

Optimal monitoring of coral biodiversity at Christmas Island

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Abstract. Coral reefs are one of the most biodiverse ecosystems in the world and are increasingly at risk due to a range of threats. Detailed species-level data is essential in developing effective management strategies for the conservation of coral reef biodiversity. For hard corals, this critical information is rarely available due to the high degree of expertise, time and costs involved in collecting species-level data, hence, the development of proxy metrics which accurately and reliably reflect coral species richness are imperative. At Christmas Island, in the north-eastern Indian Ocean, little species-level baseline data is available to inform managers regarding spatial (or temporal) variations of coral diversity. Here we examine the ability of four proxy metrics to reflect patterns in hard coral species richness, compared across depth gradients at eight sites around Christmas Island using regression analysis. Generic richness measured on a belt transect was the strongest explanatory variable for species richness (68–88% variation explained) regardless of the scale of analysis. Percent live hard coral cover has traditionally been used to assess and monitor coral reef health; however, our results suggest that it is not related to coral species richness as a significant linear function. Overall, at Christmas Island, monitoring generic richness on replicated belt transects offers the simplest and most robust proxy metric for estimating species richness.

Key words. hard coral, conservation, coral cover, Indian Ocean, proxy, species richness

INTRODUCTION

Maintaining species diversity is important for ecosystem functions and services (Baillie et al., 2008) and enhances ecosystem resilience (Reusch et al., 2005), thus conserving species richness is essential to biodiversity management (Brooks et al., 2004; MacNally & Fleishman, 2004). Coral reefs are the most biodiverse marine ecosystems (Roberts et al., 2002; Hughes et al., 2011) and support an estimated 35% of all known marine biodiversity (Knowlton et al., 2010). As hard corals are the major habitat-forming organism in this ecosystem, it is imperative that coral diversity be maintained to ensure the future of all biodiversity in the ecosystem. A range of anthropogenic impacts are however threatening this diversity (Roberts et al., 2002; Wilkinson, 2008; Hughes et al., 2011). Currently, 19% of the world's coral reefs are destroyed and unlikely to recover and a further 35% are at risk of being lost (Wilkinson, 2008). Furthermore, one third of reef-building corals have been listed by IUCN as at risk of extinction this century (Carpenter et al., 2008). To halt this decline and conserve coral reef biodiversity requires the development to effective management strategies based on reliable and accurate data.

Conservation management is hindered by a critical lack of baseline data about species richness (Hess et al., 2006; Collen et al., 2008), particularly in marine systems (Hendricks et al., 2006). Collecting species level data on corals requires a high level of expertise, is time-consuming and expensive (MacNally & Fleishman, 2004; Favreau et al., 2006). Due to the complexity and difficulty of measuring species richness, a range of proxy metrics have been adopted which reduce the cost, time and effort required to collect data (Humphries et al., 1995; Baillie et al., 2008). Biodiversity proxies include indicator species (Hess et al., 2006; Lindenmayer & Liken, 2011), cross-taxa surrogates (Dalleau et al., 2010) and environmental or habitat surrogates (Araújo et al., 2001). Each proxy has different advantages and problems (Brooks et al., 2004) and varying effectiveness and efficiency (Margules & Pressey, 2000; Favreau et al., 2006; Rodrigues & Brooks, 2007). The choice of an indicator species, taxa or surrogate can be challenging, especially if the behaviour of the response and predictor variables are not known across analytical, spatial and temporal scales (Landers et al., 2005; Hess et al., 2006; Lindenmayer & Liken, 2011).

On coral reefs, attributes of the habitat, such as live hard coral cover and habitat complexity are relied upon to inform management (Sweatman et al., 2008, 2011; Ateweberhan et al., 2011; Arias-González et al., 2011). Percent live hard coral cover is the most common habitat-based surrogate (Bruno & Selig, 2007; Arias-González et al., 2011; De'ath et al., 2012). Hard coral cover is an important variable to monitor because it provides an indication of the overall reef condition. Furthermore the level of hard coral cover is positively correlated with density-dependant processes such as disease prevalence (Bruno et al., 2007) and the abundance

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and composition of reef fishes (Bell & Galzin, 1984; Jones et al., 2004; Bellwood et al., 2006). It is not however, a robust indicator of coral species richness because reefs with high coral cover can have low species diversity and vice versa (Richards, 2012; Richards & Hobbs, 2014a).

Similarly habitat complexity (defined as the physical three-dimensional structure of an ecosystem) is an important habitat-based variable because it can influence the diversity of associated organisms (MacArthur & MacArthur, 1961). On coral reefs, habitat complexity is particularly important for the density and biomass of reef fish (Luckhurst & Luckhurst, 1978; Chong-Seng et al., 2012; Graham & Nash, 2013). A loss of complexity has been linked with overall reef degradation (Alvarez-Flip et al., 2009) and declines of commercially important fishery species (Graham, 2014). Habitat complexity is not however, associated with coral species richness as a positive linear function (Richards, 2012). Hence, it cannot be used as a proxy for coral biodiversity.

Considering species-level monitoring is often not feasible for corals, an alternative proxy measure is needed to detect changes in coral diversity and community structure and to effectively manage coral diversity. It has been shown that coral species richness and generic richness are closely associated (Richards, 2012; Richards & Hobbs, 2014a). Thus monitoring generic richness may provide a meaningful way to monitor and detect changes in coral diversity and provides an opportunity to predict species richness with a reasonable amount of certainty. Because the effectiveness of proxies is likely to vary geographically (Pressey, 2004; Rodrigues & Brooks, 2007), empirical testing is needed to assess the efficacy of potential proxy metrics at the location in question.

Christmas Island in the eastern Indian Ocean is an isolated oceanic island situated on a biogeographic border that represents the confluence of Pacific and Indian Ocean marine biotas (Hobbs et al., 2012). The island's narrow fringing coral reefs support a diverse and unique community that includes a high proportion of endemic and hybridising species (Allen, 2008; Hobbs et al., 2009; other papers in this supplement). The conservation of the Island's marine biodiversity is reliant on conserving the key habitat-forming organism—hard corals. An estimated 169 species of hard corals have been recorded at Christmas Island (for a full species list see Done & Marsh, 1988; and Richards & Hobbs, 2014b). However, there is a lack of species-level baseline and monitoring data regarding temporal changes in the spatial variations of coral diversity and community composition around Christmas Island. As a result, any changes in coral communities have gone undetected and no information is available for management to ensure maximum diversity is conserved. Currently, there is no information on how much coral diversity is protected in the marine reserves at Christmas Island and there are no monitoring programmes that can detect whether there have been any changes in coral diversity. In the absence of local taxonomic expertise on the island, effective management of the marine environment at Christmas Island requires a reliable proxy that accurately reflects coral species richness. This study aims to assess the effectiveness of a range of proxy

metrics (percent live hard coral cover, colony abundance, generic richness on a belt transect, generic richness on a point-intercept-transect) to reflect coral species richness across spatial and depth gradients.

METHODS

The hard corals at Christmas Island in the north-eastern Indian Ocean (10°30'S, 105°39'E) were surveyed through the use of underwater visual censuses between 26th April and 6th May 2013. The generic and species richness and abundance of hard corals and percent hard coral cover were quantified at eight sites and across three depth zones (5 m, 12 m and 20 m). Generic and species richness was assessed using three replicate 15 × 2 m belt transects at each depth zone. Every hard coral colony within the belt was identified and counted. Juvenile corals (less than 5 cm diameter) were not included in the assessment due to the difficulty in accurate identification. In the case of large colonies (>1 m²), two colonies were recorded for every 1 m² to account for the increased biomass (Richards, 2012). The point-intercept-transect (PIT) method involved identifying the benthos directly below 30 uniformly distributed points per transect, i.e., every 50 cm along the transect tape. Hence, on the first pass of each 15 m transect, every hard coral within a 2 m wide belt was identified and counted. On the return pass, a point-intercept transect was surveyed to estimate genus-level percent live hard coral cover.

Collectively, the above approach enabled comparative data to be collected pertaining to hard coral species richness (response variable, measured on a belt transect) and four proxy variables—percent live hard coral cover measured on PIT's (HCC); total colony abundance measured on belt transects (TCA); generic richness measured on PIT's (GR_p); and generic richness measured on belt transects (GR_b). Corals were identified in-situ where possible; otherwise reference skeletal material was collected to enable further examination. Voucher specimens have been lodged with the Western Australian Museum coral collection.

The relationship between coral species richness and the four proxy metrics were assessed using regression analyses at the levels of site, transect and depth using the free R statistical program version 2.15.3 (R Core Team, 2013). We used a one-way analysis-of-variance (ANOVA) on untransformed data to test the hypothesis that differences in species richness would exist between depth zones. If the ANOVA gave a significant result, a post-hoc Tukey's Honestly Significant Difference (HSD) test was conducted. The means (SE) for species richness and each of the proxy metrics were calculated for site and for depth using R. The adjusted goodness of fit (adj r²) was used to determine the best performing proxy metric. The null hypothesis was that a linear relationship existed between the proxy metrics and species richness. If a significant linear relationship existed, the function in the form of $\hat{y} = ax + b$ was fitted to the model, where \hat{y} is species richness and x is the proxy metric. Orthogonal polynomial functions were computed and fitted to non-significant linear associations. Further analysis explored the relationship

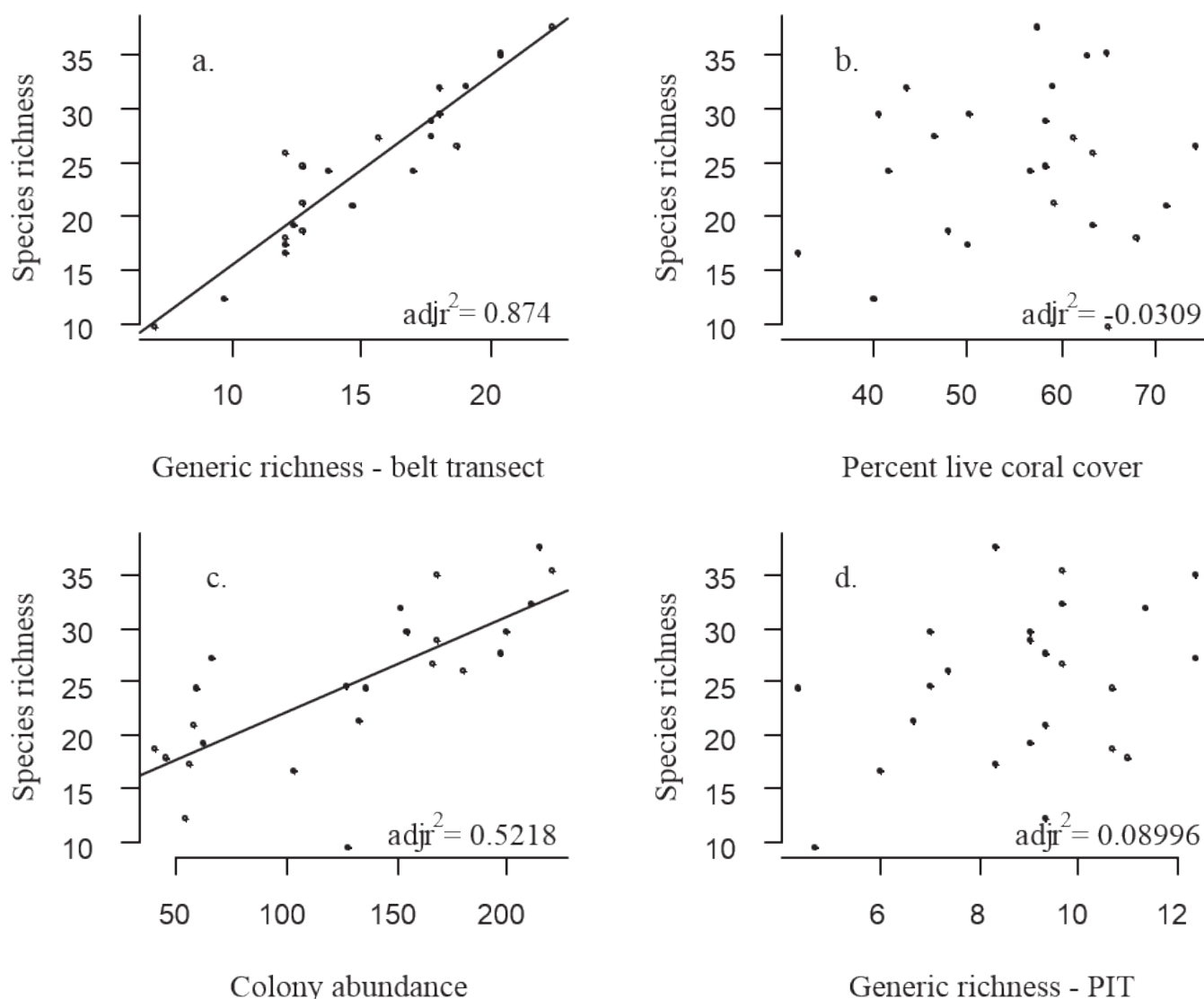


Fig. 1. Transect-level linear regressions of species richness on predictor variables based on pooled depth data. a, generic richness measured on a belt transects (GR_b); b, percent live coral cover (HCC); c, total colony abundance (TCA); and d, generic richness measured on point-intercept transects (GR_p). The linear regression line is shown for significant associations.

between the proxy metric and species richness when a power model was used to transform both the independent and the dependent variables. Transformed and non-transformed data regressions were conducted with and without outliers.

RESULTS

A total of 72 replicate transects were surveyed at 8 sites around Christmas Island. A total of 9,793 colonies were identified representing 133 species from 43 genera. Mean species richness varied significantly between depth zones (one-way ANOVA: $F = 22.3$, $df = 2$, $p < 0.001$), being highest at 20 m depth (31.5 ± 1.02 SE), followed by 5 m depth (23.2 ± 1.64 SE) and lowest at 12 m (19.8 ± 1.07 SE). Tukey’s HSD test revealed that the 12 m depth zone had significantly lower species richness than the 5 and 20 m depth zones ($p < 0.001$).

The four metrics HCC, TCA, GR_b and GR_p were analysed across three spatial scales: site (overall mean for each site,

$n = 8$), depth (mean for each depth at each site, $n = 24$) and transect ($n = 72$) (Fig. 1).

Across all spatial scales, GR_b provided a strong explanatory variable for spatial patterns in species richness as a positive linear function. Measured at the scale of mean depth, 87% of the variation in species richness is explained by GR_b (Fig. 1a). When examined at a single depth level, GR_b was most strongly related to species richness at 5 m with 80% of the variation explained (Fig. 2a). The amount of variation in species richness explained by GR_b increased when two depth levels were combined (84–88%, Fig. 2d–f) and peaked with the combination of 12 m and 20 m data (Fig. 2f).

The relationship between species richness and proxy metrics declined at most scales of analysis when the dependent and independent variables had been log transformed. The effect of outliers on the relationship between the proxy metric and species richness was also investigated. While the removal of any outliers reduced clustering of data points, they were

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ultimately included in the regression analysis as they represent sites of exceptionally low (or high) species richness and are hence, biologically meaningful.

No significant ($p > 0.05$) linear or polynomial relationships were found between percent live hard coral cover (HCC) and species richness at any spatial scale (site, depth, transect). For example, at the scale of mean depth, HCC was not positively or linearly correlated to species richness ($\text{adj } r^2 = -0.0309$, $\text{SE} \pm 7.397$, $\text{df} = 22$, $p = 0.5831$) (Fig. 1b). Significant linear relationships between total colony abundance (TCA) and species richness were detected across all spatial scales (site, depth and transect), with TCA explaining 52% variation in species richness when all depth data was pooled (Fig. 1c). There were no significant relationships (linear or polynomial) between generic richness measured on PIT (GR_p) and species richness at the scale of depth or site (Fig. 1d).

Reliable and easily quantifiable biodiversity proxies are essential for developing effective management strategies. In this study, generic richness (measured on belt transects) (GR_b) was the best of four measured proxies for representing coral species richness at Christmas Island. GR_b consistently explained over 68% of variation in species richness regardless of the scale of analysis (mean site, mean depth, transect). Unsurprisingly, given the significant difference in species richness across the depth zones examined, the strength of the relationship between GR_b and species richness varied considerably between depth zones. The greatest percent of variation (88%) was explained for the 12 m and 20 m depth zones.

The results of this study concur with Richards (2012), who found that GR_b was the most robust of six proxies used

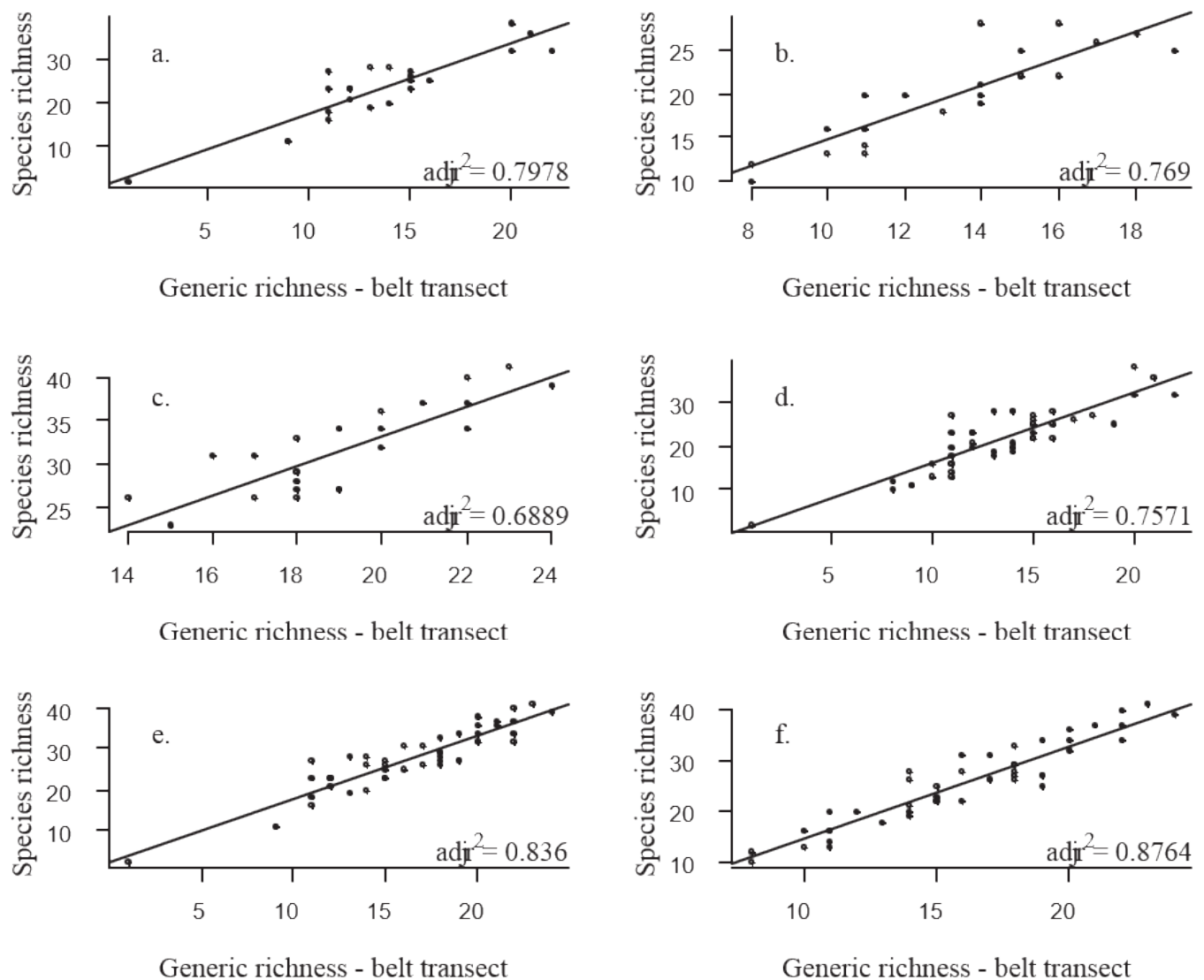


Fig. 2. Linear associations exist between species richness and generic richness (GR_b) across single and dual depth zones. a, 5 m; b, 12 m; c, 20 m; d, 5 + 12 m; e, 5 + 20 m; f, 12 + 20 m. The 1:1 relationship is shown for significant associations.

Table 1. Regression equations for predicting species richness (\hat{y}) based on generic richness (x) on belt transects where $\text{adj } r^2 > 0.78$.

Depth zone and regression equation	Range for \hat{y} where $x = 10, \dots, 50$				
	$x = 10$	$x = 20$	$x = 30$	$x = 40$	$x = 50$
5 m $\hat{y} = 1.614 (\pm 0.168) x + 1.4176 (\pm 2.392)$	14–22	28–39	42–57	57–75	71–93
5 m + 20 m $\hat{y} = 1.586 (\pm 0.102) x + 1.574 (\pm 1.723)$	15–20	30–37	44–54	59–71	74–88
12 m + 20 m $\hat{y} = 1.8412 (\pm 0.1007) x - 4.044 (\pm 1.671)$	14–15	32–33	50–53	67–72	85–91

to represent coral species richness at Lizard Island on the Great Barrier Reef, and Cabaitan et al. (2012), who state that monitoring coral assemblages at coarser taxonomic resolution is sufficient to depict change. In the Lizard Island study, mean species richness ranged from 21.3 (± 2.2) to 82 (± 3.1) species between survey sites. While the mean species richness at Christmas Island was lower than that recorded at Lizard Island (ranging from 19.8 ± 1.07 to 31.5 ± 1.02 species), which is partly attributable to the smaller transect length in this study (15 m versus 50 m) and the lower overall diversity of the isolated Christmas Island community; the general finding that GR_b is a robust proxy measure across locations and sites of varying species richness is supported. Another study that examined the efficacy of GR_b as a proxy of species richness at three other locations (Kosrae, Marshall Islands, and Ashmore/Cartier Reefs) also provides further empirical support for using generic richness as a proxy measure of species richness in situations where logistic or budgetary constraints prohibit on-going species-level monitoring of diversity (Richards & Hobbs, 2014a).

Coral diversity can differ considerably among depth zones (Huston, 1985; Karlson & Cornell, 1998) due to a range of physical (e.g., gradients in light, temperature and water movement), biological (e.g., physiological tolerances, growth rates, reproduction) and ecological factors (e.g., competition, predation, recruitment) (Done, 1982; DeVantier et al., 2006; Hughes et al., 2012). Furthermore, considering the logistical and time constraints associated with surveying multiple depths, we examined the influence of depth on proxy efficacy and whether single depth zones or multiple depth zones provides optimal results for monitoring species richness using GR_b . Our data clearly shows then when examining single depth zones, GR_b provides the strongest explanatory variable for patterns in species richness at 5 m (explaining 79% of the variation). While still significant, the strength of the relationship between species richness and GR_b declines with increasing depth zone, i.e., 77% of variation is explained at 12 m and 69% is explained at 20 m. This may be a reflection of the fact that species richness was highest at the 20 m depth and the strength of the generic-species richness relationship may diminishes at that depth because species-rich genera dominate.

At 5 m depth, species richness can be predicted using the equation $\hat{y} = 1.417 (\pm 2.392) x + 1.614 (\pm 0.168)$ (see Table

1). Thus, if 20 genera were recorded we would expect to count between 28 and 39 species. If 40 genera were recorded, we would expect between 57 and 75 species (Table 1). If time or other logistical constraints prevented sampling across multiple depth zones, surveying GR_b within only the 5 m depth zone would still be an effective way to predict species richness and more effective than collecting data on hard coral cover and/or habitat complexity alone. However, considering the highest mean species richness was recorded at 20 m, a number of species could potentially be missed if only the 5 m depth zone is surveyed; we examined the performance of GR_b at dual depths (5 + 12 m, 5 + 20 m, 12 + 20 m). From this series of regression analyses, we found analysing GR_b at both 12 m and 20 m is the best combination of two depth zones to represent patterns of species richness (88% of the variation in species richness explained). In this case, the equation $\hat{y} = 1.8412 (\pm 0.1007) x - 4.044 (\pm 1.671)$ could be used to reliably predict species richness. Therefore, if 20 genera were recorded we would expect to count between 32 and 33 species. If 40 genera were recorded, we would expect between 67 and 72 species (Table 1).

Investigation into the effect of log transforming the dependent and independent variables found that the relationship between the proxy metric and species richness declined at most scales of analysis. In some cases, the adjusted r^2 improved somewhat when compared to the adjusted r^2 of the raw data, but the results of the log transformed analyses are not discussed further because the additional power terms were not significant and a simple linear model still explained a high amount of variation in species richness (more than 68%).

Traditionally, percent live hard coral cover (HCC) has been the most common approach in assessing and monitoring coral communities (Bruno & Selig, 2007; Arias-González et al., 2011; De'ath et al., 2012). Our data clearly shows that at Christmas Island, the level of hard coral cover is not significantly related to species richness as linear or polynomial functions. This is because high coral cover can occur at any stage of community development, when species richness is low, moderate or high (Richards, 2012). In the 5 m depth zone at Ethel beach there is a high level of hard coral cover (65%) but low species richness. This is because two species dominate the community (*Galaxea fascicularis* and *Galaxea astreata*) and form large stands. As illustrated at Ethel Beach, hard coral cover does not provide reliable

information about coral species richness. The limitations of using live HCC as a proxy for species richness mean that management actions designed using a reefscape approach based on HCC data alone may not be optimal for conserving coral diversity.

Results for total colony abundance (TCA) as a proxy for patterns in species richness were variable. While performing reasonably well at the dual mean depth zone level (12 m and 20 m, explaining 69% of the variation in species richness); at other scales TCA poorly represented species richness. This may relate to the potential for high abundance of one or two species (as demonstrated here at Ethel Beach) or that coral communities naturally have a large number of rare species (Richards et al., 2013). The variable performance of this metric makes it difficult to recommend its use. While there may be some scope to apply this function in locations where there is no taxonomic expertise available (even at a coarse genus level), we consider at Christmas Island, there is scope to survey corals to genus level and we recommend that GR_b will provide the most accurate and robust estimates of coral species richness.

While GR_b performed consistently well, it is interesting to note the poor performance of GR_p . Generic richness measure on point-intercept transects did not have a significant relationship with species richness across most scales of analysis. Where a significant linear function did fit, the strength of the relationship was weak-moderate. Richards (2012) found that GR_p was the second best performing proxy (after GR_b) and a significant linear relationship with species richness of moderate strength was determined. The contrasting results of these two studies may be explained by the shorter transect lengths in our study and the smaller number of intercept points documented per transect. Furthermore, because the Christmas Island community was dominated by the genus *Porites* (see Richards & Hobbs, 2014b), this genera would be more likely to be recorded on the PIT, rather than other rare genera, thus decreasing the strength of the relationship between GR_p with species richness.

Ideally, proxies need to be reliable, easily quantified and accurately reflect coral species richness. The results indicate that generic richness measured on a belt transect can be used as a robust proxy metric of species richness with a relatively high level of precision. Overall, species richness at Christmas Island can be reliably predicted from GR_b in three ways by surveying at (in order decreasing adjusted r^2 strength); dual depth zones (12 + 20 m), across three depth zones (5 + 12 + 20 m), and at a single depth of 5 m. To obtain the most precise estimates of coral species richness, we recommend surveying at the dual depth zone. Using the equation $\hat{y} = 1.8412 (\pm 0.1007) x - 4.044 (\pm 1.671)$ at this depth scale results in the smallest amount of variation surrounding the estimates of species richness. However, if surveyors are time-limited, or if logistical constraints prevent surveying multiple depths, rapid assessments of GR_b could be done at only 5 m depth. This would still provide robust estimates of species richness.

This study concludes that coral generic richness measured on a belt transect provides a reliable representation of specie-level trends of corals at Christmas Island across a number of scales. The ability of the equations provided to predict species richness have been based on data only collected at Christmas Island and so the effectiveness of this proxy to predict species richness elsewhere would need to be determined. Even at Christmas Island, the effectiveness of these equations may potentially vary temporally and after large-scale disturbance events so it is important to evaluate the performance of GR_b over time. Although coral generic richness provides representation of species richness on a broader taxonomic scale, there is still a risk of silent extinctions or local depletions at the species level. Thus, the use of proxies does not mean that species-level population trends should be ignored by management, as this data is critical to the conservation of threatened species.

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