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Baseline

Coral benchmarks in the center of biodiversity

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ABSTRACT

There is an urgent need to quantify coral reef benchmarks that assess changes and recovery rates through time and serve as goals for management. Yet, few studies have identified benchmarks for hard coral cover and diversity in the center of marine diversity. In this study, we estimated coral cover and generic diversity benchmarks on the Tubbataha reefs, the largest and best-enforced no-take marine protected area in the Philippines. The shallow (2–6 m) reef slopes of Tubbataha were monitored annually, from 2012 to 2015, using hierarchical sampling. Mean coral cover was 34% ($\sigma \pm 1.7$) and generic diversity was 18 ($\sigma \pm 0.9$) per 75 m by 25 m station. The southeastern leeward slopes supported on average 56% coral cover, whereas the northeastern windward slopes supported 30%, and the western slopes supported 18% coral cover. Generic diversity was more spatially homogeneous than coral cover.

Coral reefs are important to many tropical countries because they support fisheries and tourism (Mumby et al., 2004), and protect shorelines from storm waves (Ferrario et al., 2014). Unfortunately, coral reefs are declining at an alarming rate, with an estimated 75% of global reefs under threat from local human pollution, and most reefs under threat from climate-change-induced thermal stress (Burke et al., 2011). Already, approximately 19% of the world's coral reefs have been effectively lost, and another 15% may be lost in the next 10–20 years (Wilkinson, 2008). Even the iconic and well-managed Great Barrier Reef has lost half of its coral cover from 1998 to 2012 (De'ath et al., 2012; but see also Sweatman et al., 2011; Hughes et al., 2011; Osborne et al., 2011). Without corals, coral reefs will lose the major framework builders, along with the architectural complexity needed to support fishes and other reef-associated organisms (Graham et al., 2006), and will lose their capacity to grow and keep up with sea-level rise (van Woesik and Done, 1997; Perry et al., 2013).

Benchmarks for common metrics, such as hard coral cover and diversity, are needed to assess the well-being of reef systems, and to determine management efficacy. Such benchmarks can: (i) provide insights into background variability across reefs through time (Murdoch and Aronson, 1999), (ii) determine what levels of change can be effectively ignored, and (iii) suggest what levels of change are indicative of significant departures from normal states. Such knowledge can be used to determine expected rates of recovery for different coral reef habitats (van Woesik, 2013), and used to improve the detectability of adverse effects of different human activities. Information on the variability of these metrics, across habitats, reefs, and regions, may even help refine appropriate scales of management for various human impacts. This knowledge could also provide a basis for evaluating the sensitivity of various assessment methodologies, and determine the adequacy of sampling designs used in describing and monitoring coral reefs. The aim of the present study is to provide new benchmarks for coral cover and generic diversity (i.e., number of coral genera) using data from the Tubbataha Reefs Natural Park, the largest and best-enforced no-take marine protected area in the Philippines (Dygico et al., 2013). Strict enforcement has been in place at Tubbataha since 2001. The marine park is located in the Sulu Sea, which has been considered among the most diverse regions of the Coral Triangle, which itself is the center of global marine diversity (Veron et al., 2009; Sanciangco et al., 2013).

Annual monitoring of the Tubbataha reefs (Fig. 1) followed a hierarchical sampling design (Green et al., 2011). The hierarchical levels were transects nested within stations, which were nested within study sites. Two sites each were established in the north and south atolls of the Tubbataha reefs. The sites were 6–28 km apart, and each site supported two stations about 250–600 m apart (electronic supplementary material). Five 50-m transect lines were randomly placed within each station. Each station was approximately 25 m × 75 m, and was located at 2–6 m depth. The transects were re-randomized for every sampling period (following Green et al., 2011). Monitoring involved photographing sections of the reef beneath each transect line, at 1-m intervals, using a

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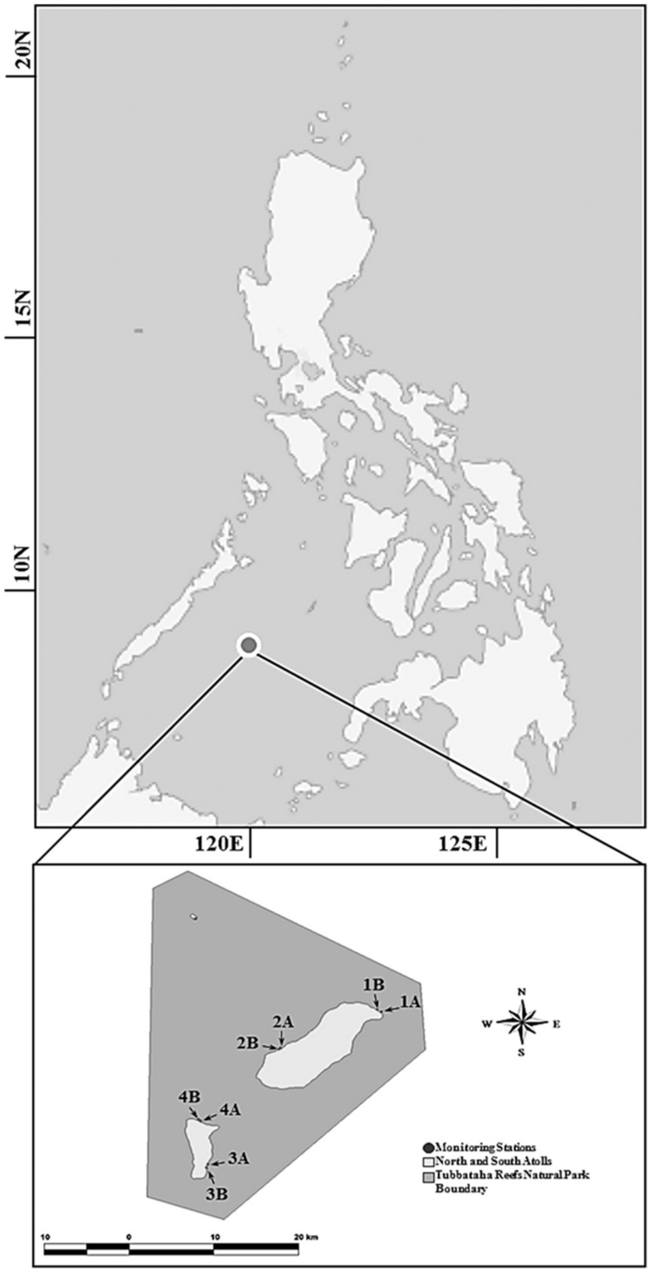

Fig. 1. Map of the Tubbataha Reefs Natural Park showing the study stations monitored.

digital camera mounted on aluminum monopods. The camera was contained in Ikelite® underwater housing, fitted with an Inon wide angle (100° field of view) lens to allow each photograph to cover one square meter of reef.

Digital images from 160 transects, sampled from 2012–2015 were processed in the laboratory using Coral Point Count with Excel extensions (CPCe; Kohler and Gil, 2006). Ten points were randomly placed on every 1 × 1 m digital image, and the corals under each point were identified to genus. Some genera were also identified to growth form, therefore in this paper taxa are occasionally referred to as Taxonomic Amalgamation Units (electronic supplementary material).

A two-level analysis of variance using repeated measures (ANOVAR) was used to examine the changes in percentage coral cover and generic diversity that occurred across sites and through time. Post-hoc Tukey tests were performed to specify which years and which sites significantly differed from each other. A two-level nested analysis of variance (ANOVA) was also applied to both coral cover and generic diversity data, collected in 2015, to compare the means and variances across sites and stations. The program R (R Core Team, 2015), version 3.1.0, was used to perform the ANOVAR and ANOVA tests. Power analysis for a one-sample *t*-test (Zar, 2010; p. 117) was used to compute the minimum detectable change in coral cover, and to compute the change in generic diversity through time at the station, site, and location levels. The alpha and beta values were arbitrarily set at 5% and 20%, respectively.

From 2012 to 2015, the average coral cover and average generic diversity on the Tubbataha reefs were 34% ($\sigma \pm 1.7$) and 18 ($\sigma \pm 0.9$), respectively. Site 2, along the western slope, had the lowest coral cover at 18% ($\sigma \pm 5.3$) and the lowest number of genera (15, $\sigma \pm 1.9$), whereas Site 3, on the southeastern slope, had the highest coral cover at 56% ($\sigma \pm 4.1$) (Fig. 2). Site 1, on the northeastern windward slope, supported the highest number of genera at 20 ($\sigma \pm 0.5$) (Fig. 3). At the station level, coral cover ranged from 14% to 57%, and the average number of genera ranged from 15 to 22.

From 2012 to 2015, there were no significant changes in hard coral cover (location level ANOVAR, $p = 0.484$) (Table 1), and no significant changes in number of genera (location level ANOVAR, $p = 0.299$) on the Tubbataha reefs (Table 1; Fig. 2). There were also no significant changes in coral cover and generic diversity at the site level ($p = 0.31$ for hard coral cover, and $p = 0.67$ for generic diversity) (Fig. 3). Coral cover was unchanged despite two thermal stress events — one in 2013, and the other in 2015 (Fig. 4).

The power analysis indicated that annual changes in coral cover as small as 3% were detectable at the location level (Table 2), suggesting that the current sampling protocol is adequate at Tubbataha reefs to detect changes in coral cover, should any changes occur. However, the minimum detectable change was approximately 7% cover at the site level, and 9% at the station level (Table 2). Sampling for the number of genera also appeared adequate, at least at the location level. The power analysis indicated that changes as small as two genera were detectable at the location level, and changes of three genera were detectable at the site and station levels (Table 2).

There were highly significant differences in coral cover across sites, but only marginally significant differences in coral cover among stations (Table 3, Fig. 2). Indeed, the greatest variance in coral cover was apparent among sites (10 km), at 71%, with only 9% variance in coral cover among stations (Fig. 5). There were no significant differences in the number of genera among sites and among stations (Table 3, Fig. 3), although most of the variance in the number of genera was apparent among stations (25%), rather than among sites (13%) (Fig. 5).

Ship groundings, typhoons, and thermal stress events disturbed the reef slopes of Tubbataha during the four-year study period, yet the coral assemblages appeared resilient. In 2013, two ship groundings were monitored, one grounding occurred 1 km from Station 4A. From 2012 to 2015, five tropical storms passed within 350 km of the monitored reefs. In 2013, one severe tropical storm passed within 40 km of the reefs, and typhoon Haiyan, the strongest typhoon ever to hit land, was a Category 3 typhoon when it passed within 350 km of Tubbataha reefs. In addition, two thermal stress events, one in 2013 and the other in 2015 (Fig. 4), had no detectable effect on coral cover and diversity, even though 2014 and 2015 were respectively the second warmest and warmest years on record, globally (NOAA, 2015). Acroporids and pocilloporids, known for their thermal sensitivity (Marshall and Baird, 2000; Loya et al., 2001; van Woesik et al., 2011, Furby et al., 2013), remained among the most common genera on Tubbataha through the study period (electronic supplementary material). Examination of past data sets suggest no measureable changes have occurred to the Tubbataha reefs since the declines associated with the 1998-thermal stress event, from which the reef recovered rapidly (Ledesma and Mejia, 2002; Dygico et al., 2013). Statistical power of these earlier monitoring studies, however, was limited (unpublished data), even though the researchers surveyed some of the same stations used in the present study.

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