allison *et al.* (2003) to aid reserve designers in accounting for severe disturbance (Fernandes *et al.* 2009). Significantly though, data limitations at the time meant that the re-zoning was not able to consider variation in the exposure of reefs to disturbances. Rather, planners relied on a risk-spreading approach that aimed to conserve biodiversity by maximizing the spatial spread and habitat diversity of the protected areas (Day *et al.* 2002; Fernandes *et al.* 2005, 2009). Risk spreading is recommended when data on spatial patterns of exposure are not available or difficult to integrate into spatial plans (Mcleod *et al.* 2008; Almany *et al.* 2009).

Ban *et al.* (2012) first suggested that GBR Marine Park management objectives should account for aspects of dynamic phenomena (e.g., spatial variation and trends in environmental conditions). This study builds on the approach and findings presented within Ban *et al.* (2012) who assessed GBR Marine Park zoning with respect to sea surface temperature anomalies. We compiled information for the GBR Marine Park on spatial patterns of historical exposure to four disturbances that cause coral mortality: (1) mass bleaching events; (2) cyclones; (3) crown-of-thorns starfish (COTS) outbreaks; and (4) low salinity. Spatially extensive or mass bleaching events are caused by higher-than-normal sea temperatures and can result in coral mortality when elevated temperatures persist (Berkelmans *et al.* 2004). The high wind speeds characteristic of cyclones can generate heavy seas resulting in structural damage to coral reefs that can persist for decades (Fabricius *et al.* 2008; Beeden *et al.* 2015). COTS outbreaks can radically reduce live coral cover on healthy reefs within weeks (Osborne *et al.* 2011). Bleaching, cyclones, and COTS outbreaks were identified as major contributors of the 50% decline in coral cover in the GBR from 1985 to 2012 described in De'ath *et al.* (2012). Finally, low salinity caused by freshwater inundation can cause coral bleaching and increase susceptibility to diseases (Kerswell & Jones 2003). We use spatial data on exposure to these four disturbances to map combined relative exposure and then: (1) conduct a post-hoc analysis of the extent to which the Marine Park zoning in 2004 accounted for exposure to disturbance, and (2) identify coral reef areas with lower relative exposure. The approach and results presented demonstrate the value of exposure mapping for adaptive, resilience-based management of coral reefs.

Methods

Reef health disturbances

For all Marine Park reef locations, we assessed the frequency of thermal stress events severe enough to cause bleaching (remote sensing, 1982–2012), damaging waves from tropical cyclones (wind field models, 1985–2014), crown-of-thorns starfish outbreaks (models and GIS-interpolation of field data, 1982–2014) and freshwater inundation (remote sensing 2001–2011). Methods for each of the disturbances can be found in the supplementary material (i.e., processing remote sensing data and developing models). Values for exposure to each disturbance were normalized by dividing by the maximum exposure frequency or probability, resulting in a standard scale of

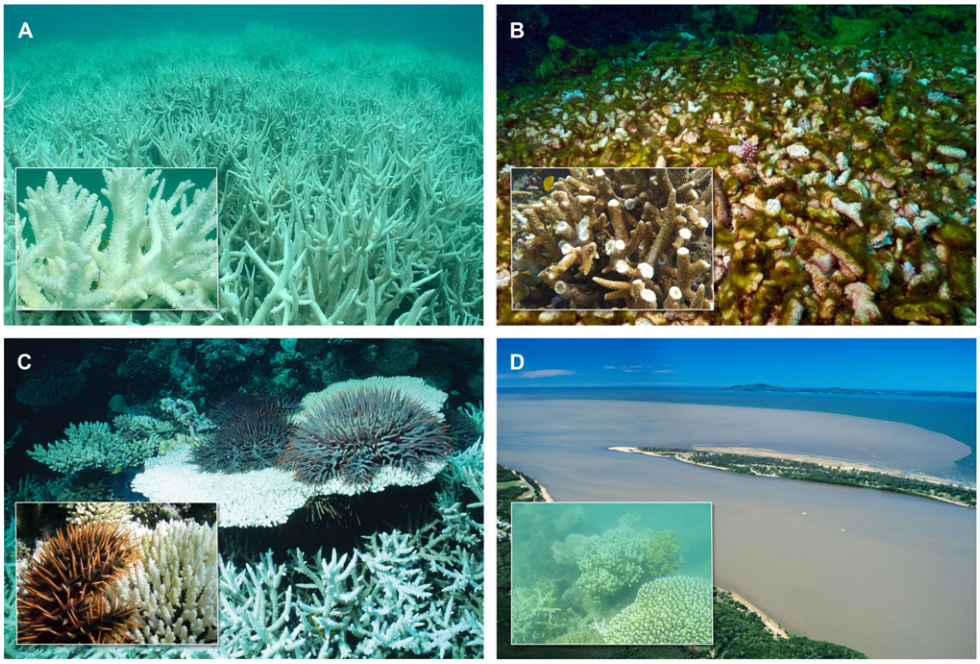

Figure 1 Landscape and macro (inset) photographs of the impacts caused by four key disturbances that cause coral mortality within the Great Barrier Reef Marine Park: thermal stress events and coral bleaching (A), damaging waves from cyclones (B), crown-of-thorns starfish outbreaks (C), and freshwater inundation from flooding (D). Photos are courtesy of GBRMPA.

0–1 (low scores equal low exposure; high scores equal high exposure). The average and standard deviation (SD) of normalized values were calculated for all disturbance types. Values were considered to represent low relative exposure if ≤ average − 1 SD and high relative exposure if ≥ average + 1 SD. Data for each disturbance were re-sampled to a standard 4-km grid.

Relative exposure and Marine Park zoning

We assessed relative exposure by averaging the normalized scores for thermal stress events (remotely sensed), damaging waves from cyclones (modeled) and COTS outbreaks (modeled and observed) for all reef locations and include freshwater inundation only for the ~4% of pixels affected (i.e., inner shelf areas). This process equally weights the disturbance types that affected each reef. The disturbances are not scaled and have comparable maximum frequencies/probabilities. The average scores were then normalized by dividing by the maximum value to express combined exposure for all reef locations as relative to the location with the greatest average combined exposure. Eleven exposure classes were set; none, and then at 0.10 intervals from >0 to 1 with values classified as relatively low and relatively high as described above. The total coral reef area was calculated based on high-resolution vector spatial data of coral reef boundaries produced by the Great Barrier Reef Marine Park (GBRMPA). The area within no-take Marine National Park green zones was calculated for the entire Marine Park and for all four Marine Management Areas (MMAs): Far Northern, Cairns-Cooktown, Townsville-Whitsunday, Mackay-Capricorn (Figure 1). Total reef area (in km^2) within each of the 11 exposure classes was calculated, as was the reef area in each exposure class that is within no-take areas.

Results

Exposure to thermal stress was relatively high (avg ± 1 sd = 0.23 ± 0.18, high >0.4) for 22.1% of the total reef area (Figure 3A). This corresponds to 7 or more thermal stress events from 1985 to 2012. These areas are concentrated between Townsville and Port Douglas and just north of Princess Charlotte Bay (Figure 3A). In contrast, a greater reef area (31.0%) had minimal to no exposure (low relative exposure, values ≤0.1). These areas are in the Far Northern MMA, and include outer-shelf reefs south of Townsville (Figure 3A).

Exposure to damaging seas from tropical cyclones was relatively high (avg ± 1 sd = 0.38 ± 0.22, high ≥0.6) for 19.5% of the total reef area (Figure 3B). Nearly all of these areas are located between Cairns and Mackay.

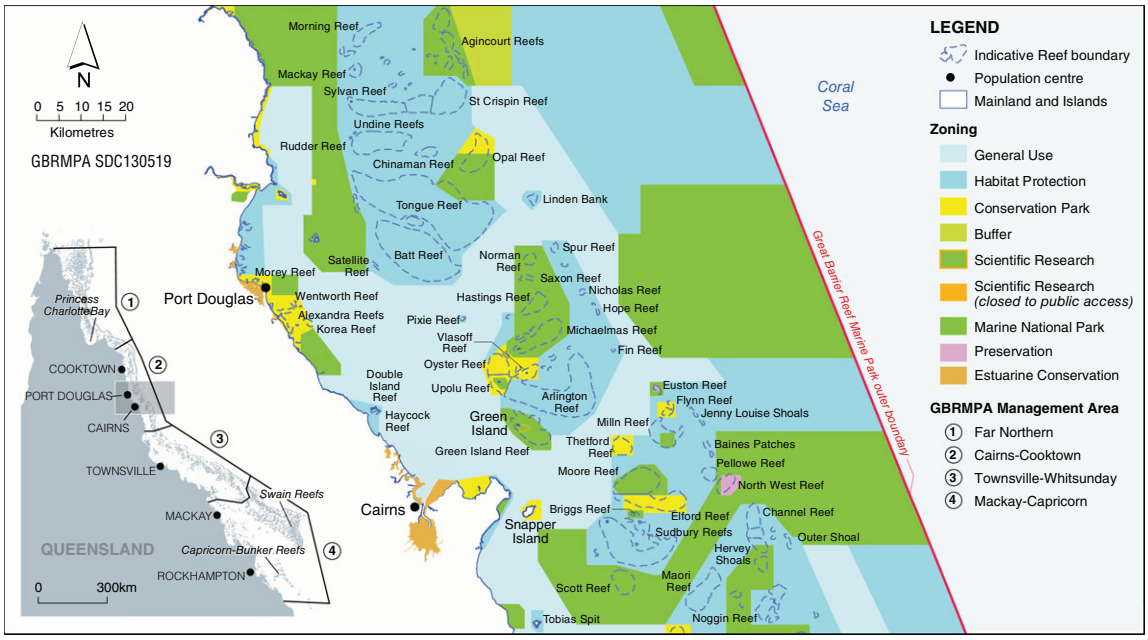

Figure 2 Zoning map for the Cairns area within the Great Barrier Reef Marine Park. The inset map shows the location of the Marine Park in NE Australia, the four Marine Management Areas, the names of prominent towns and some features used to describe results presented in Figures 3 and 4. Greater than 95% of the Park area has one of the four main zoning designations: Marine National Park (green), Conservation Park (yellow), Habitat Protection (dark blue), and General Use (light blue). Marine National Park green zones are no-take areas.

This corresponds to a probability of cyclone wave exposure in any given year of up to 0.234 (~1 in 4) at the most exposed reefs. Of the total reef area, 28.2% had low relative exposure (values ≤0.2) and there are locations (6.9% of total reef area) that were never exposed to damaging seas from cyclones. Areas with low relative cyclone wave exposure are within the inner to mid shelf in the far north and the inner shelf in the far south.

Exposure to predation from COTS was relatively high (avg ± 1 sd = 0.19 ± 0.19, high ≥0.4) for 14.4% of the total reef area. These locations are concentrated just north and south of Townsville and in the Swains reefs in the Mackay-Capricorn MMA (Figure 3C). Of the total reef area, 8.5% did not experience any COTS outbreaks between 1986 and 2014. Areas that the modeling suggests have very limited exposure are most common in the Far Northern MMA and include inshore reefs south of Bowen, some inshore reefs north of Townsville and the outer shelf reefs south of Townsville.

Almost the entire reef area (96%) was never exposed to freshwater inundation from flooding (Figure 3D). However, nearly half of the remaining 4% were exposed at least once during 10 of the 11 years from 2001 to 2011. These areas are all close to the coast and are scattered along the entire length of the GBR Marine Park (Figure 3D) near river outflows.

Less than 0.1% of the total reef area was not exposed to any of the four disturbance types (Figure 4A, Table S2). The distribution of reef area within each of the remaining 10 exposure classes was near-normal. The average value was 0.46 ± 0.20 so we considered values to represent low relative exposure if ≤0.3 and high relative exposure if ≥0.7. Of the total reef area, 23.6% had lower relative exposure. These areas are concentrated mainly in the far north as well as south of Townsville (Figures 3A–C and 4A). A lower proportion of the total reef area was relatively highly exposed (16.9%). These reefs extend from just north of Princess Charlotte By in the far north to just south of Townsville in the center of the Marine Park (Figures 3A,C and 4).

Reef areas with lower and higher relative exposure are shown in Figure 4(B) and colored as being within or outside no-take zones. The total reef area with low relative exposure to the combined disturbances is 6,226 km^2, of which 34.2% (2,129 km^2) is within no-take zones (Table 2, Figure 4). The total reef area with high relative exposure is 4,453 km^2, of which 24.6% (1,097 km^2) is included within no-take zones (Table 1, Figure 4). A minimum of 13% (average of 31%) of each of the 11 exposure classes is included within no-take zones and >25% of 9 of the 11 classes are within no-take zones (Table 1). Park-wide, 76.5% of the low relative exposure

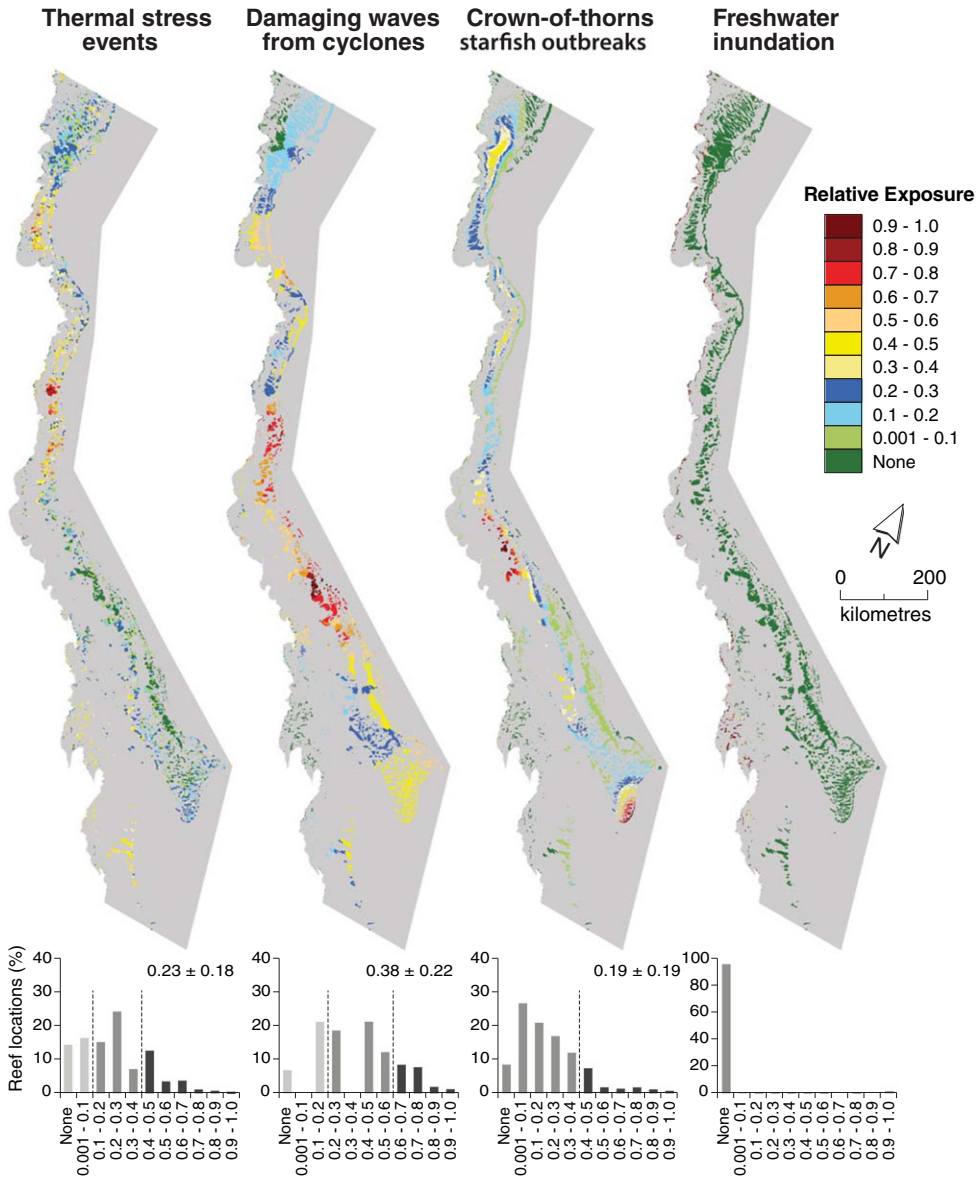

Figure 3 Relative exposure at each reef location (4-km) to each of the four disturbances. Exposure frequencies and probability estimates are expressed relative to the maximum value for reef locations within the timeframes included, which are 1982–2012 for thermal stress events (coral bleaching), 1985–2014 for damaging waves from cyclones, 1986–2014 for COTS and 2001–2011 for freshwater inundation. Histograms refer to the maps above and show the % of reef area in each of the 11 exposure classes (see Table S1 for data). Dashed lines divide bins based on the average ± 1 SD with bins left of the left line representing low relative exposure (calculated this way there are no low exposure areas for COTS) and bins right of the right line high exposure. Town and place names used to help describe these results in the text are shown in the inset map in Figure 2.

areas inside current no-take zones are in the Far Northern MMA, followed by 22.4% in Mackay/Capricorn. Park-wide, 44.9% of the high relative exposure areas inside current no-take zones are in the Townsville-Whitsunday MMA and ~25% are in each of the Far Northern and Cairns-Cooktown MMAs (Table 2).

Discussion

Our analysis shows that the GBR Marine Park re-zoning in 2004 included a range of disturbance regimes within no-take areas even though this was not an explicit goal. This demonstrates risk spreading via representation and replication can ensure habitats are protected that are not

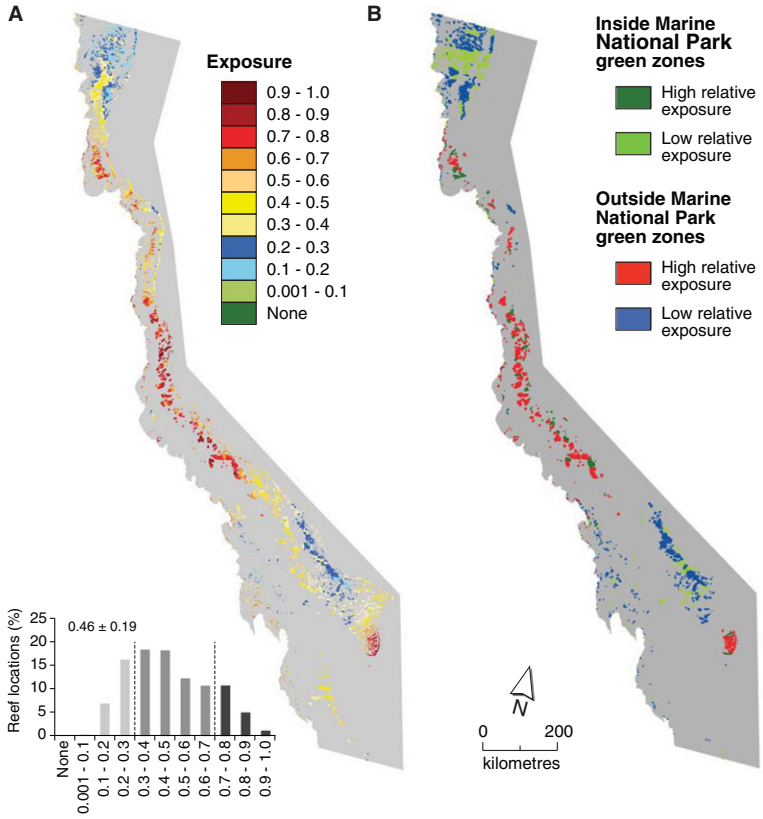

Figure 4 Relative frequency of disturbances is shown in (A) based on averaging the frequency values for the four disturbances (freshwater inundation is only included for the 4% of total reef area affected by flooding (see Figure 3D)). The histogram and dashed line are as per Figure 3 (see Table 1 for data). Areas of low (<0.3 in a) and high (>0.7 in a) relative exposure that are inside and outside Marine National Park green zones are shown in (B). Town and place names used to help describe these results in the text are shown in the inset map in Figure 2.

Table 1 Total reef area and reef area within no-take zones for each of the 11 exposure classes (see Figure 4A). Light and dark grey shading refers to low and high relative exposure, respectively.

Exposure classes	Total reef area in km^2 (% of grand Total)	Reef area within no-take zones in km^2 (% of reef area in class)
0	23 (0.09)	3 (13.25)
>0 – 0.1	82 (0.31)	50 (61.67)
0.1 – 0.2	1823 (6.90)	744 (40.82)
0.2 – 0.3	4298 (16.27)	1331 (30.96)
0.3 – 0.4	4857 (18.39)	1574 (32.40)
0.4 – 0.5	4817 (18.24)	1231 (25.56)
0.5 – 0.6	3236 (12.25)	833 (25.75)
0.6 – 0.7	2825 (10.70)	964 (34.11)
0.7 – 0.8	2838 (10.74)	715 (25.19)
0.8 – 0.9	1319 (4.99)	308 (23.34)
0.9 – 1	296 (1.12)	75 (25.17)

fated to be frequently disturbed, at least when protection: is spread across habitat types (30 reef bioregions), over a large geographic area (10-24 °S), and includes a high proportion of habitat area (>30%). The risk spreading during the 2004 re-zoning was achieved without explicit knowledge of spatial variation in historic exposure to disturbances (i.e., pre-2004) or any projections of likely spatial variation in future exposure (Fernandes *et al.* 2009). Importantly though, mapping exposure to disturbances provides the additional benefit of helping conservation planners and managers strategically target management actions to areas of low or high exposure. This ensures management actions are targeted when they are most needed and where they are likely to be most effective.

We found that twice the total area and a greater percentage area of low-exposure locations were included within no-take zones during the 2004 Marine Park re-zoning than high-exposure locations. We make the case here that this is beneficial. Ideally, more low-exposure areas should be included within no-take areas than high-exposure areas. Two points underpin this argument: (1) exposure can pragmatically be used as a proxy for vulnerability, and (2) management actions are more likely to be effective at low-exposure (i.e., lower vulnerability) locations in this era of increasing disturbance frequencies.

Exposure as a proxy for vulnerability

In the IPCC's framework for assessing vulnerability, exposure and sensitivity combine to produce a potential impact that is moderated by adaptive capacity to yield the overall vulnerability (Turner *et al.* 2003). Sensitivity

Table 2 Coral reef area with low (<0.3, Table 1, Figure 4A) and high (>0.7) relative exposure that is within and outside of the no-take zones. Data are organised by Marine Management Area (see Figure 2) and values are in km^2. Bracketed values are percentages of the sum for each row. Reef area estimates are based on the 4-km grid used for all disturbances (see. Figures 3 and 4) and all analyses (see also Table 1).

Marine management areas	Far Northern	Cairns-Cooktown	Townsville-Whitsunday	Mackay-Capricorn
Total reef area	9,780	3,437	6,017	7,180
Reef area in no-take zones	3,900	741	1,455	1,733
Low relative exposure in no-take zones	1,629 (76.5)	10 (0.5)	476 (22.4)	14 (0.7)
Low relative exposure *outside* no-take zones	2,266 (55.3)	75 (1.8)	1,632 (39.8)	124 (3.0)
High relative exposure in no-take zones	281 (25.6)	278 (25.3)	492 (44.9)	46 (4.2)
High relative exposure *outside* no-take zones	256 (7.6)	1,099 (32.8)	1,739 (51.8)	262 (7.8)

and adaptive capacity are key components of system resilience (Marshall & Marshall 2007). However, such information on spatial variation in the processes that underlie resilience is usually only known or can only be reliably modeled for a small percentage of the reef area in a management jurisdiction (Mumby & Steneck 2008; Mcleod *et al.* 2008; Maynard *et al.* 2010). In contrast, information on spatial variation in exposure to disturbances (from remote sensing and models) is available for all reef locations. Exposure information is often the only information available on spatial variation in vulnerability. Therefore, managers can pragmatically use exposure to disturbance as a proxy for vulnerability. Low-exposure sites have lower relative vulnerability and vice versa.

Management actions are more likely to benefit low-exposure locations

Game *et al.* (2008b) explore whether we should be protecting the strong (low vulnerability) or the weak (high vulnerability). Their conclusion is that we should protect high vulnerability sites if we expect sites to spend most of their time in a healthy state and low-vulnerability sites if we expect sites to spend most of their time in a degraded state. The global decline of coral reefs is now well established (Hoegh-Guldberg *et al.* 2007), and coral cover on mid-and outer-shelf reefs of the Marine Park has declined 50% over a recent 27-year period (De'ath *et al.* 2012). This trend of degradation is likely to continue into the future, with ~90% of coral reef areas projected to annually experience conditions that currently cause severe bleaching before 2050 under the emissions scenario that best characterizes current conditions (RCP8.5, van Hooidonk *et al.* 2013, 2014, 2015). Management efforts are more likely to be effective if invested in low-exposure locations as these are more likely to persist as disturbance frequencies increase.

A greater proportion of the low-exposure locations we identified are in the Far Northern MMA than in the other MMAs, with over 40% of these within no-take zones. This MMA also contains more than half of the low-exposure locations that are not in no-take zones. Cyclones and related damaging seas are less frequent in this region as the Coriolis effect is small close to the equator, hindering large-scale rotation and therefore cyclogenesis. Warming rates have also been lower in the Far Northern MMA (Heron *et al.* in review) and exposure to bleaching conditions has been relatively low. The Cairns epicentre of Marine Park COTS outbreaks mostly results in COTS larvae moving south, meaning much of the Far Northern has thus far also had limited exposure to COTS outbreaks. The Far Northern MMA is the relative refuge of the four MMAs. Therefore, the Far Northern is a priority area for use of special management areas or other place-based management initiatives to increasingly protect low-exposure locations and supplement current no-take reserves (see also Ban *et al.* 2012).

While our analysis demonstrates the utility of considering exposure in MSP, it has some important limitations. First, historic patterns in exposure to disturbances affecting coral reefs are not necessarily indicative of future patterns. Ideally, MPAs should account for both historic and projected future spatial variation in exposure to disturbances (e.g., McLeod *et al.* 2010). For example, statistical and dynamical downscaling of climate model projections of coral bleaching conditions are now available at ~11-km resolution for the Caribbean (van Hooidonk *et al.* 2015). Available climate model projections could be downscaled further to produce projections at the same resolution (4-km) as the historic exposure patterns presented here. Once downscaled projections are available globally, analyses can examine whether Marine Park zoning includes a range of projected future disturbance regimes within no-take zones. Secondly, we assumed the disturbances included in our analysis affect coral reefs equally; this is defensible from the perspective of normalizing disturbance frequencies because maximum frequencies of exposure are comparable for each disturbance (10–12 events over a 22–27 year period).

However, the impacts caused by the disturbances will vary in space and time. Our processed datasets from our analysis enable more sophisticated approaches that could include assumptions of the degree of impact caused by each disturbance. Such modeling approaches (e.g., belief networks) could include other aspects of vulnerability (i.e., sensitivity and adaptive capacity) by setting initial and boundary conditions for benthic reef communities using available field data and interpolation (Renken & Mumby 2009; Wooldridge & Done 2009; Anthony *et al.* 2013).

The key future direction for the type of applied research presented here is the development of a dynamic understanding of spatial variation in all vulnerability components. Coral reef managers can develop a dynamic understanding of the exposure component of vulnerability by regularly undertaking the analysis that we conducted retrospectively. In future years, these analyses can include downscaled climate model projections once available for all coral reef areas. Consequently, managers can identify low-exposure areas that represent long-term conservation priorities. Managers can also identify high-exposure areas that have recently been severely impacted and that have high value (e.g., commercially, recreationally, or culturally). These are short-term conservation priorities that may warrant actions that support recovery processes. Managers can also maintain a dynamic understanding of resilience, the sensitivity and adaptive capacity components of vulnerability (Marshall & Marshall 2007), by establishing and maintaining monitoring networks (Anthony *et al.* 2015). In the GBR Marine Park, there is the Australian Institute of Marine Science's Long-Term Monitoring Program (Sweatman *et al.* 2011) and GBRMPA's Eye on the Reef participatory monitoring program (Beeden *et al.* 2014). These networks can assess ecosystem condition and ground-truth disturbance information to assess impact extent and severity. Maintaining an up-to-date understanding of exposure and resilience increases capacity for the adaptive, *resilience-based* management that can maximize the chances reefs can continue to provide ecosystem goods and services as disturbance frequencies increase.

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