Contributed Paper

Using Coral Disease Prevalence to Assess the Effects of Concentrating Tourism Activities on Offshore Reefs in a Tropical Marine Park

JOLEAH B. LAMB*† AND BETTE L. WILLIS*†

*School of Marine and Tropical Biology, James Cook University, Townsville, QLD 4811, Australia
†ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia

Abstract: *Concentrating tourism activities can be an effective way to closely manage high-use parks and minimize the extent of the effects of visitors on plants and animals, although considerable investment in permanent tourism facilities may be required. On coral reefs, a variety of human-related disturbances have been associated with elevated levels of coral disease, but the effects of reef-based tourist facilities (e.g., permanent offshore visitor platforms) on coral health have not been assessed. In partnership with reef managers and the tourism industry, we tested the effectiveness of concentrating tourism activities as a strategy for managing tourism on coral reefs. We compared prevalence of brown band disease, white syndromes, black band disease, skeletal eroding band, and growth anomalies among reefs with and without permanent tourism platforms within the Great Barrier Reef Marine Park. Coral diseases were 15 times more prevalent at reefs with offshore tourism platforms than at nearby reefs without platforms. The maximum prevalence and maximum number of cases of each disease type were recorded at reefs with permanently moored tourism platforms. Diseases affected 10 coral genera from 7 families at reefs with platforms and 4 coral genera from 3 families at reefs without platforms. The greatest number of disease cases occurred within the spatially dominant acroporid corals, which exhibited 18-fold greater disease prevalence at reefs with platforms than at reefs without platforms. Neither the percent cover of acroporids nor overall coral cover differed significantly between reefs with and without platforms, which suggests that neither factor was responsible for the elevated levels of disease. Identifying how tourism activities and platforms facilitate coral disease in marine parks will help ensure ongoing conservation of coral assemblages and tourism.*

Keywords: Acroporidae, anthropogenic impacts, coral disease, Great Barrier Reef, marine park, reef tourism, visitor concentration

Utilización de la Prevalencia de Enfermedades del Coral para Evaluar los Efectos de la Concentración de Actividades Turísticas en Arrecifes en un Parque Marino Tropical

Resumen: *La concentración de actividades turísticas puede ser una manera efectiva para manejar parques de alto uso y minimizar el alcance de los efectos de visitantes sobre plantas y animales, aunque se puede requerir una considerable inversión en instalaciones turísticas permanentes. En arrecifes de coral, se ha asociado una variedad de perturbaciones relacionadas con humanos con niveles elevados de enfermedades del coral, pero los efectos de infraestructura turística en los arrecifes (e.g., plataformas permanentes para los visitantes) sobre la salud del coral no han sido evaluados. En asociación con los manejadores de arrecifes y la industria turística, probamos la efectividad de la concentración de actividades turísticas como una estrategia para manejar al turismo en arrecifes de coral. Comparamos la prevalencia de la enfermedad de la banda café, síndromes blancos, enfermedad de la banda negra, banda erosiva del esqueleto y crecimiento*

**Paper submitted July 7, 2010; revised manuscript accepted October 30, 2010.*
**email joleah.lamb@jcu.edu.au*

Conservation Biology, Volume **, No. **, ***–***

DOI: 10.1111/j.1523-1739.2011.01724.x

anómalo entre corales con y sin plataformas turísticas permanentes en el Parque Marino Gran Barrera Arrecifal. Las enfermedades de corales fueron 15 veces más prevalentes en arrecifes con plataformas que en los arrecifes cercanos sin plataformas. La prevalencia máxima y el número máximo de casos de cada tipo de enfermedad fueron registrados en arrecifes con plataformas turísticas permanentes. Las enfermedades afectaron a 10 géneros de coral de 7 familias en arrecifes con plataformas y 4 géneros de 3 familias en arrecifes sin plataformas. El mayor número de casos de enfermedad ocurrió en los corales acropóridos espacialmente dominantes, que presentaron una prevalencia 18 veces mayor en arrecifes con plataformas. No hubo diferencia significativa en el porcentaje de cobertura de acropóridos ni en la cobertura total de coral entre arrecifes con y sin plataformas, lo cual sugiere que ningún factor fue responsable de los niveles elevados de enfermedad. La identificación de la manera en que las actividades turísticas y las plataformas facilitan las enfermedades de corales en los parque marinos ayudará a garantizar la conservación de los ensambles de coral y el turismo.

Palabras Clave: Acroporidae, concentración de visitantes, enfermedades del coral, Gran Barrera Arrecifal, impactos antropogénicos, parque marino, turismo en arrecifes

Introduction

Infectious diseases are emerging as an important issue in the conservation of terrestrial and marine species (Harvell et al. 2002). Disease is now recognized as a major factor in the accelerating degradation of coral reefs in many regions of the world (Harvell et al. 1999, 2007). The causes of most diseases of corals are largely unknown (Richardson 1998; Harvell et al. 2007), but it is assumed that a variety of human activities may alter environmental conditions on reefs and potentially reduce coral resistance to microbial infections or increase pathogen virulence (Harvell et al. 2002). For example, coral diseases are associated with elevated nutrient concentrations (Bruno et al. 2003; Voss & Richardson 2006) from terrestrial runoff (Littler & Littler 1996) and sewage outfalls containing human enteric microorganisms (Patterson et al. 2002). Other human activities implicated in rising disease prevalence (i.e., the number of cases of a disease in a given population at a specific time) in corals include aquaculture (Harvell et al. 1999), unsustainable levels of fishing (Pandolfi et al. 2005), and introduced chemicals (Owen et al. 2002; Danovaro et al. 2008).

Although first-hand experience of local flora and fauna is one of the best ways to promote public awareness of conservation issues (Dixon 1993), achieving the dual objectives of providing recreational opportunities and preserving natural environments is challenging (Higginbottom et al. 2003). Management actions implemented to direct the location of tourist activities have minimized the aggregate extent of visitor effects on animals and plants in many terrestrial parks and protected areas (Leung & Marion 1999), particularly by concentrating visitor effects at remote tourist attractions, backcountry campsites and along trails (Marion & Farrell 2002). However, this strategy may require substantial use of infrastructure. Although installations of permanent buildings and trails may make the tourism experience more convenient and comfortable for visitors and are often desired features for safety and social reasons (Leung & Marion 1999), they can cause substantial changes to surrounding areas (Higginbottom et al. 2003). Thus, managers of some protected areas have sought to minimize the effects of infrastructure by dispersing visitor numbers over extensive areas. The effects of such management strategies have been evaluated for many terrestrial nature reserves (Leung & Marion 1999), but not for marine parks.

Tourism on the Great Barrier Reef is one of the most economically important industries in Australia and is geographically concentrated in the Cairns and Whitsunday Island sections of the Great Barrier Reef Marine Park (Harriott 2002). Approximately half of the 1.4 million visitors to these 2 regions each year take a day trip to 1 of 4 reefs with permanently moored offshore tourism platforms (Harriott 2002; Smith et al. 2005). Platforms are in shallow, sheltered waters adjacent to offshore reefs and provide visitors with easy access to reefs for viewing fish and coral communities. Since the first platforms were moored in the early 1980s, they have developed from small, simple platforms to large platforms with multiple levels (averaging 45 × 12 m) that can each accommodate roughly 400 visitors. There is a growing demand for offshore tourism platforms to facilitate and enhance reef visitor experience; thus, the number and size of tourism platforms are forecast to increase (Smith et al. 2005).

Much of what is currently known about the effects of tourism activities on coral reefs comes from studies of changes in percent coral cover in response to direct physical contact, for example, coral breakage due to activity of divers (Hawkins & Roberts 1992) and swimmers along snorkeling trails (Plathong et al. 2000), construction of permanent platforms and moorings (Smith et al. 2005), and movement of anchor chains (Schafer & Inglis 2000). The results of previous studies show that the effects of tourism platforms on coral cover are few and isolated (Smith et al. 2005). However, ongoing tissue loss caused by slowly progressing diseases could cause greater levels of coral mortality than immediate but short-term effects associated with breakage or localized shading. For example, in the Caribbean, 2 dominant reef-building corals, *Acropora cervicornis* and *A. palmata,* have been nearly extirpated on some reefs by an outbreak of white band disease that caused tissue loss of 0.5 cm/day on average (Patterson et al. 2002). On the Great Barrier Reef, reported rates of tissue loss vary from 1 cm/day for black band disease to 10 cm/day for brown band disease (Page & Willis 2006; Boyett et al. 2007).

Human activity on coral reefs may stress the ecosystem and reduce coral health at reefs in close proximity to offshore tourism platforms. Near these platforms, nutrient levels may increase from seabird guano that accumulates on platforms and is washed onto the reef by rain or by cleaning of the platform, from visitors and tourism operators feeding fish, and from tourists entering the water. Tourists also introduce pollutants and may physically damage the coral while snorkeling and diving. The platform infrastructure itself (e.g., chains used for anchoring the platform, snorkeling trail boundaries, and reef viewing stations) may also physically damage corals exposed by low and varying tides. However, there are no published studies on the prevalence of coral diseases as a measure of coral health in relation to tourism activities. Here we compare coral disease prevalence among reefs with permanently moored tourism platforms and adjacent reefs without platforms.

Methods

Study Sites and Data Collection

We conducted surveys in the Great Barrier Reef Marine Park off the northeast coast of Australia during late June and early July of 2009 (Fig. 1). We selected 8 reefs located within 2 adjacent management sections that are the most frequently visited in the Great Barrier Reef Marine Park (Central and Cairns sections in the central-northern region of the park). We selected 180-m^2 survey sites on the

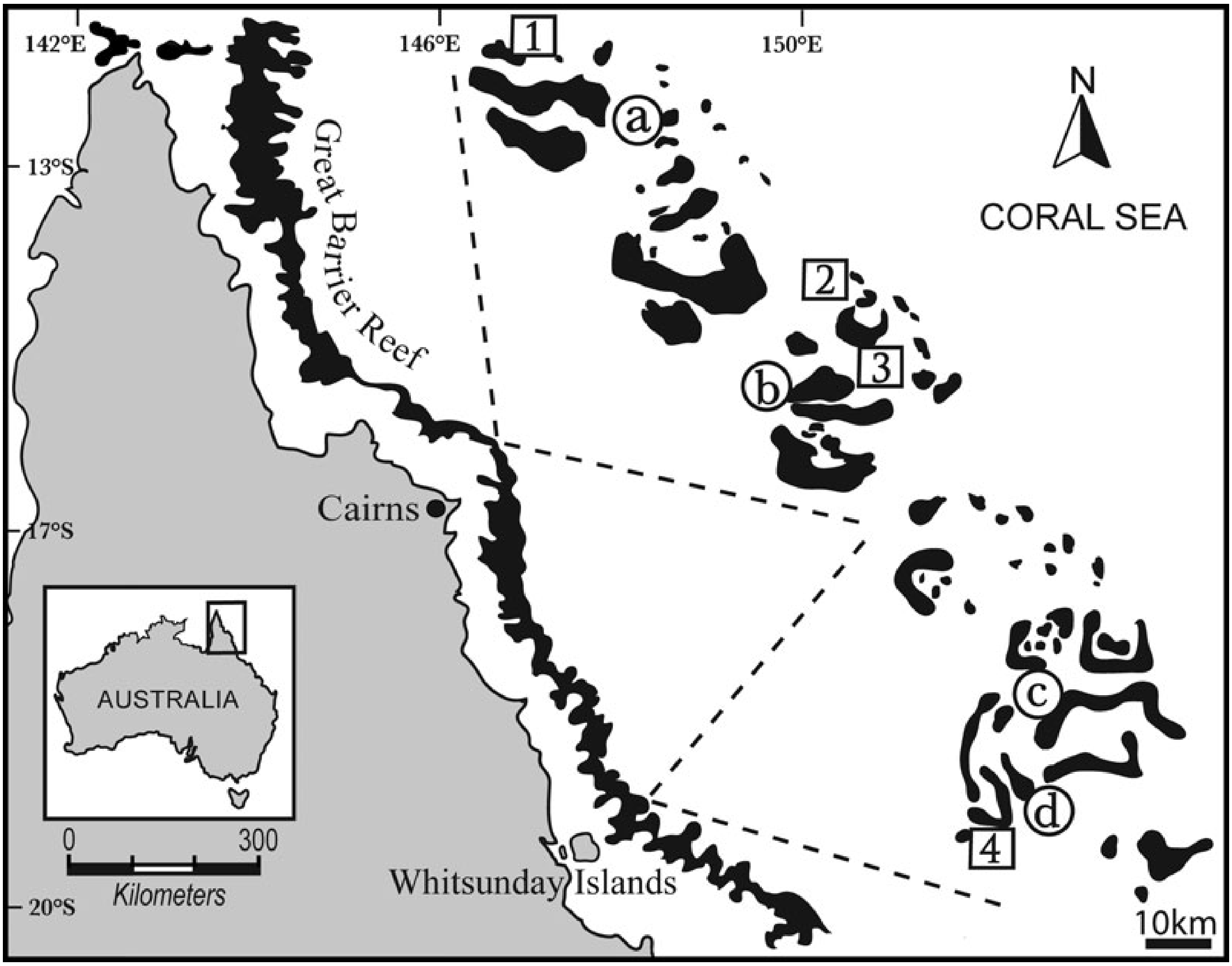

Figure 1. Locations of 8 reefs surveyed for coral disease within 2 latitudinal sectors (dashed lines) of the Great Barrier Reef Marine Park off the northeast coast of Australia (reefs with permanent tourism platforms, a–d circles; reefs without tourism platforms, 1–4 squares).

sheltered sides of mid-shelf reefs, which were located 40–50 km offshore and between latitudes 16°11′S and 16°44′S in the Central section and latitudes 19°32′S and 19°48′S in the Cairns section. We surveyed 2 reefs with permanently moored tourism platforms in each of the 2 sections. We selected 4 reefs without permanent platforms and lower levels of reef-based tourism (i.e., at most a single boat mooring with a maximum of 40 in-water visitors/site/day) on the basis of their proximity to reefs with tourism platforms (within 10–25 km of the nearest reef with a platform) and taxonomic composition of the coral assemblage. Thus, 3 reefs were selected in the Cairns section and 1 reef was selected in the Central section.

At each reef, we used scuba to examine corals for disease. We surveyed along 6 randomly placed 15 × 2 m belt transects, except at Milln Reef, where we surveyed 3 transects. We randomly placed transects along depth contours of 2–6 m and 5 m apart on upper reef slopes close to the main entry point of in-water visitors. Within each 30-m^2 belt transect, we identified each coral colony over 5 cm in diameter to genus and further classified it as either healthy (no disease observed) or affected by one or more of the following: black band disease (and other cyanobacterial mats), brown band disease, white syndromes, which are among the most virulent diseases, growth anomalies, and skeletal eroding band (Willis et al. 2004). We estimated how much coral cover was present for each genus using standard line-intercept surveys along each 15-m transect by recording the extent of each coral to the nearest centimeter.

Data Analyses

We calculated disease prevalence within each 30-m^2 belt transect by dividing the number of colonies in the 5 disease classes by the total number of colonies present (24 prevalence values at reefs with platforms; 21 prevalence values at reefs without platforms). To analyze broad taxonomic patterns in disease prevalence, we assigned coral families to 1 of 3 groups on the basis of spatial abundance on the Great Barrier Reef (Willis et al. 2004): Acroporidae, the spatially dominant family; common reef-building families (Pocilloporidae, Poritidae, and Faviidae); and less common families (Agariciidae, Fungiidae, Merulinidae, Mussidae, Oculinidae, Pectiniidae, and Siderastreidae).

We compared differences in mean disease prevalence and coral cover among platform and control reefs with a 3-factor nested analysis of variance. We classified effect (reefs with versus without platforms) and location (Central vs. Cairns sections) as fixed factors and nested reef within both effect and location. To assess individual variation among reefs, we treated reef as a random factor. Prior to analyses, we tested assumptions of normality (Shapiro-Wilks) and homogeneity of variance (Levene's test of homogeneity). We transformed data to the square root to meet assumptions of normality. We tested associations between disease prevalence and both total hard coral and acroporid cover with Pearson product-moment correlations. We performed all analyses in STATISTICA 9 (StatSoft, Tulsa, Oklahoma).

Results

Disease Prevalence Relative to Tourism Platforms

Mean disease prevalence was 15-fold greater at reefs with tourism platforms (mean [SE] = 3.27% [0.62]) than at reefs without platforms (0.21% [0.07]; Fig. 2 & Table 1). The mean of minimum disease prevalence values recorded at reefs with platforms was 4 times greater than the mean of maximum prevalence values at reefs without platforms. Disease prevalence ranged from 0.2% to 12.0% (median = 2.5%) at individual reefs with tourism platforms, whereas prevalence at individual reefs without platforms ranged from 0% to 1.1% (median = 0%).

At each of the 4 reefs with tourism platforms, corals surveyed (n = 7043) exhibited 5 of the 7 diseases typically recorded on the Great Barrier Reef (172 disease cases at reefs with platforms; Table 1 & Fig. 2). The virulent diseases, white syndromes, brown band disease, and black band disease, were most prevalent. Prevalence values for skeletal eroding band and growth anomalies were approximately 4 times lower than virulent diseases (Table 1). The maximum number of cases and prevalence of each disease were recorded at reefs with tourism platforms. In contrast, 14 cases of disease were recorded at reefs without platforms (n = 9468 colonies surveyed), where black band disease and white syndromes were the most prevalent diseases. We observed one case of skeletal eroding band and no cases of brown band diseases at reefs without tourism platforms. Disease prevalence for each of the 5 diseases recorded was significantly higher

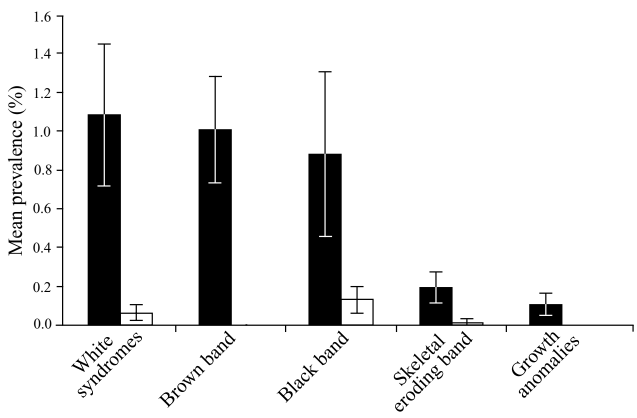

Figure 2. Mean (SE) disease prevalence between reefs with tourism platforms (black bars, 24 transects) and without tourism platforms (white bars, 21 transects) for the 5 disease classes recorded in surveys.

Table 1. Abundance and mean prevalence[a] of coral disease at reefs with and without tourism platforms and results of 3-level-nested analysis of variance.

	With platform (n = 24 transects)		*Without platform (n = 21 transects)*					
	no. of cases	*mean (SE) prevalence (%)*	*no. of cases*	*mean (SE) prevalence (%)*	*Effect* F, p	*Location* F, p	*Effect × location* F, p	*Reef (effect × location)* F, p
All diseases	172	3.27 (0.62)	14	0.21 (0.07)	25.4, < 0.009*	0.5, < 0.51	0.1, < 0.77	2.1, < 0.10
White syndromes	55	1.08 (0.37)	7	0.06 (0.04)	32.4, < 0.008*	3.4, < 0.15	1.9, < 0.26	0.8, < 0.51
Brown band	64	1.01 (0.27)	0	–	13.3, < 0.02*	0.02, < 0.91	0.02, < 0.92	1.5, < 0.23
Black band	35	0.88 (0.42)	6	0.13 (0.06)	47.7, < 0.04*	0.4, < 0.54	0.6, < 0.48	2.6, < 0.06
Skeletal eroding band	10	0.19 (0.08)	1	0.13 (0.01)	53.3, < 0.02*	47.7, < 0.04*	24.1, < 0.06	0.2, < 0.92
Growth anomalies	8	0.18 (0.06)	0	–	19.3, < 0.01*	0.001, < 0.97	0.05, < 0.83	2.2, < 0.09
Coral family[b]								
Acroporidae	137	2.63 (0.57)	6	0.08 (0.05)	20.8, < 0.01*	0.3, < 0.58	0.007, < 0.94	2.3, < 0.08
common	13	0.23 (0.10)	8	0.13 (0.06)	2.0, < 0.25	0.1, < 0.73	3.5, < 0.16	0.7, < 0.60
less common	22	0.41 (0.33)	0	–	0.9, < 0.40	2.0, < 0.23	1.5, < 0.30	2.8, < 0.04*

[a] *Mean prevalence calculated as the percentage of colonies with disease for each disease type or family group as a percentage of the total number of corals per transect. Analyses performed on data transformed to the square root (*significant difference for $\alpha = 0.05$).*
[b] *Families grouped on the basis of spatial abundance on the Great Barrier Reef: Acroporidae, the spatially dominant family; common families, Pocilliporidae, Poritidae, and Faviidae; and less common families, Agariciidae, Fungiidae, Merulinidae, Mussidae, Oculinidae, Pectiniidae and Siderastreidae.*

at reefs with tourism platforms than at reefs without platforms (white syndromes, $p < 0.01$; brown band disease, $p < 0.05$; black band disease, $p < 0.05$; skeletal eroding band, $p < 0.05$; growth anomalies, $p < 0.01$; Table 1).

Patterns in Disease Prevalence among Coral Families

Diseases affected a 2.5-fold greater range of corals on reefs with tourism platforms than on reefs without such platforms. Diseases were present in 10 genera from 7 families of reef-building corals at reefs with tourism platforms and in 4 genera from 3 families at reefs without nearby platforms. The difference in the number of coral taxa present between effect groups was not statistically significant.

On average, corals in the family Acroporidae accounted for the largest proportion of coral cover at reefs with and without platforms (Fig. 3a). Acroporid corals accounted for 76% of all disease cases at reefs with tourism platforms (Fig. 3b). Approximately 4% of acroporid corals at the 4 reefs with platforms, particularly the staghorn (branching) species, were affected by at least one disease, whereas 0.2% of acroporids at reefs without platforms were affected by disease. Thus, disease prevalence on acroporid corals was 18-fold greater at reefs with platforms. All 5 of the diseases we recorded were observed on acroporid corals at all 4 reefs with tourism platforms, whereas a maximum of 2 diseases was recorded on acroporid corals at 1 reef without a platform.

The prevalence of disease within the group of common coral families (Pocilloporidae, Poritidae, and Faviidae) was approximately 0.1% and not significantly different between reefs with and without platforms (Table 1). White syndromes, black band disease, and skeletal eroding band affected these families at reefs both with and without platforms (Fig. 3b).

All 22 cases of disease at reefs with tourism platforms affected hard corals in the less common families Agariciidae, Merulinidae, and Siderastreidae (Fig. 3b). The prevalence of black band disease and other cyanobacterial mats in the Agariciidae and Merulinidae was 10.6% and 7.2%, respectively; however, these cases were observed at a single reef in the group with platforms. Of all other reef-building corals, 1.4% had disease, and prevalence values did not differ significantly between platform and control reefs (Table 1).

Relation between Hard Coral Cover and Disease Prevalence

The total hard coral cover did not differ significantly between reefs with and without platforms (mean [SE] = 46.2% [2.4] and 45.7% [3.8], respectively; $F = 0.007$, $p = 0.94$). Moreover, disease prevalence was not correlated with hard coral cover, either at sites with ($r = 0.31, p = 0.14$; Fig. 4a) or without tourism platforms ($r = -0.72, p = 0.76$; Fig. 4b).

The mean percent cover of acroporid corals was slightly higher at reefs with tourism platforms (mean

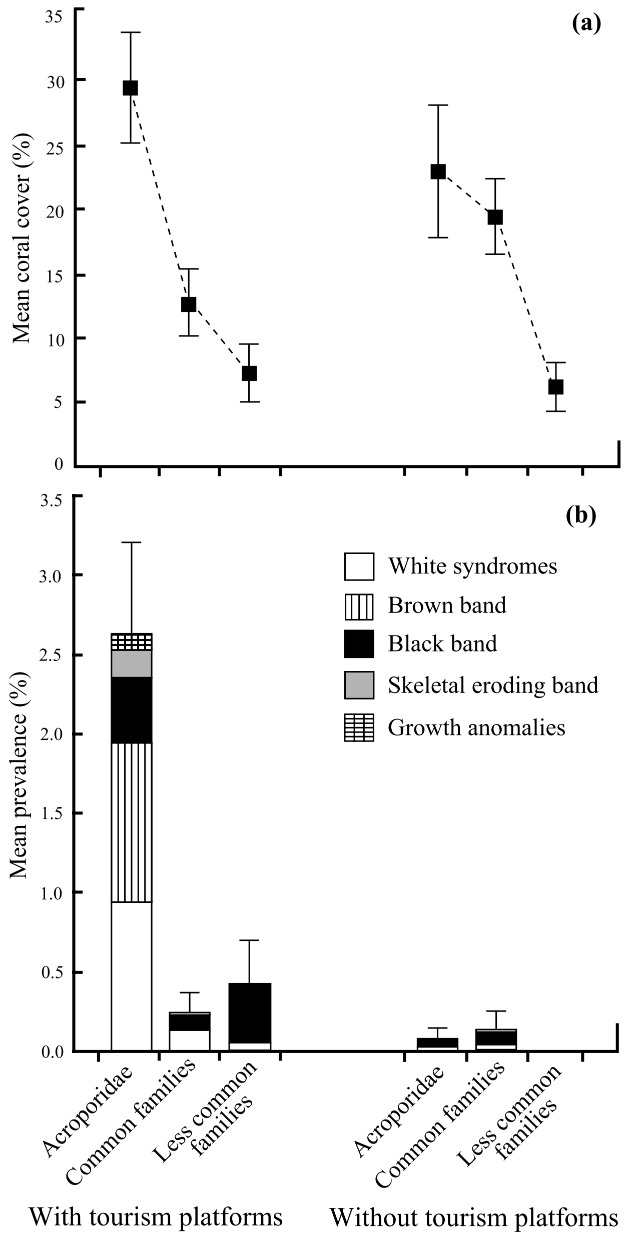

Figure 3. Taxonomic patterns of (a) mean (SE) coral cover and (b) mean (SE) coral disease prevalence between reefs with (24 transects) and without (21 transects) tourism platforms. (Acroporidae, spatially dominant family; common reef-building families, Poritidae, Pocilloporidae, and Faviidae; less common families, Agariciidae, Fungiidae, Merulinidae, Mussidae, Oculinidae, Pectiniidae, and Siderastreidae).

[SE] = 29.2% [3.3] vs. 22.5% [4.8]; Fig. 3a); however, the difference was not statistically significant ($F = 1.7$, $p = 0.26$). Although the majority of disease cases occurred within the acroporid family (see above), there was no association between disease prevalence and percent acroporid cover at reefs either with ($r = 0.29$, $p = 0.16$; Fig. 4c) or without tourism platforms ($r = 0.26$, $p = 0.26$; Fig. 4d).

Discussion

The consistently elevated prevalence of coral disease on reefs with tourism platforms compared with reefs without such platforms over an extent of 600 km suggests that either offshore tourism platforms or activities associated with them reduce resistance of reef corals to disease. Because we found no significant differences in percent cover of all corals or of the dominant, disease-susceptible Acroporidae among reefs with and without platforms, we believe differences in host density or family composition are unlikely to have caused the difference in disease prevalence. Models link increases in the abundance of corals with diseases with increases in host density (Bruno et al. 2007), presumably reflecting transmission of pathogens via direct colony-to-colony contact (Riegl 2002). However, we detected no associations between disease prevalence and cover of all scleractinian corals or of acroporid corals. Increased susceptibility to infection from normally nonpathogenic local microbial communities, as a consequence of proximity to tourism platforms (cf. Ritchie 2006), could have played a role in the prevalence of coral diseases at these reefs. Thus, coral disease prevalence may represent a useful metric of human disturbance on coral reefs.

Identifying and Managing Potential Disease Drivers

Pathogens may spread rapidly in marine systems (McCallum et al. 2003). For example, the coral disease white plague spreads along the coast of Florida at rates of approximating 200 km/year (Richardson et al. 1998). Tracing the origins and halting known environmental inputs that influence the abundance and severity of coral disease is the most viable option for alleviating the effects of coral diseases (Harvell et al. 2007). However, the overall increase in coral disease on reefs with tourism platforms may represent the cumulative effect of a number of factors that might otherwise not negatively affect corals, which may have disproportionate, long-term effects when they occur in combination with other stressors.

POLLUTANTS

Tourist platforms and in-water viewing stations are often used as resting sites by sea birds, and their guano may increase levels of nitrogen and phosphorus near these platforms (Bosman & Hockey 1986). Bird guano also

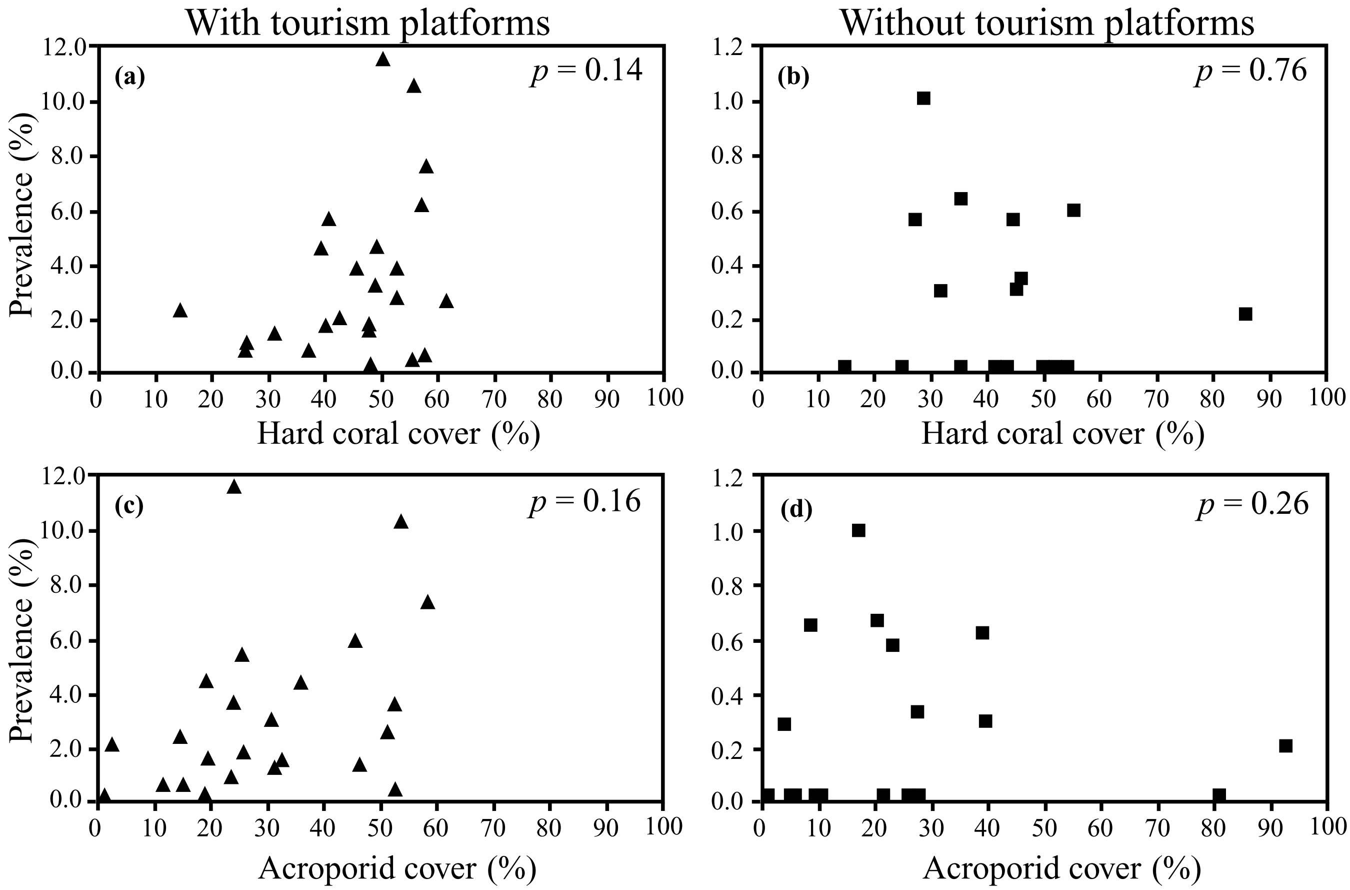

Figure 4. Associations between prevalence of all coral diseases and total hard coral cover at reefs (a) with tourism platforms (24 transects) and (b) without tourism platforms (21 transects) and associations between disease prevalence and acroporid cover at reefs (c) with tourism platforms and (d) without tourism platforms. Y-axis values in (a) and (c) are larger by a factor of 10 than those in (b) and (d).

may contain toxins, including dichlorodiphenyltrichloroethane (DDT), mercury, and hexachlorobenzene (HCB) (Blais et al. 2005). Even moderate nutrient enrichment can significantly increase the severity of both aspergillosis on sea fans and yellow band disease on corals in situ (Bruno et al. 2003), and the abundance of black band disease is positively correlated with concentration of nitrogen (Kuta & Richardson 2002). We suggest removal of any platforms that are not used regularly by tourists and washing guano into gutters placed around the edges of platforms that drain into wastewater tanks already in place. Nitrogen isotope analysis, which can separate nitrogen inputs originating from wastewater versus other anthropogenic sources (Baker et al. 2007), may prove useful for assessing potential sources of nutrients at platform sites, potentially including human waste.

Chemical compounds contained in sunscreens and other such products can reach detectable levels in both freshwater and seawater (Daughton & Ternes 1999; Giokas et al. 2007). Danovaro et al. (2008) estimate 4000–6000 tons of sunscreen may be released per year into tropical reef areas. In laboratory studies, organic ultraviolet filters from sunscreens induce lytic viral cycles in symbiotic zooxanthellae, causing bleaching in acroporid corals (Danovaro et al. 2008). Although the degree to which pollutants come into contact with reef corals is unknown, a precautionary approach that limits the entry of nutrients and chemicals into the water could include enforcement of alternative measures of sun protection (e.g., hats and full-body sun suits) and increased tourist education.

PHYSICAL DAMAGE

A major challenge for managers of coral reefs is control of activities in heavily used areas that could severely damage corals, particularly branching species of *Acropora* (Plathong et al. 2000). The availability of energy for allorecognition and cell-mediated immune responses declines during regeneration of damaged tissue in corals, sponges, and other invertebrates (Mydlarz et al. 2006). Therefore, even if coral colonies survive breakage or damage from recreational activities, reductions in immunocompetence may increase their subsequent susceptibility to disease.

The ciliate diseases brown band and skeletal eroding band occurred only at reefs with tourism platforms. These are the only two diseases known to be associated with ciliates on the Great Barrier Reef (Willis et al. 2004). The ciliate that causes brown band disease, the most prevalent coral disease at reefs with tourism platforms, may be transmitted via the water column and spread through human activity around tourism platforms. Physical damage to corals may allow ciliates to become established, which may lead to skeletal eroding band lesions (Page & Willis 2008). Thus, increased injury to corals near platforms may be contributing to increased disease prevalence and diversity. Injured colonies can become infected with black band disease after being transplanted downstream from diseased corals (Rützler & Santavy 1983). Thus, dislodged black band mats, which comprise primarily cyanobacteria, may transmit the disease as they are transported by water currents and divers' fins (Bruckner et al. 1997). Tourists themselves could serve as vectors of coral disease.

Although it has been suggested that more than 5000 visitors per year damages reefs (Hawkins & Roberts 1997), each of the 4 tourism platform operators in this study reported over 40,000 visitors per year, although not all visitors enter the water. Boundaries limiting snorkeling activities are in place at all tourism platforms in our study, but much of the physical contact with corals is a result of uninformed or careless behavior. Managers can educate and compel visitors to reduce high-impact behavior (e.g., standing on and touching corals) and to engage in low-impact behavior (e.g., use of personal flotation devices when resting). Large groups of visitors have greater potential to damage coral than the same number of individuals in smaller groups (Higginbottom et al. 2003). Therefore, probability of disease may be reduced by limiting group sizes, extending the length of snorkeling trails to reduce crowding, and varying trail location according to tides to standardize distance to the reef throughout the day.

Different growth forms and species of coral vary in their response to trampling (Plathong et al. 2000; Marion & Farrell 2002). Locating viewing sites and moorings away from more susceptible families and growth forms may reduce disease.

Longer-Term Effects of Increased Disease Prevalence

Although the mean disease prevalence at platform reefs in autumn and winter was low, increases in prevalence are typical in summer (Willis et al. 2004), and it is likely that increases in ocean temperature associated with climate change will further increase the abundance and severity of coral diseases (Harvell et al. 1999, 2002; Bruno et al. 2007). Summer increases in disease prevalence in all Great Barrier Reef coral families, which are up to 15-fold higher for acroporid corals during summer months than in winter months (Willis et al. 2004), suggest that high summer temperatures and thermal anomalies may stress corals and reduce their immunity to disease, potentially concurrent with increased growth of pathogens or pathogen virulence as temperatures increase (Harvell et al. 1999; Mydlarz et al. 2006). Increasing distances of snorkeling trail boundaries to the reef or reducing visitor numbers in summer could reduce stress to corals. However, peak tourist season is during summer on the Great Barrier Reef; therefore, enforcing limits on reef visitor numbers during peak periods would severely affect the local economy.

We suggest that measuring and monitoring coral disease near popular tourism destinations is necessary to inform strategies for controlling visitor use. Results of studies of visitor effects on terrestrial trails and campsites (Marion & Farrell 2002) and marine snorkeling trails (Plathong et al. 2000) and dive sites (Hawkins & Roberts 1992) show that most negative effects on natural resources have a curvilinear relation to visitor-use levels (i.e., the majority of damage accumulates rapidly during initial use of the visitor area and subsequent use causes little additional change) (Higginbottom et al. 2003). Lower coral disease prevalence at our control sites, which were used by fewer than 5000 recreational divers per year (levels recommended by Hawkins & Roberts 1997), suggests that dispersing visitors and creating low-use sites without permanent platforms may benefit coral health.

The status of corals and fishes influences the satisfaction of day visitors to coral reefs (Schafer & Inglis 2000). If visitor activities degrade local environments, the financial benefits of tourism may not be sustainable and conservation objectives will not be met (Dixon 1993; Higginbottom et al. 2003). Quantifying spatio-temporal coral disease prevalence to establish reference points for future comparisons may help evaluate the success or failure of management actions.

Acknowledgments

We thank the staff and crew of the tourism operations on the Great Barrier Reef for their partnership and support. We thank Y. Sato for field assistance and C. Syms for statistical advice.

Literature Cited

Baker, D. M., S. A. MacAvoy, and K. Kim. 2007. Relationship between water quality, ^{15}N, and aspergillosis of Caribbean sea fan corals. Marine Ecology Progress Series **343:**123–130.

Blais, J. M., L. E. Kimpe, D. McMahon, B. E. Keatley, M. L. Mallory, M. S. V. Douglas, and J. P. Smol. 2005. Arctic seabirds transport marine-derived contaminants. Science **309:**445.

Bosman, A. L., and P. A. R. Hockey. 1986. Seabird guano as a determinant of rocky intertidal community structure. Marine Ecology Progress Series **32:**247–257.

Boyett, H. V., D. G. Bourne, and B. L. Willis. 2007. Elevated temperature and light enhance progression and spread of black band disease on staghorn corals of the Great Barrier Reef. Marine Biology **151:**1711–1720.

Bruckner, A. W., R. J. Bruckner, and E. H. Williams. 1997. Spread of a black-band disease epizootic through the coral reef system in St Ann's Bay, Jamaica. Bulletin of Marine Science **61:**919–928.

Bruno, J. F., L. E. Petes, C. D. Harvell, and A. Hettinger. 2003. Nutrient enrichment can increase the severity of coral diseases. Ecology Letters **6:**1056–1061.

Bruno, J. F., E. R. Selig, K. S. Casey, C. A. Page, B. L. Willis, C. D. Harvell, H. Sweatman, and A. M. Melendy. 2007. Thermal stress and coral cover as drivers of coral disease outbreaks. Public Library of Science Biology **5:**1–8.

Danovaro, R., L. Bongiorni, C. Corinaldesi, D. Giovannelli, E. Damiani, P. Astolfi, L. Greci, and A. Pusceddu. 2008. Sunscreens cause coral bleaching by promoting viral infections. Environmental Health Perspectives **116:**441–447.

Daughton, C. G., and T. A. Ternes. 1999. Pharmaceuticals and personal care products in the environment: agents of subtle change? Environmental Health Perspectives **107:**907–938.

Dixon, J. A. 1993. Economic benefits of marine protected areas. Oceanus **36:**35–40.

Giokas, D. L., A. Salvador, and A. Chisvert. 2007. UV filters: from sunscreens to human body and the environment. Trends in Analytical Chemistry **26:**360–374.

Harriott, V. J. 2002. Marine tourism impacts and their management on the Great Barrier Reef. Technical report 46. CRC Reef Research Centre, Townsville, Queensland.

Harvell, C. D, et al. 1999. Emerging marine diseases-climate links and anthropogenic factors. Science **285:**1505–1510.

Harvell, C. D., C. E. Mitchell, J. R. Ward, S. Altizer, A. P. Dobson, R. S. Ostfeld, and M. D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. Science **296:**2158–2162.

Harvell, C. D., E. Jordan-Dahlgren, S. Merkel, E. Rosenberg, L. Raymundo, G. Smith, E. Weil, and B. L. Willis. 2007. Coral disease, environmental drivers, and the balance between coral and microbial associations. Oceanography **20:**173–195.

Hawkins, J. P., and C. M. Roberts. 1992. Effects of recreational SCUBA diving on fore-reef slope communities of coral reefs. Biological Conservation **62:**171–178.

Hawkins, J. P., and C. M. Roberts. 1997. Estimating the carrying capacity of coral reefs for recreational scuba diving. Proceedings of the 8th International Coral Reef Symposium **2:**1923–1926.

Higginbottom, K., R. Green, and C. Northrope. 2003. A framework for managing the negative impacts of wildlife tourism on wildlife. Human dimensions of wildlife **8:**1–24.

Kuta, K. G., and L. L. Richardson. 2002. Ecological aspects of black band disease of corals: relationships between disease incidence and environmental factors. Coral Reefs **21:**393–398.

Leung, Y., and J. L. Marion. 1999. Spatial strategies for managing visitor impacts in national parks. Journal of Park & Recreation Administration **17:**20–38.

Littler, M. M., and D. S. Littler. 1996. Black band disease in the South Pacific. Coral Reefs **15:**20.

Marion, J. L., and T. A. Farrell. 2002. Management practices that concentrate visitor activities: camping impact management at Isle Royale National Park, US. Journal of Environmental Management **66:**201–212.

McCallum, H., C. D. Harvell, and A. Dobson. 2003. Rates of spread of marine pathogens. Ecology Letters **6:**1062–1067.

Mydlarz, L. D., L. E. Jones, and C. D. Harvell. 2006. Innate immunity, environmental drivers and disease ecology of marine and freshwater invertebrates. Evolution & Systematics **37:**251–288.

Owen, R., A. H. Knap, M. Toaspern, and K. Carbery. 2002. Inhibition of coral photosynthesis by the antifouling herbicide Irgarol 1051®. Marine Pollution Bulletin **44:**623–632.

Page, C. A., and B. L. Willis. 2006. Distribution, host range and large-scale spatial variability in black band disease prevalence on the Great Barrier Reef, Australia. Diseases of Aquatic Organisms **69:**41–51.

Page, C. A., and B. L. Willis. 2008. Epidemiology of skeletal eroding band on the Great Barrier Reef and the role of injury in the initiation of this widespread coral disease. Coral Reefs **27:**257–272.

Pandolfi, J. M., et al. 2005. Are U.S. coral reefs on the slippery slope to slime? Science **307:**1725–1726.

Patterson, K. L., J. W. Porter, K. B. Ritchie, S. W. Polson, E. Mueller, E. C. Peters, D. L. Santavy, and G. W. Smith. 2002. The etiology of white pox, a lethal disease of the Caribbean elkhorn coral, *Acropora palmata*. Proceedings of the National Academy of Sciences USA **99:**8725–8730.

Plathong, S., G. J. Inglis, and M. E. Huber. 2000. Effects of self-guided snorkeling trails in a tropical marine park. Conservation Biology **14:**1821–1830.

Richardson, L. L. 1998. Coral diseases: What is really known? Trends in Ecology & Evolution **13:**438–443.

Richardson, L. L., K. G. Goldberg, R. B. Kuta, R. B. Aronson, G. W. Smith, K. B. Ritchie, J. C. Halas, J. S. Feingold, and S. M. Miler. 1998. Florida's mystery coral killer identified. Nature **392:**557–558.

Riegl, B. 2002. Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases and fish in the Arabian Gulf (Dubai, UAE). Marine Biology **140:**29–40.

Ritchie, K. B. 2006. Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. Marine Ecology Progress Series **322:**1–14.

Rützler, K., and D. L. Santavy. 1983. The black band disease of Atlantic reef corals: 1. Description of the cyanophyte pathogen. Marine Ecology **4:**301–319.

Schafer, C. S., and G. J. Inglis. 2000. Influence of social, biophysical, and managerial conditions on tourism experiences within the Great Barrier Reef World Heritage Area. Environmental Management **26:**73–87.

Smith, A., J. Monkivitch, P. Koloi, G. Hamilton, and S. Myers. 2005. A review of environmental impact assessment of tourism pontoons on the Great Barrier Reef. Institute of Australia and New Zealand report. Great Barrier Reef Marine Park Authority, Townsville, Queensland.

Voss, J. D., and L. L. Richardson. 2006. Nutrient enrichment enhances black band disease progression in corals. Coral Reefs **25:**569–576.

Willis, B. L., C. A. Page, and E. A. Dinsdale. 2004. Coral Disease on the Great Barrier Reef. Pages 35–68 in E. Rosenberg and Y. Loya, editors. Coral health and disease. Springer-Verlag, Berlin.