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Assessing coral health and disease from digital photographs and in situ surveys

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Abstract Methods for monitoring the status of marine communities are increasingly adopting the use of images captured in the field. However, it is not always clear how data collected from photographic images relate to historic data collected using traditional underwater visual census methods. Here, we compare coral health and disease data collected in situ by scuba divers with photographic images collected simultaneously at 12 coral reef sites. Five globally relevant coral diseases were detected on 194 colonies from in situ surveys and 79 colonies from photos, whilst 698 colonies from in situ surveys and 535 colonies from photos exhibited signs of compromised health other than disease. Comparisons of in situ surveys with photographic analyses indicated that the number of disease cases occurring in the examined coral populations (prevalence) was six times higher (4.5 vs. 0.8% of colonies), whilst compromised health was three times higher (14 vs. 4% of colonies) from in situ surveys. Skeletal eroding band disease, sponge overgrowth and presence of *Waminoa* flatworms were not detected in photographs, though they were identified in situ. Estimates of black band disease and abnormally pigmented coral tissues were similar between the two methods. Estimates of the bleached and healthy colonies were also similar between methods and photographic analyses were a strong predictor of bleached (r^2 = 0.8) and healthy (r^2 = 0.5) colony prevalence from in situ surveys. Moreover, when data on disease and compromised health states resulting in white or pale coral colony appearance were pooled, the prevalence of 'white' colonies from in situ (14%) and photographic analyses (11%) were statistically similar. Our results indicate that information on coral disease and health collected by in situ surveys and photographic analyses are not directly comparable, with in situ surveys generally providing higher estimates of prevalence and greater ability to identify some diseases and compromised states. Careful sampling of photographs can however identify signs of coral stress, including some coral diseases, which may be used to trigger early-warning management interventions.

Keywords Coral disease · Bleaching · Methods comparison · Coral reef monitoring methods · Underwater visual census

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Introduction

Coral reef health is deteriorating globally due to increasing pressures from multiple stressors, including pollution, habitat destruction, overfishing, climate change and associated increases in coral bleaching and disease (Bruno and Selig 2007; Carpenter et al. 2008; Gardner et al. 2003). Initially considered to be restricted to reefs of the Caribbean, coral disease outbreaks are now impacting and structuring coral communities globally (Bruno 2015; Green and Bruckner 2000; Harvell et al. 2007; Ruiz-Moreno et al. 2012). Moreover, many stressors that decrease coral host resistance to disease pathogens are predicted to continue increasing and will likely result in an increase in the frequency and severity of coral disease outbreaks (Epstein 2001; Harvell et al. 1999; Harvell et al. 2002; Ward and Lafferty 2004). Climate warming in particular is predicted to drive an increase in coral disease, emphasising the importance of understanding coral disease dynamics and mitigating impacts of disease outbreaks (Harvell et al. 2002; Maynard et al. 2015).

Observed increases in the prevalence and impact of coral diseases as a result of increased reef stress highlights the importance of incorporating coral disease assessments in local marine monitoring programs (Harvell et al. 2008). Coral disease monitoring programs, particularly those covering large temporal and/or spatial scales, have contributed significantly to our understanding of factors that influence disease and how this affects coral community composition and cover (Bruno 2015; Heron et al. 2010; Randall and Van Woesik 2015; Ruiz-Moreno et al. 2012). For example, long-term monitoring of coral disease on the Great Barrier Reef identified the co-occurrence of thermal stress and high coral cover as drivers of elevated levels of the disease white syndromes (Bruno et al. 2007), whilst winter temperatures were also found to influence coral disease prevalence (Heron et al. 2010). Other monitoring programs have documented disease outbreaks following bleaching events, highlighting the importance of thermal stress as a driver of coral disease outbreaks (Miller et al. 2006). Additionally, coral disease prevalence may provide a more immediate and sensitive indicator of human disturbance on reefs than can be obtained from simply monitoring coral cover (Lamb et al. 2014). These examples underscore the importance of including coral disease assessment in marine monitoring programs in order to document changes in reef health and to identify the natural and anthropogenic factors that increase coral disease. However, many reef monitoring programs do not prioritise coral disease assessment due to the costly and time consuming nature of in situ coral health surveys (Page et al. 2009; Ruiz-Moreno et al. 2012; Willis et al. 2004).

Underwater visual census (UVC) is one of the most commonly utilised methods for surveying coral disease levels on reefs (Weil et al. 2008). This method does not require a great deal of specialised equipment or post-survey data processing, but it does require that the observer have a high level of diagnostic expertise in coral taxonomy and disease identification. Globally standardised assessments of coral health and coral disease prevalence require detailed examination of all coral colonies in a defined survey area, which often demands considerable field time at each site (Harvell et al. 2008). For example, prevalence surveys within a 120-m^2 area (as described in Willis et al. 2004) may take two scuba divers up to 2.5 h on reefs with high coral colony densities and diversity (Page, pers. obs.). The financial cost of collecting coral health data in the field can place large burdens on the budgets of marine monitoring programs, and a lack of skilled staff with the experience to accurately and rapidly diagnose disease in situ may further prevent inclusion of disease surveys into long-term monitoring programs. In addition, the use of scuba is often impractical or impossible due to physical limitations (e.g. depth or currents) or the presence of unacceptable risks (e.g. the presence of crocodiles).

Technological advancements improving image quality and resolution along with decreasing costs of digital imagery equipment, both photographic and video, has resulted in their increased use in marine monitoring programs (Mallet and Pelletier 2014; Murphy and Jenkins 2010). Digital imagery now provides a widely utilised, inexpensive, and rapid method for monitoring marine benthos (Great Barrier Reef Marine Park Authourity 2014; Jonker et al. 2008; Miller et al. 2006; Turner et al. 2015) and fish assemblages (Goetze et al. 2015; Holmes et al. 2013; Langlois et al. 2010), whilst providing a permanent record of monitored sites. Qualitative analyses of photographs have already revealed a wider spatial and temporal distribution of coral diseases than was previously appreciated (Page and Stoddart 2010) and could provide important data on historical disease levels (Pauly 1995). However, no studies to date have quantitatively compared disease assessments conducted using digital photography with those performed in situ.

This study collected digital photography over transects surveyed in situ for disease to determine whether assessments of the percentage of disease colonies (prevalence) and other signs of compromised health occurring in the examined coral populations were comparable between methods.

Methods

In situ surveys of belt-transects

Coral health surveys were conducted in situ at 12 sites on the reefs of the Montebello and Barrow Islands, located in the Pilbara region of Northwest Australia during December 2011. Sites were selected to represent a range of coral assemblages, coral cover and environmental factors across which the prevalence of coral disease, bleaching and compromised health states were likely to vary (Pollock et al. 2014).

Three 15-m transects were haphazardly placed at least 5 m apart at each of the 12 sites, apart from one site where only three 10-m-long transects could be fit within constraints of the site. All scleractinian corals over 5 cm in diameter and within a 1 m belt on one side of the central transect line were recorded to genus and in some cases growth-form level (for instance, for *Acropora* and *Porites* corals). A 1-m pole held perpendicular to the transect line was used to ensure only colonies within the belt were surveyed. All corals were further categorised as diseased, compromised or healthy, according to categories outlined in Willis et al. (2004). Colonies categorised as diseased showed signs of black band disease, brown band disease, white syndromes, skeletal eroding band, atramentous necrosis and/or growth anomalies. Colonies categorised as compromised showed signs of predation by coral feeding snails (*Drupella cornus*) or crown-of-thorns starfish (*Acanthaster planci*), tissue necrosis associated with sediment accumulation, bleaching, pigmentation responses, physical injury (broken branch tips or colony pieces), *Waminoa* flatworm infestations, overgrowth by sponges or algae and/or unknown white scars. Colonies categorised as having unknown white scars showed signs of tissue loss that could not be readily attributed to disease, physical damage or predation. Colonies categorised as healthy showed no visible signs of disease lesions or other indicators of compromised health.

The prevalence of coral diseases, bleaching and other signs of compromised health was calculated for each belt transect by dividing the number of colonies showing signs of each disease, bleaching or compromised health category by the total number of colonies present within each transect. Disease, bleaching and compromised health states resulting in white or pale coral colony appearance (bleaching, white syndromes, brown band disease, physical injury, predator feeding scars and unknown white scars) were pooled to allow calculation of the prevalence of 'white' colonies, given the difficulty of differentiating these health states both in situ and in photographs.

Analysis of photo-transects

Each transect was photographed using a Canon G12 PowerShot 10 MP digital still camera. Photographs were taken at intervals along the length of the belt transect, incorporating 1 m to the side of the transect line, until the entire transect had been photographed. A metal pole was attached to the camera to indicate the height the camera needed to be held above the benthos to ensure that the width of the photograph was 1 m wide. Each photograph was high quality, approximately 4400 × 3300 pixels and between 6 and 9 MB in size.

Photo-transects were analysed using the same methods described above for in situ coral health assessments. Corals visible within each photograph were recorded and categorised as described above. Each photograph was scanned and examined in detail using the zoom function to ensure all corals were recorded and categorised appropriately. Data from all colonies in photographs of the same transect were summed and the prevalence of diseased, bleached and compromised corals calculated as above for in situ surveys. The prevalence of 'white' colonies was calculated the same for photos and in situ surveys.

Analysis of photos was undertaken by a single observer (CP), and in situ surveys were carried out by two observers (JL and FP). All observers had previous experience identifying coral disease and had received extensive training using standard methods in the in situ identification and categorisation of coral disease and compromised categories (Willis et al. 2004) prior to their conducting coral health surveys.

Statistical analysis

The total number of coral colonies diseased, bleached, compromised and healthy within each belt transect was summed to provide site totals. The prevalence of disease, bleaching and other compromised health indicators was averaged across the three transects to determine the mean prevalence of these health indicators per site. Differences in the total number of colonies and prevalence of disease, bleaching, other compromised health indicators and healthy coral colonies analysed using photographic and in situ methodologies were investigated using site level data and a single factor (method: in situ vs. photographs) analysis of variance (ANOVA). The relationship between methodological values of disease, bleaching, other compromised health indicators and healthy colonies were also investigated using linear regressions and the significance of the relationship between variables assessed by ANOVA. Homogeneity of variance was assessed using Levene's test and normality by visualising partial plots. Square root transformations were required to fulfil ANOVA assumptions for colony count data, but not for prevalence data. Statistical analyses were performed in Statistica version 9 (Statsoft, Tulsa, OK).

Results

Mean coral disease prevalence calculated from photographs (0.8 ± 0.2% mean +/− SE) was sixfold lower than from in situ surveys performed by divers on scuba (4.5 ± 1.2%, $F_{1,22} = 9.17$, $p = 0.006$; Fig. 1). Similarly, the prevalence of compromised health was threefold lower in photographs (4.4 ± 1%) than in situ (14.1 ± 1.6%, $F_{1,22} = 11.5$, $p = 0.002$; Fig. 1). In contrast, the prevalence of bleached and healthy corals did not differ significantly between the two methodologies (bleaching: $F_{1,22} = 2.26$, $p = 0.15$; healthy: $F_{1,22} = 2.55$, $p = 0.12$; Fig. 1). Bleaching prevalence averaged 8.6 ± 3.0% of corals per site in photographs compared to 3.5 ± 1.6% of corals in situ, whilst prevalence of healthy corals averaged 86.6 ± 3.0% of corals per site when calculated from photographed compared to 78.0 ± 4.2% of colonies in in situ surveys. The total number of colonies counted in photographs ($n = 12{,}996$ colonies) was over twofold higher than counted by divers in situ ($n = 5498$). When the two methods are compared using colony rather than prevalence data, the incidence of disease is still greater when using in situ surveys (Table 1). The number of bleached and healthy colonies recorded in photographs is however higher when using photographs, whilst the number of compromised cases are statistically similar between the two methods.

The prevalence of disease and compromised health from analysis of photos was generally not a good predictor of the prevalence of disease or compromised health measured in situ (Fig. 2, disease: $F_{1,10} = 3.93$, $p = 0.07$; compromised $F_{1,10} = 0.43$, $p = 0.53$). The number of diseased colonies from photos was a reasonable predictor of diseased colonies from in situ surveys ($F_{1,10} = 5.37$, $p = 0.04$, $r^2 = 0.3$), although estimates of colonies with compromised health from photos remained a poor predictor of the number of in situ compromised colonies ($r^2 < 0.1$). The prevalence of bleaching in photographs was more closely associated with the prevalence of bleaching in situ ($r^2 = 0.8$), although the positive relationship between the methods is driven by high levels of bleaching at one site ($F_{1,10} = 51.9$, $p < 0.001$; Fig. 2b). When data from this site is removed from the analysis, bleaching recorded in

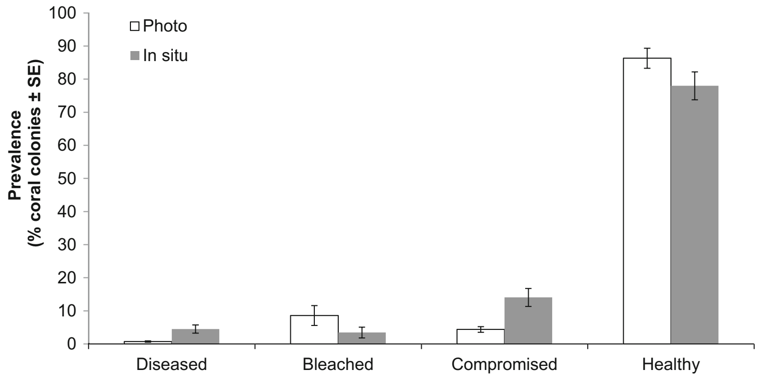

Fig. 1 Comparisons of the prevalence of diseased, bleached, compromised and healthy coral colonies (mean +/− SE, $n = 12$ sites) between photos and in situ surveys conducted simultaneously on SCUBA

Table 1 Number of diseased, bleached and compromised health colonies recorded using photo-transects and in situ surveys. Mean and standard errors calculated as colonies per site based on surveys at 12 sites for each method

	Total		Mean (SE)			
	Photo	In situ	Photo	In situ	$F_{1,22}$	*P*
Diseased	79	194	6.6 (2.2)	16.2 (4.5)	4.9	0.04
Bleached	802	266	66.8 (16.1)	22.2 (10.8)	5.6	0.03
Compromised	535	698	44.6 (13.5)	58.2 (14.5)	0.9	0.34
Healthy	11,580	4340	965.0 (219.0)	361.7 (46.4)	10.9	<0.01

photographs is no longer a good predictor of bleaching in situ ($F_{1,9} = 1.17$, $p = 0.31$). Similarly, the number of bleached colonies from photos was a poor predictor of bleached colonies in situ ($r^2 < 0.1$). In contrast to the other health indicators, the prevalence of healthy colonies in photographs was a good predictor ($r^2 = 0.5$) of the prevalence of healthy colonies in situ when using prevalence data ($F_{1,10} = 9.18$, $p = 0.01$; Fig. 2d). Though this relationship was weaker when using the number of healthy colonies recorded by both methods ($r^2 = 0.2$).

Four of the five diseases observed during in situ surveys were also observed in photographs (Fig. 3a, Table 2). Colonies with signs of white syndromes, brown band disease, black band disease and growth anomalies were all recorded using both photography and in situ methods. Skeletal eroding band was not recorded from photographs even though this was the second most prevalent disease recorded in situ. Fewer cases of white syndromes and brown band were recorded from photographs than in situ surveys (Table 2) and accordingly prevalence of these diseases was lower in photographs (Fig. 3a). White syndromes were the most prevalent disease recorded using both methods (Table 2); however, white syndromes' prevalence was sevenfold higher in situ (2.8 ± 1.1% of colonies) than in photographs (0.4 ± 0.2% of colonies; Fig. 3a). A greater

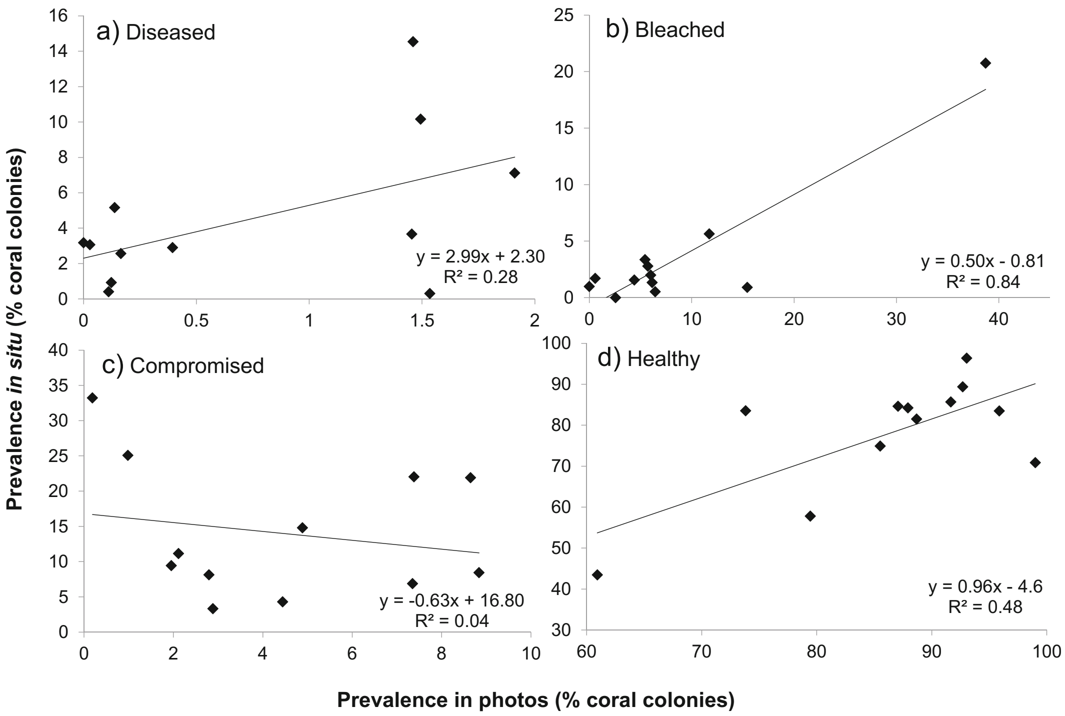

Fig. 2 Relationships between photograph and in situ methods for estimating prevalence of **a** diseased, **b** bleached, **c** compromised and **d** healthy scleractinian corals. Each *point* represents a site average (*n* = 12) calculated from 3 transects

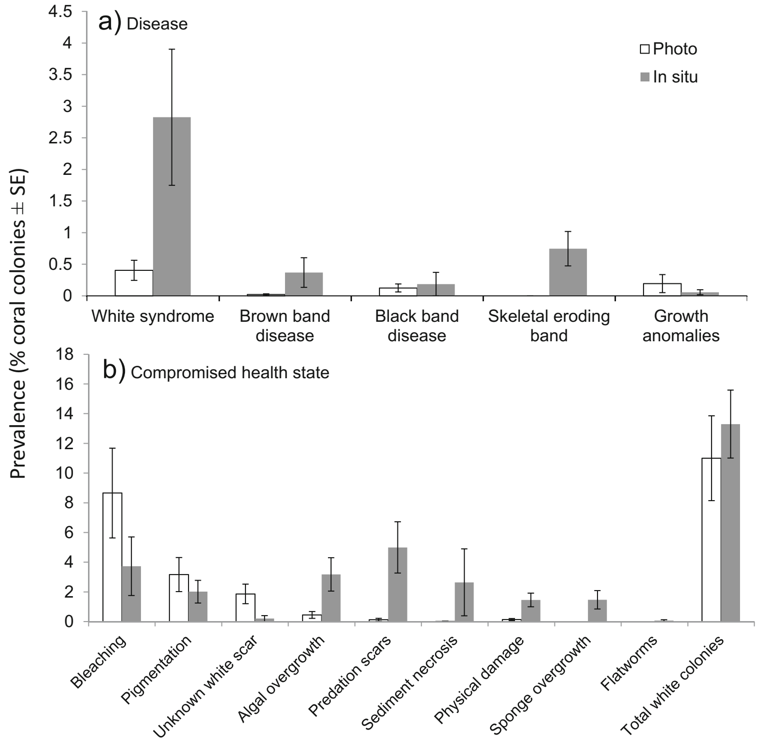

Fig. 3 Mean prevalence (+/−SE) of **a** disease and **b** compromised health using photo and in situ methodologies. Averages and standard errors calculated from 12 sites

number of growth anomalies were also recorded from photographs (18 cases) than in situ surveys (3 cases), though the prevalence of growth anomalies was similar for the two methods. Likewise, the number of colonies and prevalence of black band using the two methods was low (<0.5%) but similar.

Of the nine compromised health indicators recorded during in situ surveys, seven were also recorded from photographs (Fig. 3b). Bleaching, pigmentation responses, overgrowth by algae, predation scars, sediment necrosis and physical damage were recorded using both methods. Overgrowth of live coral tissues by sponges and infestations of *Waminoa* flatworms were recorded in situ, but not from photographs (Fig. 3b). Unknown white scars showed the greatest disparity between the two methods (both prevalence and the number of colonies recorded). The prevalence of unknown white scars was over ninefold higher in photographs (1.9 ± 0.7% of colonies) than in situ (0.2 ± 0.2% of colonies), where 73 cases were recorded on photos, but only 4 cases in situ. The number and prevalence of bleached colonies was over twofold higher in photographs than in situ surveys. In contrast, predation scars, physical damage and overgrowth by algae tended to be higher in terms of both numbers of colonies and prevalence in situ than in photographs. The prevalence of predation scars was over 40-fold higher in situ (5.0 ± 1.8% of colonies) than in photographs (0.1 ± 0.1% of colonies), the prevalence of physical damage was 11-fold higher in situ (1.5 ± 0.5% of colonies) than in photographs (0.1 ± 0.1% of colonies) and algal overgrowth sevenfold higher in situ (3.2 ± 0.5%) than in photographs (0.5 ± 0.2%). The prevalence of pigmentation responses was similar for the two methods; however, the number of cases of sediment necrosis was 37-fold higher in situ than in photographs (Fig. 3b).

Table 2 Number of different diseased colonies recorded using photo-transects and in situ surveys. Mean and standard errors calculated as cases per site based on surveys at 12 sites for each method

	Total		Mean (SE)	
	Photo	In situ	Photo	In situ
White syndrome	41	107	3.4 (1.5)	8.9 (2.9)
Brown band disease	4	28	0.3 (0.2)	2.3 (1.8)
Black band disease	15	11	1.3 (0.7)	0.9 (0.9)
Skeletal eroding band	0	45	0	3.8 (1.5)
Growth anomalies	18	3	1.5 (1.1)	0.3 (0.2)

The total number of ‘white’ colonies (colonies exhibiting signs of bleaching, white syndromes, brown band, physical injury, predator feeding scars and unknown white scars) recorded from photographs (n = 1187 colonies) was approximately twofold higher than in situ surveys (710 colonies). When all these white-like disease and compromised categories were summed into a total white colony category, we found that the prevalence of white colonies was similar using both photographs (11.0 ± 2.9% of colonies) and in situ surveys (13.3 ± 2.3% of colonies; $F_{1,22} = 0.42$, $p = 0.53$; Fig. 3b). The prevalence of white colonies from photo analyses was also a good predictor of white colonies from in situ surveys ($F_{1,10} = 8.4$, $p = 0.016$, $r^2 = 0.40$).

Disease was detected in 11 scleractinian families in situ and 9 families from analyses of photos (Fig. 4a). Disease affected more than 5% of colonies in six families (Acroporidae, Agariciidae, Mussidae, Oculinidae, Pocilloporidae and Poritidae) in situ, whilst disease was not recorded in more than 5% of colonies from any family using photographs (Fig. 4a). Nonetheless, the scleractinian families where disease was most frequently recorded were relatively consistent between the two survey methods (Fig. 4a). Most of the diseased colonies were from the families Acroporidae, Poritidae and Faviidae. Prevalence was however highest in the families Oculinidae, Agariciidae, Pocilloporidae and Poritidae when assessed in situ, whilst photographs recorded high disease prevalence amongst these same four families and the family Merulinidae (Fig. 4a).

Bleaching was recorded most frequently amongst the Acroporidae, Poritidae and Favidae, which also had the most colonies (Fig. 4b). When expressed as prevalence, bleaching was recorded from over 10% of colonies in seven families in photographs (Dendrophylliidae, Faviidae, Fungiidae, Oculinidae, Pocilloporidae, Poritidae and Siderastreidae), compared to just one family in situ (Fungiidae) (Fig. 4b). There were also inconsistencies in terms of the families that recorded high bleaching between the two methods with the family Pocilloporidae being the only family to rate amongst the most bleached families for both methods (Fig. 4b).

The number of colonies with compromised health was high amongst the Acroporidae, Faviidae and Poritidae, irrespective of the method used, though both absolute values and prevalence of colonies with compromised health tended to be lower from the analysis of photographs, than from in situ surveys (Fig. 4c). The prevalence of compromised health only exceeded 10% in the family Poritidae when using photographs, compared to six families from in situ surveys (Acroporidae, Agariciidae, Oculinidae, Pocilloporidae, Poritidae and Siderastreidae). The families Acroporidae and Poritidae were amongst the families most compromised using both methods (Fig. 4c).

The occurrence of healthy colonies was generally lower in situ when comparing the number of colonies; however, the prevalence of healthy colonies was similar for many scleractinian families and the families least susceptible to disease, bleaching and compromised health signs combined were relatively consistent using the two methodologies (Fig. 4d). The families Caryophylliidae, Pectiniidae and Mussidae were amongst those most often recorded as healthy using both methods (Fig. 4d). There were some discrepancies when comparing data for uncommon families; for example, in situ surveys recorded four healthy Astrocoeniidae colonies, whilst no colonies of this family were recorded from photographs.

Discussion

In this study, we found that coral disease and compromised health was underestimated from photographs compared to in situ assessments by highly skilled assessors of coral disease. Moreover, estimates varied inconsistently with differing levels of disease prevalence or compromised health, suggesting data sets collected using the two methods are not easily comparable for even these broad health categories. Estimates of some highly visible diseases (black band disease, growth anomalies) and compromised states (abnormally pigmented coral tissues) were however similar and may be useful indicators of environmental impacts on coral health when photographs are used for monitoring and in situ methodologies not feasible.

Metrics from photographic-methods are often lower than measurements made in situ due to insufficient image resolution or because the subject matter is partially obscured, which prevents a thorough examination of the subject matter (Burgess et al. 2010; Holmes et al. 2013). In our study, image quality was high (6–9 MB, 4400 × 3300 pixels); however, an inability to zoom in very closely to carefully examine lesions, unusual colouring, ciliates, cyanobacteria, algal and sponge overgrowth amongst others likely contributed to lower estimates of disease and other compromised health

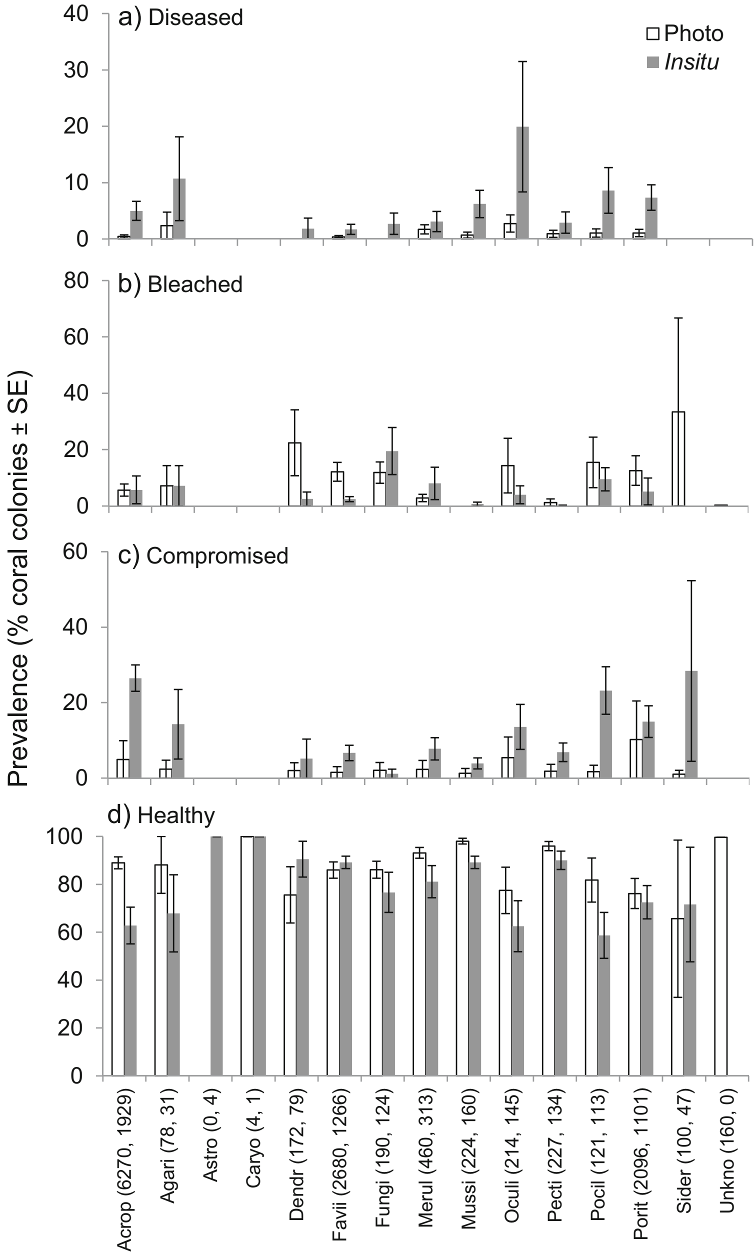

Fig. 4 Mean prevalence of **a** diseased, **b** bleached, **c** compromised and **d** healthy colonies per scleractinian family. Averages and error bars are calculated from 12 sites. *Number shown in parentheses* represents total number of colonies recorded per family using the photo and in situ methodologies, respectively. *Acrop* Acroporidae, *Agari* Agariciidae, *Astro* Astrocoeniidae, *Caryo* Caryophylliidae, *Dendr* Dendrophylliidae, *Favii* Faviidae, *Fungi* Fungiidae, *Merul* Merulinidae, *Mussi* Mussidae, *Oculi* Oculinidae, *Pecti* Pectiniidae, *Pocil* Pocilloporidae, *Porit* Poritidae, *Sider* Siderastreidae, *Unkno* unknown

states from photographs. Furthermore, many Indo-Pacific coral diseases and compromised health states originate at coral colony bases (Willis et al. 2004) and their detection requires careful examination of the lower parts of the coral colony. Photographic images for monitoring programs are typically taken from above colonies (Bennett et al. 2016), and the coral base is often partially or completely obscured by the upper part of the colony or other objects, particularly for branching, tabular, corymbose and foliose growth-forms. This is likely to have been a major factor contributing to the underestimation of disease and compromised health in photo-transects relative to in situ methods, particularly at sites having high densities of branching, tabulate, corymbose and foliose growth-forms. For this same reason, in situ rapid survey methodologies that do not allow careful examination of colony bases are also likely to underestimate levels of disease and compromised health. For example, surveys completed on snorkel may underestimate disease and compromised health states, particularly where reef depth and weather conditions preclude detailed examination of colony bases. Conversely, in situ methods that do not have a reference for transect width are more likely to include subjects of interest from outside transect boundaries than photographic techniques that have a fixed field of view (Harvey et al. 2004). This may inflate in situ estimates of highly mobile organisms, but is less likely to be a problem for sessile organisms like corals and where a reference is used in situ (as was in this study).

Variability in the detectability of disease types in photographs suggests that the analysis of photo-transects may be more suitable for the monitoring of some disease than others. For example, a similar number of colonies of black band disease were recorded from photographs and in situ surveys, indicating that more visually obvious diseases may be adequately monitored using photo-transects. Nonetheless, care would need to be taken to ensure colony bases are photographed wherever possible given that black band often originates at colony bases on Indo-Pacific corals, particularly on branching *Acropora* colonies which are particularly susceptible to this disease (Page and Willis 2006; Willis et al. 2004). Other less visible or difficult to categorise diseases were underestimated using photo-transects in this study. For example, brown band disease and skeletal eroding band are often difficult to identify in situ, particularly when ciliates are present at low densities (Page et al. 2016; Page and Willis 2008; Willis et al. 2004) and prevalence of both diseases was much lower in photo-transects in this study. Results of this study indicate that whilst highly visible diseases may be detectable using photo-transects, studies aimed at identifying the full suite of diseases should be conducted using in situ methods that allow detailed examination of coral colonies. Nonetheless, photo-transects may provide initial information on disease types present in a region, in the absence of other data sources (Page and Stoddart 2010). General consistency between methods in the families most susceptible to disease, bleaching and other compromised health states also suggests there is no major bias arising from the use of photo-transects to identify some disease and other compromised health states.

White syndrome prevalence was twofold lower in photo-transects than in situ, though many colonies exhibiting white lesions in photo-transects were categorised as unknown white scars due to the inability to zoom in and examine lesions in detail and preclude the presence of corallivores or identify causes of white lesions, for example ciliates in the case of skeletal eroding band and brown band diseases. The inability to get a clear look at white lesions to discern disease from bleaching is also likely to have contributed to overestimates of bleaching and underestimates of white syndromes in photo-transects. In contrast, the ability to examine colonies closely in situ, particularly colony bases and any lesions, and search for cryptic corallivores (*Drupella* spp. and crown-of-thorns starfish) resulted in greater confidence of assigning white lesions to specific disease or compromised health categories. It is not surprising that predation scars were underestimated from photo-transects given that the categorisation of a lesion as a predation scar is contingent on the nearby presence of cryptic corallivores that are often inadequately assessed using photo-transects (Forde 1992; Miller et al. 2009). Interestingly, when the prevalence of all white colonies, including colonies categorised as having white syndromes, brown band, bleaching, predator feeding scars and physical breakage, were combined, the prevalence of these white colonies in photos explained 40% of the variance of the same data for the in situ method. Thus, monitoring with photographs may not be capable of discerning between white compromised states (bleaching or white lesions resulting from disease, predation or physical breakage), but the high occurrence of these pooled white categories could be used to alert managers and trigger more detailed studies aimed at identifying the cause of the high occurrence of white colonies.

Both methods sought to identify physiologically discrete colonies, as is typical of in situ coral health surveys (as described in Willis et al. 2004). However, when colony bases were obscured in photographs and continuity of tissues between branches could not be confirmed, it was assumed that each branch was a physiologically discrete colony. This resulted in an inflation in colony counts (the denominator for calculating prevalence) for photo-transects, particularly at sites with high densities of branching *Acropora* colonies or where colonies were large and were counted in multiple images, for example massive *Porites* colonies. Large *Porites* colonies were observed to span up to three adjacent photographs at some sites. Greater numbers of colonies observed in photo-transects may therefore have contributed to lower estimates of disease and compromised health prevalence. General trends in assessing disease were however similar when using counts of colonies and prevalence data, indicating analysis of photos detects fewer disease cases than in situ surveys, though detectability in photos varied between diseases.

Differences between methods may also be partially attributable to differences amongst observers; however, the influence of this bias was minimised by using highly experienced observers and careful standardised training (Thompson and Mapstone 1997). Indeed, informal, qualitative in situ comparisons of surveys of the same transects by JL and JP and extensive discussions regarding data management and analysis between CP and JL revealed similarities in coral health categorisation amongst these observers. Furthermore, our findings are consistent with previous studies that have compared coral or fish data collected in situ with analysis of video or images and found in situ surveys allow more thorough search patterns resulting in more refined descriptions of the subject (Holmes et al. 2013; Turner et al. 2015; Bennett et al. 2016).

Whilst estimates of disease and compromised health from photo-transects were not good indicators when compared to the same coral health indicators in situ, estimates of healthy colonies from photo-transects were a relatively good predictor of the prevalence of healthy colonies in situ. Measuring the prevalence of healthy colonies may therefore be a more viable method of monitoring coral health than specific disease or compromised categories when using photographs, although this relationship is weaker when using colony counts. In addition, Lamb et al. (2014) found that the prevalence of healthy coral colonies was halved at high-use tourist sites compared to low-use sites, suggesting coral health can be a relatively good indicator of disturbance.

Photo-transects are already widely used to monitor coral cover and the composition of coral assemblages in many regions (Moore et al. 2012; Sweatman et al. 2005), and these same photo-transects may be used to measure the prevalence of coral health. Thus, a low-cost assessment and permanent record of coral health may be obtained using the same photographs currently gathered to monitor benthic cover and community composition (Jonker et al. 2008). This would allow non-specialists in coral taxonomy and coral disease diagnostics to collect the photos in situ for later analysis. Monitoring of healthy and white colonies via photo-transects should also be possible by staff skilled in coral taxonomy, but not skilled in coral disease diagnostics, ensuring this method is usable more widely across reef monitoring programs whilst also potentially reducing the cost of such monitoring.

Results of this study indicate that whilst assessments from photo-transects underestimated the suite of diseases and compromised health states affecting corals, as well as the frequency of all but the most visible disease and compromised health states, photo-transects may still be a useful tool in identifying trends in coral health. Estimates of healthy colonies from photo-transects were a relatively good predictor of the prevalence of healthy colonies in situ, whilst the prevalence of white compromised health states was similar using both methods, despite the inability to examine corals closely in photo-transect resulting in difficulties in the categorisation of other white compromised health states and thus overestimating bleaching. Nonetheless, assessments of the occurrence of healthy colonies and white compromised health states from photo-transects could be used by reef managers to identify changes in coral health and instigate investigations aimed at identifying the causes of these changes (e.g. Beeden et al. 2012), particularly in the absence of staff skilled in disease diagnostics or monitoring programs targeting coral health.

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