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Incidence of black band disease, brown band disease, and white syndrome in branching corals on the Great Barrier Reef

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ABSTRACT

Impacts from human-induced direct-use perturbations on coral colonies are on the rise. Despite significant incidences of coral disease on a global-wide basis, too few studies have verified the sources of diseases affecting coral colonies. To determine if branching coral communities are prone to infection with black band disease, brown band disease, and white syndrome, this study compared the prevalence of coral disease between Great Barrier Reef Marine Park Zones in the Great Barrier Reef Marine Park, Australia. We found evidence for coral disease on 9.06% of sites, with white syndrome being the most prevalent, found on 5.46% of sites, brown band found on 2.90% of sites, and black band found on 1.45% of sites. Coral disease of any kind, specifically black band and white syndrome, were significantly less abundant in areas where line fishing was permitted than where it was prohibited. Moreover, there was an interaction between fishing regulations and location, such that fishing regulations did not predict the presence of disease offshore, but inshore coral disease was significantly more prevalent where line fishing was prohibited than where line fishing was permitted. Coral disease was most frequently found in General Use, Scientific Research Open to the Public, and Marine National Park Zones; and reliably least commonly found in Habitat Protection, Conservation Park, and Preservation Zones. There were also differences among Marine Park Management Zones with coral disease most prevalent in the Cairns/Cooktown (Offshore) zone and least prevalent in the Mackay/Capricorn (Offshore) zone. Cairns/Cooktown (Offshore and Inshore) were the highest zones for black band and brown band, and Mackay/Capricorn (Inshore) was the highest management zone for white syndrome.

1. Introduction

Coral reef ecosystems are constantly in a state of flux and are frequently known for providing an environment that supports an abundance of diverse marine species across the globe (Kittinger et al., 2012). While coral reefs have been gradually progressing for hundreds of millions of years (Riegl et al., 2009), approximately one-fifth of the world's coral reefs are edging towards extinction, and another 40% are in jeopardy (National Ocean Service, 2015). As human activities in and around marine ecosystems continue to escalate, negative impacts are beginning to unfold (Chabanet et al., 2005; Green and Bruckner, 2000).

Scientists are now well aware of the crucial need to understand the causes of degradation of coral reef health (Bruno and Selig, 2007; Green and Bruckner, 2000; Hughes et al., 2003). This topic has become a worldwide concern in the past few decades (Osborne et al., 2011). Although coral reefs aid in protecting seaside communities from natural disasters, provide a means of living for millions of people, and offer an abundant supply of food to the human population, many of the top threats to coral reef health directly relate to human-induced disturbances (Chabanet et al., 2005; Kittinger et al., 2012; Marshall and Schuttenberg, 2006; National Ocean Service, 2015). Threats result from land-based pollution and destructive fishing practices (Marshall and Schuttenberg, 2006; National Ocean Service, 2015), in addition to shoreline development, recreation, and tourism activities (Chabanet et al., 2005). When anthropogenic pressures merge with the effects of climate change, extreme weather-related events, and invasive species, the consequences could potentially devastate biologically diverse coral reef ecosystems (National Oceanic and Atmospheric Administration, 2015).

Marshall and Schuttenberg (2006) stressed the importance of differentiating between diseases and other stressors affecting coral. Ainsworth, Kramasky-Winter, Loya, Hoegh-Guldberg, and Fine (2007)

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claimed global accounts of coral disease have increased substantially in recent years. Although cases of coral disease were initially observed on stony corals over forty years ago (Green and Bruckner, 2000), limited research has connected the escalation of diseases to their exact sources (Pollock et al., 2011).

Green and Bruckner (2000) suggested that most incidences of coral disease in the Caribbean were linked to regions with increased levels of anthropogenic activity. In addition, Aeby and Santavy (2006) discovered a coral's ability to fight infection may become inhibited due to injuries when comparing the susceptibility to disease between injured and uninjured corals. The results from their study indicated that a coral's weakened immune system may provide pathways for opportunistic pathogens to infect the stressed coral (Aeby and Santavy, 2006). Similarly, Lirman's (2000) study found that the size of a wound on branching coral affects the colony's ability to recover. When a large lesion is slow to recover, coral colonies continue to use energy to regenerate new polyps and consequently, their immune system becomes weakened (Lirman, 2000). Considering disease can spread rapidly to a healthy colony (Miller et al., 2014) and may increase coral mortality rates because of gradual tissue loss (Lamb et al., 2015), using technology to discover the best diagnostic tools and new techniques could potentially provide researchers the capabilities to accurately identify and confirm the presence of coral diseases (Pollock et al., 2011). Additionally, Bruno and Selig (2007) suggested that quantitative assessments of reef health on regional scales are necessary to measure the effectiveness of management procedures as well as determine the causes of coral reef degradation.

The present study investigated the possible relationship between GBR Marine Park Zones and an increase in the percentage of branching coral colonies exhibiting signs of black band disease (BBD), brown band disease (BrB), and white syndrome (WS). The US Endangered Species Act listed *Acropora palmata* (elkhorn coral) and *Acropora cervicornis* (staghorn coral), two major reef-building, branching coral species as threatened in 2006 (Garrison and Ward, 2008). Although many diseases including WS, BrB, and those yet to emerge threaten coral communities, BBD appears to be one of the most problematic diseases affecting the health of coral reefs across the globe (Ainsworth et al., 2007).

2. Methods

2.1. Data source

Survey samples were extracted from the Great Barrier Reef Marine Park Authority's (GBRMPA) Eye on the Reef, Reef Health and Impact Survey (RHIS). This continual year-round survey designed for volunteer reef users is conducted by scientists, citizen scientists, and community stakeholders (Great Barrier Reef Marine Park Authority, 2011). Utilizing the public for monitoring coral reefs has substantial economic benefits in addition to enabling managers to expand the range of monitoring sites while also raising awareness of the increasing threats to coral reef health (Hill et al., 2004).

2.2. Criteria for RHIS observations

Volunteer participants submitting RHIS observational data to the GBRMPA's Eye on the Reef program were required to partake in five online training modules followed by a more highly developed in-water session for individuals closely connected to the reef (Great Barrier Marine Park Authority, 2015). The RHIS is an efficient monitoring tool as it encompasses a large expanse of the Great Barrier Reef (GBR) (Hill et al., 2004). The RHIS monitoring consists of several twenty-minute observations recorded at the same location (Great Barrier Reef Marine Park Authority, 2011).

2.3. Survey area

The RHIS monitoring took place on coral reefs scattered throughout the GBR Marine Park bordering the eastern coastline of Queensland, Australia. Survey sites ranged from the Far Northern Marine Park Management Section to the southern MacKay/Capricorn Management Section. For this study, the GBR Marine Park region was defined by seven different Marine Park Zones identified by specific regulations and restrictions on permissible activities. The General Use, Habitat Protection, and Conservation Park Zones permit fishing but restrict the number of lines and hooks allowed per person depending on the zone, whereas the Buffer, Scientific Research, Marine National Park, and Preservation Zones do not allow line fishing whatsoever (Great Barrier Reef Marine Park Authority, 2011).

2.4. Surveillance

To determine disease prevalence, visual recordings of in situ observations specifying signs of BBD, BrB, and WS in branching coral colonies were extracted from the RHIS database. BBD is recognized by a black band margin comprised of a microbial consortium that separates living tissue from necrotic tissue in coral colonies (Sato et al., 2009) (see Fig. 1). BrB is characterized by a brown pigmented band separating live tissue from the white skeleton (see Fig. 2) whereas WS is recognized by linear bands of white exposed skeleton (National Ocean Service, 2016) (see Fig. 3).

2.5. Data collection

Data-gathering required formal permission to collect and analyze historical observational data from the GBRMPA's Eye on the Reef program database. Data utilized in this study consisted of recorded results from the Eye on the Reef, RHIS conducted within the GBR Marine Park Zones. The RHIS monitoring occurred between June of 2007 and September of 2015. The official request for a data user licence was submitted to Chris Jones, Project Officer, Policy and Stewardship, GBRMPA on August 19, 2015. Final approval was granted by the Licensor, the GBRMPA on behalf of the Commonwealth of Australia. The Licence Deed for the non-commercial use of Data was received on Monday, September 7, 2015.

The licensed data set was requested, gathered from the Eye on the

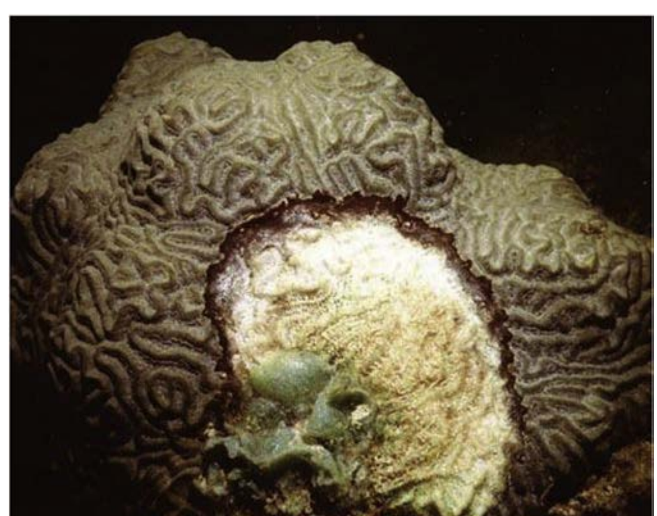

Fig. 1. Black band disease (BBD) affecting *Diploria strigosa* (brain coral). Image courtesy of Bruckner, NOAA, National Ocean Service, June 22, 2015. Adapted from: http://oceanservice.noaa.gov/education/tutorial_corals/coral10_disease.html.

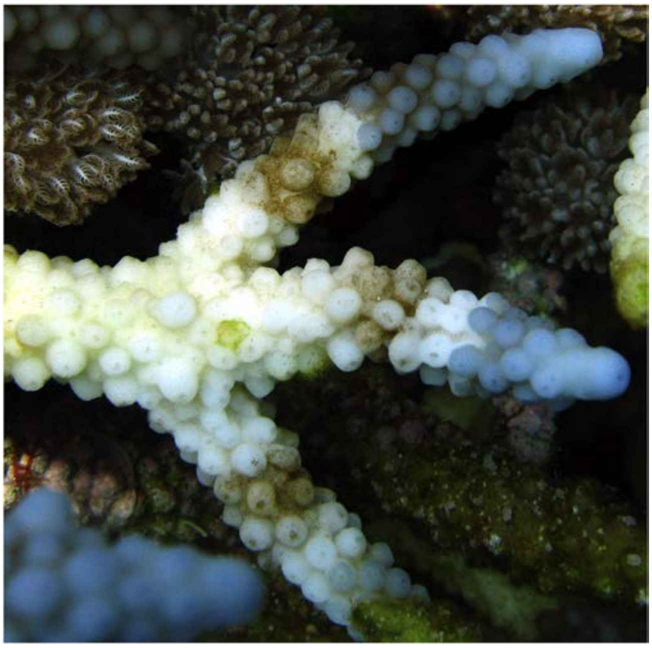

Fig. 2. Brown band disease (BrB) affecting *Acropora hemprichii*. Image courtesy of Bruckner, Coral Reef CPR, May 11, 2008.

Fig. 3. White syndrome (WS) affecting *Acropora acuminata*. Image courtesy of Bruckner, Coral Reef CPR, November 18, 2014.

Reef program, and shared with the licensee utilizing an Excel spreadsheet. Data included coral disease prevalence, number and type of coral colonies affected as recorded on the RHIS from macroscopic observations in Marine Park Zones where line fishing is prohibited and Zones where line fishing is allowed.

2.6. Sample size

This study accessed a database containing 8713 records of coral reef monitoring surveys conducted over a 6 year time period. However, on 652 surveys, RHIS observers failed to indicate the specific Marine Park Zone monitored. Furthermore, the type of Management Section was not identified on 273 surveys.

2.7. Statistical analysis

We used X^2 and logistic regression to assess the presence or absence of disease in different sites under different conditions.

3. Results

3.1. Surveys

Positive identifications of coral disease as recorded on the RHIS surveys were filtered and categorized according to the type of GBR Marine Park Zone to assess differences in the prevalence of branching coral colonies affected by BBD (see Fig. 4), BrB (see Fig. 5), and WS (see Fig. 6).

3.2. Relationship between Marine Park Zone and presence of disease

Overall, we found that 9.06% of sites (1257/13877) had some presence of disease with 1.45% (201/13876) of sites including BBD, 2.90% (402/13876) of sites exhibiting BrB, and 5.46% (757/13876) of sites exhibiting WS. Table 1 presents the frequency of disease by Marine Park Zone. We examined the relationship between Marine Park Zone and the presence of coral disease using a logistic regression model. For all diseases we found a significant relationship between Marine Park Zone and the presence of disease $X^2(9) = 37.05$, $p < 0.001$. Disease was reliably most prevalent in the General Use, Scientific Research Open to the Public, and Marine National Park zones; and reliably least commonly found in Habitat Protection, Conservation Park, and Preservation sites (see Table 1). We calculated odds ratios to assess differences among specific zones for the presence or absence of disease of any type (BBD, BrB, and WS). We found that General Use sites were significantly more likely to have a disease of any kind than Conservation Park sites (odds ratio 0.522, $p = 0.023$), and Preservation sites (odds ratio 6.232, $p < 0.0001$). Scientific Research zone sites Open to the Public were significantly more likely to have a disease than Habitat Protection sites (odds ratio 0.629, $p = 0.045$), Conservation Park sites (odds ratio 0.531, $p = 0.010$), and Preservation sites (odds ratio 0.163, $p < 0.0001$). Marine National Park zone sites were significantly more likely to have diseased corals than Habitat Protection sites (odds ratio 0.830, $p = 0.0056$), Conservation Park sites (odds ratio 0.700, $p = 0.0004$), and Preservation sites (odds ratio 0.215, $p < 0.0001$). In addition, Buffer zone sites had significantly more disease than Habitat Protection sites (odds ratio 0.522, $p = 0.0233$) and Conservation Park sites (odds ratio 1.428, $p = 0.0004$). Other differences were not statistically significant, and some sites, specifically Commonwealth Island GBRMPA, Scientific Research Closed to the Public, and Commonwealth Island Other had too few observations to make reliable claims about differences in disease frequency.

Next we conducted a series of analyses for each particular disease. For BBD we found a significant relationship between Marine Park Zone and the presence of disease $X^2(9) = 17.17$, $p = 0.046$. Marine National Park zone sites had a significantly higher rate of BBD than Habitat Protection sites (odds ratio 0.560, $p = 0.0003$; see Table 1). No other differences were statistically significant. For BrB we found a significant relationship between Marine Park Zone and the presence of disease $X^2(9) = 18.61$, $p = 0.029$. Preservation Zone sites reliably had the lowest rate of BrB (see Table 1). Preservation Zone sites had significantly lower rates of BrB than Buffer Zone sites (odds ratio 14.0, $p = 0.030$), Scientific Research Zone sites Open to the Public (odds ratio 10.271, $p = 0.004$), Habitat Protection (odds ratio 6.907, $p = 0.005$), Marine National Park (odds ratio 6.759, $p = 0.068$), Conservation Park (odds ratio 4.68, $p = 0.048$). In addition, Conservation Park sites had significantly lower rates of BrB than Habitat Protection sites (odds ratio 0.668, $p = 0.023$) and Marine National Park sites (odds ratio 1.444, $p = 0.0397$). No other differences were statistically significant. For WS we found a significant relationship between Marine Park Zone and the presence of disease $X^2(9) = 28.10$, $p = 0.0009$. General Use sites had the highest rate of WS (see Table 1). General Use sites had significantly higher rates of WS than Marine National Park

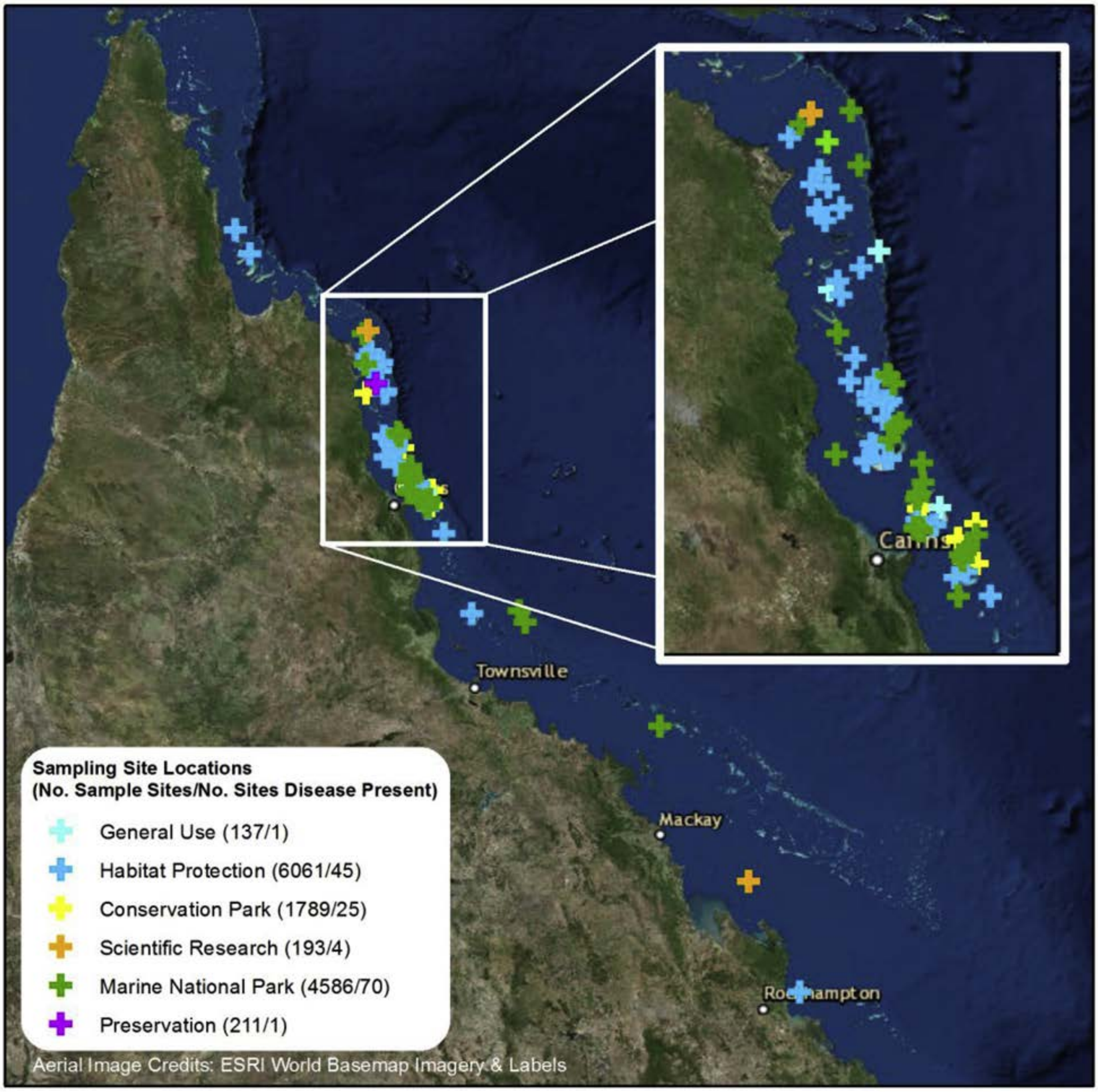

Fig. 4. Map displays the Great Barrier Reef in Australia including the Great Barrier Reef Marine Park Zones combined with the number of survey sites where BBD was observed affecting branching coral and recorded by participants on the GBRMPA, Eye on the Reef, RHIS. Base map: ESRI (2018).

sites (odds ratio 2.105, $p = 0.0124$), Habitat Protection sites (odds ratio 2.557, $p = 0.0020$), Conservation Park sites (odds ratio 2.901, $p = 0.0009$), and Preservation sites (odds ratio 9.168, $p < 0.0001$). Preservation sites had the lowest reliable rate of WS with significantly lower rates than Scientific Research Zone sites Open to the Public (odds ratio 0.1997, $p = 0.0048$), Marine National Park sites (odds ratio 4.394, $p = 0.0012$), Habitat Protection sites (odds ratio 3.585, $p = 0.0068$) and Conservation Park sites (odds ratio 6.366, $p = 0.020$). In addition, Marine National Park sites had significantly higher rates of WS than Habitat Protection sites (odds ratio 0.823, $p = 0.0246$) and Conservation Park sites (odds ratio 1.378, $p = 0.0125$). No other differences were statistically significant. As with overall disease rates, Commonwealth Island GBRMPA, Scientific Research Closed to the Public, and Commonwealth Island Other had too few observations to make reliable claims about differences in any particular disease frequency.

3.3. Relationship between shore location, fishing regulation, and presence of disease

The presence of coral disease was not predicted by whether sites were located inshore or offshore, with 9.02% of inshore sites exhibiting a disease of any kind, and 9.19% of offshore sites, $X^2(1) < 1$. There were no significant differences for BBD with 1.66% of inshore sites and 1.31% of offshore sites having samples with BBD, $X^2(1) = 2.72$, $p = 0.099$; for BrB with 3.05% < 1.72, $p = 0.099$; and for WS with 5.23% of inshore sites and 5.61% of offshore sites having samples with WS, $X^2(1) < 1$. However, there was a significant interaction for any disease between fishing regulation and shore location. As shown in Table 2, in offshore locations fishing regulations did not predict the presence of disease, but for inshore locations the incidence of any disease was significantly higher where there was no line fishing permitted at 11.52% than where line fishing was permitted at 7.92%, with the interaction of fishing regulation and shore location confirmed by

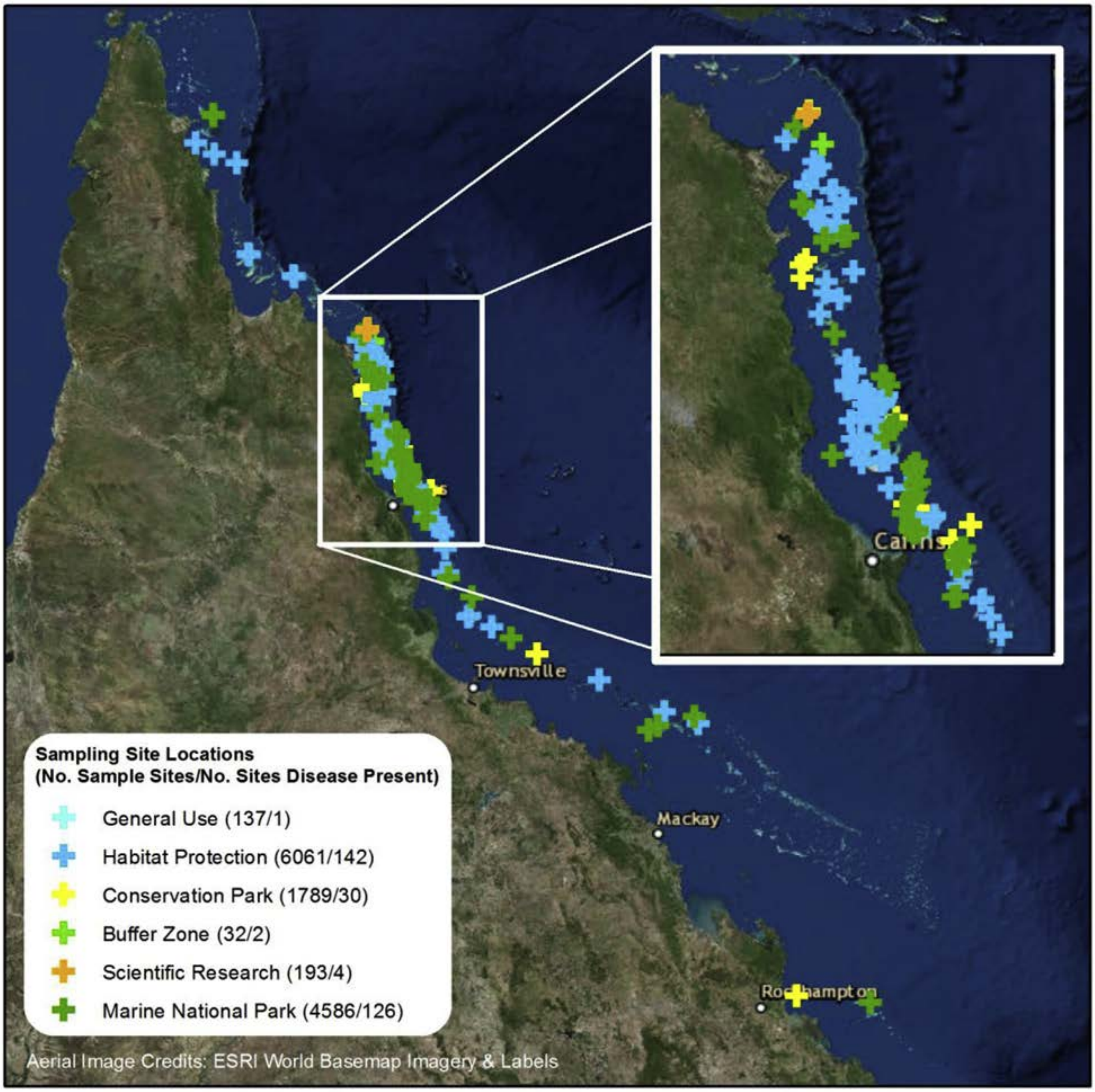

Fig. 5. Map displays the Great Barrier Reef in Australia including the Great Barrier Reef Marine Park Zones combined with the number of survey sites where BrB was observed affecting branching coral and recorded by participants on the GBRMPA, Eye on the Reef, RHIS. Base map: ESRI (2018).

logistic regression $X^2(1) = 10.53$, $p = 0.0012$. The same pattern holds for BBD with fishing regulations not predicting the presence of BBD offshore, but significantly higher rates of BBD inshore where line fishing was prohibited, 2.76%, than for inshore sites where fishing was permitted, 1.20%, the interaction from logistic regression $X^2(1) = 9.00$, $p = 0.0027$. We found a comparable result for WS with fishing regulations not predicting the presence of WS offshore, but significantly higher rates of WS inshore where line fishing was prohibited, 6.42%, than for inshore sites where fishing was permitted, 4.54%, the interaction from logistic regression was $X^2(1) = 4.51$, $p = 0.0336$. For BrB the interaction was not significant, $X^2(1) = 1.82$, $p = 0.18$.

3.4. Relationship between Park Management Zone and disease presence

There were significant differences in the prevalence of any type of coral disease in different Park Management Zones $X^2(7) = 175.47$, $p < 0.0001$ (see Table 3). Disease was most prevalent in the Cairns/Cooktown (Offshore) Park Management Zone, with logistic regression confirming that any disease found in 11.56% of these sites was significantly higher than any other zone, $X^2(1) = 1830.6$, $p < 0.0001$. Disease was least prevalent in the Mackay/Capricorn (Offshore) Park Management Zone, with logistic regression confirming that any disease found in 0.99% of sites was significantly lower than any other zone, $X^2(1) = 45.11$, $p < 0.0001$. Logistic regression also indicates that disease of any type was significantly more common in the Cairns/Cooktown (Inshore) Zone at 9.67% of sites than in the Townsville/Whitsunday (Inshore) Zone with 5.30% of sites having coral disease (odds ratio 0.5232, $p = 0.0003$), and in the Far Northeastern (Inshore) Zone with 4.87% of sites exhibiting disease (odds ratio 0.4785, $p = 0.0012$). Logistic regression demonstrates that disease of any type was significantly more frequent in the Mackay/Capricorn (Inshore) Zone, 9.41% of sites, than in the Far Northeastern (Inshore) with 4.87% of sites (odds ratio 0.4929, $p = 0.0075$). In the Far Northeastern (Offshore) Zone, 9.39% of sites had coral disease which was significantly

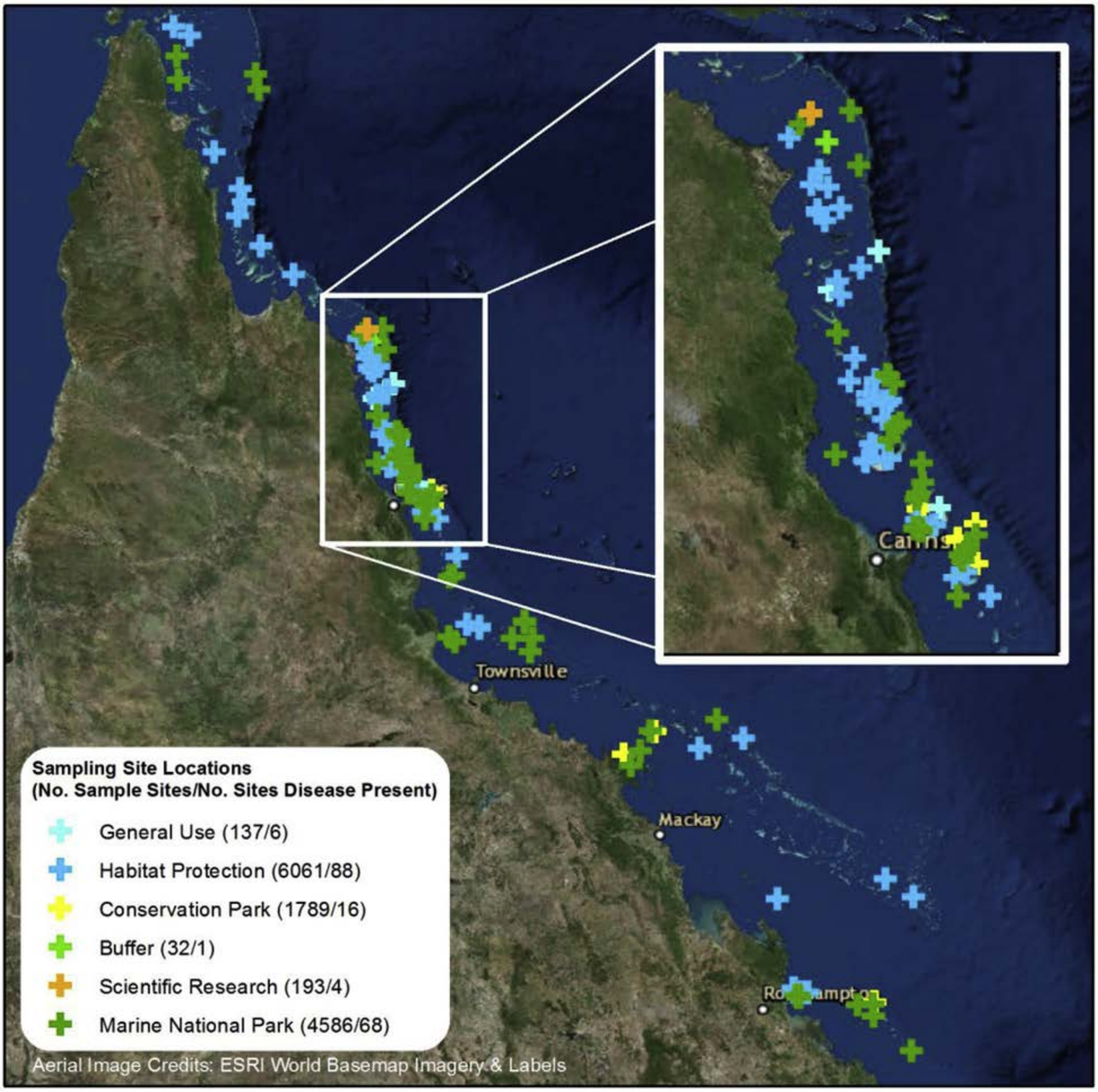

Fig. 6. Map displays the Great Barrier Reef in Australia including the Great Barrier Reef Marine Park Zones combined with the number of survey sites where WS was observed affecting branching coral and recorded by participants on the GBRMPA, Eye on the Reef, RHIS. Base map: ESRI (2018).

higher than for Townsville/Whitsunday (Inshore) with 5.30% (odds ratio 0.5403, p = 0.0142) and for Far Northeastern (Inshore) with disease present in 4.87% of sites (odds ratio 0.4941, p = 0.0147). No other differences were statistically significant for the presence of any disease.

Turning to specific coral diseases, logistic regression indicates that there were significant differences among sites for BBD among Park Management Zones, $X^2(7) = 97.92$, $p < 0.0001$ (see Table 3). Cairns/Cooktown (Offshore and Inshore) sites, with 2.05% and 2.12% exhibiting BBD respectively, were significantly more likely to exhibit BBD than all other sites except for Far Northeastern (Inshore) (which was of borderline significance) with $p < 0.01$ in each case (see Table 3). The Townsville/Whitsunday (Inshore) and Mackay/Capricorn (Offshore) zones had no sites with BBD, and were significantly different from all other sites, $p < 0.01$ in each case (see Table 3). No other differences in BBD were statistically significant. For BrB there were significant differences among Park Management Zones, $X^2(7) = 133.44$, $p < 0.0001$ (see Table 3). For BrB, Cairns/Cooktown (Offshore and Inshore) sites, with 4.06% and 3.85% exhibiting BrB respectively, were significantly more likely to exhibit BrB than all other sites with $X^2(1) = 49.88$ for Cairns/Cooktown (Inshore), $X^2(1) = 53.03$ for Cairns/Cooktown (Offshore), and $p < 0.0001$ in each case (see Table 3). Moreover, Far Northeastern (Offshore), Far Northeastern (Inshore), and Townsville/Whitsunday (Offshore) exhibited a significantly greater portion of sites with BrB than Mackay/Capricorn (Inshore or Offshore) or Townsville/Whitsunday (Inshore), $p < 0.01$ in each case (see Table 3). No other differences in BrB were statistically significant. For WS there were significant differences among Park Management Zones, $X^2(7) = 91.14$, $p < 0.0001$ (see Table 3). Mackay/Capricorn (Inshore) had the highest rate, with 9.13% of sites having WS, which was significantly higher than all other sites $X^2(1) = 29.48$, $p < 0.0001$ (see Table 3). Conversely, Mackay/Capricorn (Offshore) had the lowest rate, with 0.99% of sites having WS, which was significantly lower than all other sites $X^2(1) = 31.40$, $p < 0.0001$. In addition, Far Northeastern (Offshore)

Table 1
Percentage and ratio of sites with black band, brown band, white syndrome and disease by Marine Park Zone (note: site numerators do not sum to the numerator for all diseases because some sampling sites have more than one disease). Relationship between Marine Park Zone and Specific Presence of Disease.

Marine Park Zone	All Disease Percent and Ratio	Black Band Percent and Ratio	Brown Band Percent and Ratio	White Syndrome Percent and Ratio
General Use Line Fishing Permitted	13.14% (18/137)	1.46% (2/137)	1.46% (2/137)	11.68% (16/137)
Scientific Research Open to Public No Line Fishing	12.95% (25/193)	1.55% (3/193)	4.66% (9/193)	6.74% (13/193)
Commonwealth Island GBRMPA	11.11% (1/9)	0% (0/9)	11.11% (1/9)	11.11% (1/9)
Unspecified	10.56% (89/842)	0.71 (6/842)	1.43% (12/842)	8.67% (73/842)
Marine National Park No Line Fishing	10.14% (465/4586)	1.98% (91/4586)	3.12% (143/4586)	5.91% (271/4586)
Buffer No Line Fishing	9.38% (3/32)	0% (0/32)	6.25% (2/32)	9.38% (3/32)
Habitat Protection Line Fishing Permitted	8.56% (519/6061)	1.12% (68/6061)	3.18% (193/6061)	4.92% (289/6061)
Scientific Research Closed to Public No Line Fishing	7.69% (1/13)	0% (0/13)	0% (0/13)	7.69% (1/13)
Conservation Park Line Fishing Permitted	7.32% (131/1789)	1.68% (30/1789)	2.18% (39/1789)	4.36% (78/1789)
Preservation No Line Fishing	2.37% (5/211)	0.47% (1/211)	0.47% (1/211)	1.42% (3/211)
Commonwealth Island Other	0% (0/3)	0% (0/3)	0% (0/3)	0% (0/3)

with WS found in 7.28% of sites was significantly higher than Cairns/Cooktown (Inshore) with 4.80% of sites (odds ratio 0.643, p = 0338), and Townsville/Whitsunday (Inshore) with 5.12% of sites (odds ratio 0.4637, p = 0.175). Cairns/Cooktown (Offshore), with 6.39% of sites exhibiting WS, was significantly higher than Cairns/Cooktown (Inshore) with 4.80% (odds ratio 0.7395, p = 0.0012) and Far Northeastern (Inshore) with 3.44% of sites (odds ratio 0.5218, p = 0.0177). Townsville/Whitsunday (Offshore), with 6.13% of sites exhibiting WS, was significantly higher than Cairns/Cooktown (Inshore) with 4.80% of sites (odds ratio 0.7740, p = 0.0369) and Far Northeastern (Inshore) with 3.44% of sites (odds ratio 0.54588, p = 0.0360). No other differences in WS were statistically significant.

3.5. *Relationship between fishing regulations and disease presence*

Our final set of analyses was on the relationship between fishing regulations in all regions and the presence of disease of any type (BBD, BrB, and/or WS). We found significantly *fewer* samples affected by any disease in areas where line fishing was permitted than in those where line fishing was prohibited, $X^2(1) = 8.96$, p = 0.0028 with 8.36% of sites affected by disease in areas permitting fishing, and 9.91% of sites affected by disease in areas where line fishing was prohibited. Analyzed by the type of disease, for BBD we found significantly fewer samples affected by BBD in areas where fishing was permitted than in those where line fishing was prohibited, $X^2(1) = 8.235$, p = 0.0041 with 1.25% of sites affected by BBD in areas permitting fishing, and 1.89% of sites affected by BBD in areas where line fishing was prohibited. For BrB there was not a significant difference for fishing regulations with BrB present in 2.93% of sites with fishing permitted and 3.09% of sites where line fishing was prohibited, $X^2(1) = 0.235$, p = 0.63. Finally, for WS we found significantly fewer samples affected by WS in areas that permitted fishing than those where line fishing was prohibited, $X^2(1) = 4.67$, p = 0.0307 with 4.91% of sites affected by WS in areas permitting fishing, and 5.78% of sites affected by WS in areas where line fishing was prohibited.

4. Discussion

The prevalence of BBD, BrB, and WS on branching coral colonies within GBR Marine Park Zones that allowed line fishing did not appear higher than in zones that prohibited line fishing. However, direct-use activities have been known to cause injuries to coral colonies (Yoshikawa and Asoh, 2004), thereby leaving open wounds that could provide potential pathways for the spread of pathogens associated with disease (Aeby and Santavy, 2006). Moreover, Lamb et al. (2015) found an association with heavily fished areas and disease incidence in their study of the effects of no-take marine reserves on disease prevalence off the coast of Australia in the Whitsunday Islands. Their study included the use of belt transects to survey scleractinian coral colonies on fringing inshore reefs in Marine National Park, Habitat Protection, and Conservation Park zones for damage and disease presence (Lamb et al., 2015). Their findings indicated the prevalence of coral disease was lower in protected areas as compared to non-reserves (Lamb et al., 2015).

4.1. *Coral disease prevalence within protected zones*

The data showed a greater prevalence of branching coral infected with BBD, BrB, and WS in zones that prohibited line fishing within the GBR Marine Park. In comparison, Lamb et al.'s (2015) study found a greater incidence of corals exhibiting signs of injury and disease as well as lost, abandoned, and discarded fishing line in non-reserve sites with

Table 2
Percent and ratio of black band, brown band, white syndrome, and any disease present by fishing regulation and shore location (when known).

Fishing Regulation and Location	Any Disease Percent and Ratio	Black Band Percent and Ratio	Brown Band Percent and Ratio	White Syndrome Percent and Ratio
Line Fishing Permitted Inshore	7.92% (323/4078)	1.20% (49/4078)	2.97% (121/4078)	4.54% (185/4078)
Line Fishing Permitted Offshore	8.99% (344/3828)	1.32% (51/3828)	2.95% (113/3828)	5.38% (206/3828)
Line Fishing Prohibited Offshore	9.08% (253/2788)	1.29% (35/2788)	2.76% (77/2788)	5.52% (154/2788)
Line Fishing Prohibited Inshore	11.52% (246/2135)	2.76% (59/2135)	3.65% (78/2135)	6.42% (137/2135)

Table 3
Percent and ratio of black band, brown band, white syndrome, and any disease present by Park Management Zone.

Park Management Zone	All Disease Percent and Ratio	Black Band Percent and Ratio	Brown Band Percent and Ratio	White Syndrome Percent and Ratio
Cairns/Cooktown (Offshore)	11.56% (456/3945)	2.05% (818/3945)	4.06% (160/3945)	6.39% (252/3945)
Cairns/Cooktown (Inshore)	9.67% (475/4913)	2.12% (104/4913)	3.85% (189/4913)	4.80% (236/4913)
Mackay/Capricorn (Inshore)	9.41% (67/712)	0.14% (1/712)	0.28% (2/712)	9.13% (65/712)
Far Northeastern (Offshore)	9.39% (40/426)	0.47% (2/426)	1.88% (8/426)	7.28% (31/426)
Townsville/Whitsunday (Offshore)	8.48% (144/1698)	0.59% (10/1698)	1.94% (33/1698)	6.13% (104/1698)
Unspecified	6.79% (19/280)	0% (0/280)	0% (0/280)	6.79% (19/280)
Townsville/Whitsunday (Inshore)	5.30% (29/547)	0% (0/547)	0.37% (2/547)	5.12% (28/547)
Far Northeastern (Inshore)	4.87% (17/349)	0.86% (3/349)	1.72% (6/349)	3.44% (12/349)
Mackay/Capricorn (Offshore)	0.99% (10/1006)	0% (0/1006)	0.20% (2/1006)	0.99% (10/1006)

restrictions on fishing gear. Several factors may have contributed to the findings. This type of association may well be caused by individuals assuming abundant fish near the no-take areas and in some cases, access to the protected sites is not as difficult as to the non-reserve sites (Lamb et al., 2015). Furthermore, Bruno et al. (2007) suggested that protected regions may have an extensive amount of coral cover that could conceivably lead to greater colony exposure and density dependence. Another potential factor could be the result of larger populations of herbivorous species existing in no-take zones and grazing on coral colonies, thereby causing physical damage by creating open lesions and exposing the colonies to disease pathogens. Aeby and Santavy (2006) detected possible correlations between the appearance of herbivorous fish, corals exhibiting open wounds, and the transmission of BBD between coral colonies.

4.2. Coral disease prevalence within inshore areas

Inshore surveys where line fishing was prohibited not only reported a greater presence of BBD, but indicated that a larger number of coral colonies were affected by BrB and WS as well. According to Aeby et al. (2015), coral disease may be more likely to proliferate because of changes in water quality. Terrestrial run-off including the release of land-based contaminants and excessive nutrients may cause a deterioration in water quality (Aeby et al., 2015). Haapkylä et al. (2011) assessed the effects of increased amounts of rainfall and poor water quality on coral disease abundance on the GBR and found higher incidences of disease along the inshore reefs. However, these results are contrary to that of Page and Willis's (2006) study, which also took place on the GBR. Page and Willis (2006) reported a greater abundance of disease prevalence on mid-shelf reefs with high quality water as opposed to inshore sites that may have been affected by poor water quality.

4.3. RHIS participants

The results of the current study may well have been influenced by the various groups that performed the observational surveys. Two of the organizations monitored coral predator, *Acanthaster planci* (Crown-of-thorns starfish) (COTS) populations (C. Jones, personal communication, September 9, 2015). Hence, survey sites with signs of COTS outbreaks may indicate a greater abundance of coral exhibiting signs of disease because of the increased stress and injured coral colony communities.

4.4. Verifying coral disease prevalence

To gain a better and more precise understanding of coral disease, Ainsworth et al. (2007) concluded that investigations of coral disease should examine the microbial communities and histopathological changes in the coral tissue and cells in addition to macroscopic methods to correctly diagnose diseases. Furthermore, Bythell et al. (2002) concluded that histopathological investigations of micro-organisms associated with coral disease might signal a gradual advancement of BBD. Although this report did not include microscopic examinations of tissue samples, performing cytological, microbial, and physiological assays on corals visually displaying signs of disease could verify the presence of disease (Ainsworth et al., 2007).

The current study did not find that coral disease is more likely to affect colonies of branching coral in management zones that allow fishing. However, the study did bring attention to the crucial need for further global-wide investigations on the specific driving factors and triggers responsible for accelerated incidences of disease on reef-building corals.

4.5. Shortcomings and limitations

First, the RHIS methodology changed around 2009 and so there may not be a direct “apples to apples” comparison of data collected between these periods. However, our statistical approach of assessing the presence or absence of disease, rather than quantifying it, should mitigate against some methodological differences. Second, many RHIS studies were conducted in response to cyclones to assess damage directly after the event and to specifically assess longer term effects, including coral disease, at longer time intervals. Because physical damage from cyclones can result in coral tissue injuries (Beeden et al., 2015) and knowing that the RHIS was used to assess the degree of disease outbreaks, such RHIS surveys may be more likely to have disease recorded. Thus, the absolute magnitude of disease in the samples we used may be different from a truly random sample collected in an ideal study.

Given that a single operator conducted most of RHIS at targeted COTS culling sites, we further analyzed the data excluding observations made by that operator, and data collected before 2010. Using a restricted data set with just 273 observations we looked at each of the research questions analyzed above. There were no cases of BBD or BrB in the reduced sample, and just 19 cases of WS, meaning that WS was present on about 7% of the locations. The relationship between WS and other variables was not significant. Thus, we cannot completely dismiss the possibility that the effects seen in our data are due to some kind of artifact.

5. Conclusions

This present study produced concerns over the threats of disease and stressors to coral reef colonies in addition to highlighting the importance of understanding and identifying the sources of threats. Whether escalations in the incidence of coral diseases are related to increased levels of human activities, environmental degradation, intensifying storms, climate change, warming ocean waters or seasonal weather patterns, different methods for surveillance may be worth exploring when designing new studies that involve monitoring diseases of coral communities.

Continued surveillance and monitoring the incidence, causes, and effects of disease in branching coral is essential. Furthermore, recording detailed information at the survey sites on existing trends, conditions, the extent of coral mortality and possible environmental triggers is highly recommended. Thus, when collecting and analyzing data in future studies, taking account of factors such as extreme wind and weather events, survey depth, visibility, air and water temperatures, and tidal flow, as well as any indications of flood plumes and suspended algal blooms occurring near the monitoring sites could prove to be beneficial considerations. Also, experimenting with the use of stationary underwater video camera transect stations may aid in tracking the movement and determine the causes and frequency of disease occurrences in various GBR Marine Park Management Zones. Moreover, an increase in long-term studies on the spatial and temporal distribution of coral community diseases could potentially lead to discovering intervention strategies and accelerating management efforts and approaches to disease, as well as finding new ways to protect and prevent corals from recurring disease infections and mortality. Developing capabilities to identify and mitigate the potential for human-influences on the susceptibility of coral to disease might ultimately lead to more resilient coral communities and avoid a worldwide coral reef ecosystem crisis.

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This post-graduate research project comparing coral disease prevalence between Marine National Park Zones and General Use Zones as recorded by the RHIS method incorporates data which is ©Commonwealth of Australia 2015 (Great Barrier Reef Marine Park Authority).

The data has been used in the Post-graduate research project comparing coral disease prevalence between Marine National Park Zones and General Use Zones as recorded by the RHIS method with the permission of the Great Barrier Reef Marine Park Authority on behalf of the Commonwealth. The Great Barrier Marine Park Authority has not evaluated the data as altered and incorporated within the Post-graduate research project comparing coral disease prevalence between Marine National Park Zones and General Use Zones as recorded by the RHIS method and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose and no liability is accepted (including without limitation, liability in negligence) for any loss, damage or costs (including consequential damage) relating to any use of the data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2018.09.005.

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