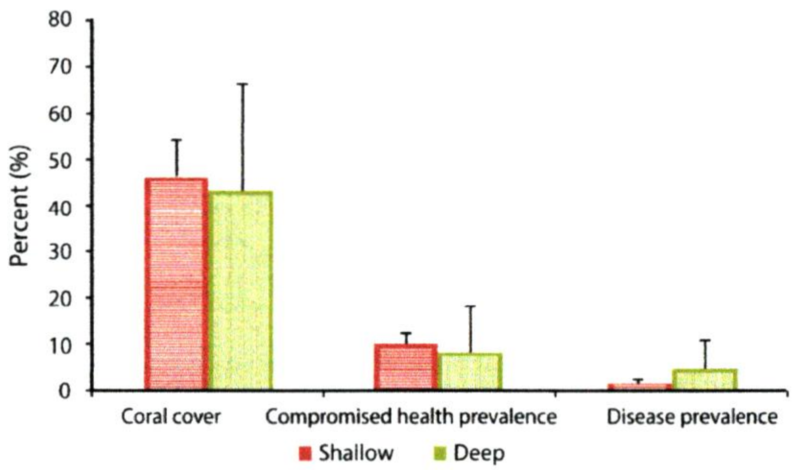

Fig 5. Comparison of coral cover (%), signs of compromised health (%), and disease prevalence (%) between a deep and shallow site at Barranglompo Island, Spermonde Archipelago, based on preliminary surveys of coral health conducted in October 2011 (n=3 transects at the deep site, n=2 transects at the shallow site). The error bars represent standard deviation.

prevalence, coral disease prevalence: Z=0, n_1=3, n_2=2, p=1.0; statistical results for each variable were the same). Since there were no significant differences between depths, the data were pooled for subsequent analyses. Overall, prevalence of compromised health signs was not significantly different than coral disease prevalence, although the average prevalence of compromised health from both depths was higher than coral disease prevalence (deep: 9.6% ± 2.7; shallow: 8.2% ± 9.9; t= -2.19, df=8, p=0.06; Fig. 5). Coral cover was relatively high at both depths, with the deep site having an average of 46.4 % (± 8.2) coral cover and the shallow site having an average of 43.6% (± [illegible]2) coral cover (Fig. 5).

A total of five coral diseases were observed during the surveys: skeletal eroding band (SEB), atramentous necrosis (AtN), white syndromes (WSs), brown band (BrB), and growth anomalies (GA) (see Fig. 6). The most common disease was WSs, observed on 42 coral colonies from 13 coral genera. Interestingly, 28 of these cases were found within a single transect, which is indicative of an infectious disease when susceptible host density is high. The other four diseases were much less common and observed on less than five individual coral colonies. Several different conditions that indicated compromised coral health were also observed. The most common conditions observed were algal overgrowth, patchy bleaching, cuts and scars, and pigmentation response (for examples see Fig. 6).

The informal surveys conducted in WNP showed high levels of a yellow tissue discoloration syndrome, similar in appearance to Caribbean yellow band disease, on *Diploastrea* (Fig. 7A). Although the syndrome was not reported in previous surveys, it had been observed in 2010 (J. Haapkylä, pers. observ). Other diseases observed around Hoga Island included black band disease, growth anomalies, skeletal eroding band, and white syndromes (for examples see Fig. 7). Patchy bleaching, a sign of compromised coral health, was also observed.

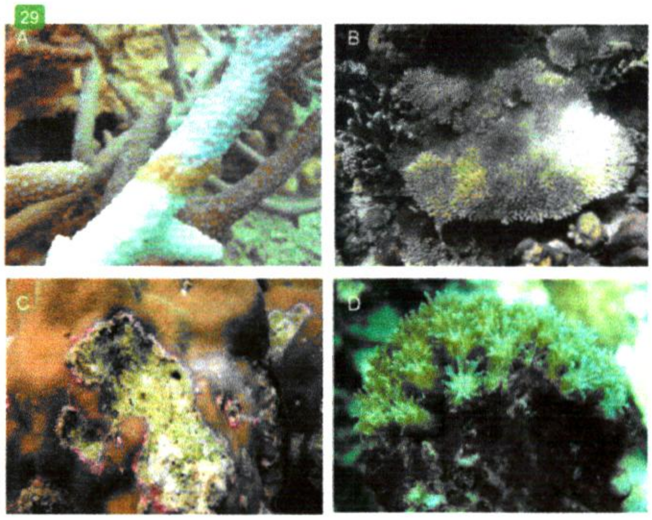

Fig 6. Images of coral diseases (A,B) and corals with compromised health (C,D) observed around Barranglompo reefs. A: brown band disease on branching *Acropora* sp. B: a white syndrome on *Acropora* sp. C: pigmentation response on *Porites* sp., and D: *Galaxea* sp. being overgrown by cyanobacteria. Photos by L. Raymundo (A,B), D. Harvell (C) and B. Willis (D).

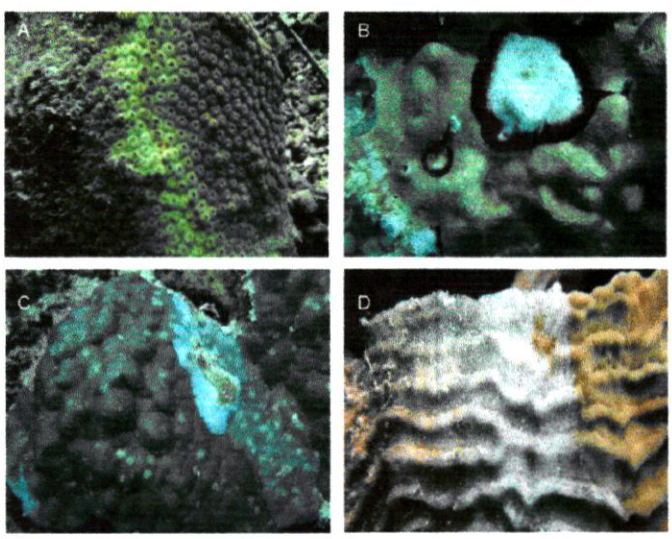

Fig 7. Images of coral diseases observed around Wakatobi National Park. A: yellow tissue discoloration on Diploastrea sp. B: black band disease on Pavona sp. C: growth anomaly on Porites sp., and D: skeletal eroding band on Pachyseris sp. Photos by D. Harvell.

DISCUSSION

Indonesian coral reefs lie within the Coral Triangle, the center of coral reef global biodiversity. Further, the Indonesian island system contains the second largest reefal surface area in the world (42,000 sq km; Bryant et al., 1998). As such, these reefs are of critical biological, cultural, and ecological importance. These very preliminary surveys of coral health indicate that even reefs in fairly impacted waters like Spermonde Archipelago have relatively low levels of coral disease. However, there are significant coral diseases present, all of which have been described from other reefs in the Indo-Pacific region, making this a critical time for completing baseline surveys.

Many of the local conditions that facilitate coral disease in other locations (for example, Philippines: Kaczmarsky et al., 2005; Garren et al., 2009; Great Barrier Reef, Australia: Lamb and Willis, 2011; Caribbean: Sutherland et al., 2010, 2011) are also impacting reefs within Indonesia, such as increasing tourism pressure, discharge of human sewage into coastal waters, aquaculture in near shore waters, eutrophication from land-based sources, and sedimentation from deforestation (Burke et al., 2011). In addition to these local factors, significant levels of bleaching occurred in 1998 and 2010. Warming events are predicted to increase some coral diseases (Bruno et al., 2007; Selig et al., 2006; Maynard et al., 2011). Fifteen years of monitoring data (1995-2010) on coral reef condition in the Spermonde Archipelago indicate that coral bleaching has only occurred in the last few years, and was especially significant in 2010 (Jompa and Yusuf, 2010). This monitoring program indicates that the average bleaching prevalence in the archipelago was around 15%, and bleaching typically spread from reef flats to slopes, with the most intense coral bleaching observed between 3–10 m depth. Seawater temperatures during the year of the bleaching event were around 2.37°C warmer (during April-May 2010; Fig. 8) than average yearly seawater temperatures around the Spermonde Archipelago, 29.08°C (Jompa and Yusuf, 2010). The higher prevalence of WSs than other diseases found in our 2011 Barranglompo surveys may partially reflect the impact of accumulated temperature stress on coral resistance to WSs (see Maynard et al., 2011). Furthermore, although coral disease prevalence was relatively low within the sites surveyed, atramentous necrosis and several cases of yellow tissue discolouration were observed in 2011 but not in the 2005 and 2007 surveys (Haapkylä et al., 2007, 2009). These results may be the first signs of an increasing impact of coral diseases in Indonesia.

Management of coral disease is in its early stages, though the urgency of the problem, in light of continuing coral loss, demands that strategies be developed (e.g. Beeden et al., 2012). Techniques to stop coral disease progression on infected colonies have been attempted on limited scales, including aspirating black band cyanobacterial mats from active lesions and then covering the lesion with epoxy (Raymundo et al., 2008) and phage therapy for known bacterial diseases (Efrony et al., 2007). Other possible methods to reduce the spread of coral disease among reefs may involve the quarantine of reefs where outbreaks are in progress and the potential removal of organisms acting as disease vectors when disease is highly prevalent (reviewed in Beeden et al., 2012). However, all of these approaches are labor- or resource-intensive and none have been attempted with any success on a large spatial scale. Given what we are learning about the role of water quality in coral health (Bruno et al., 2003; Kaczmarsky, 2006; Voss and Richardson, 2006; Garren et al., 2009), a logical first step is to improve water quality by reducing anthropogenic inputs into nearshore marine systems. This approach simply relies on the principle that corals growing in clean water will be under less stress than those growing in contaminated, high-nutrient, high-turbidity water. This will allow corals to develop and maintain strong defense and immune responses when they are exposed to pathogens. In addition,

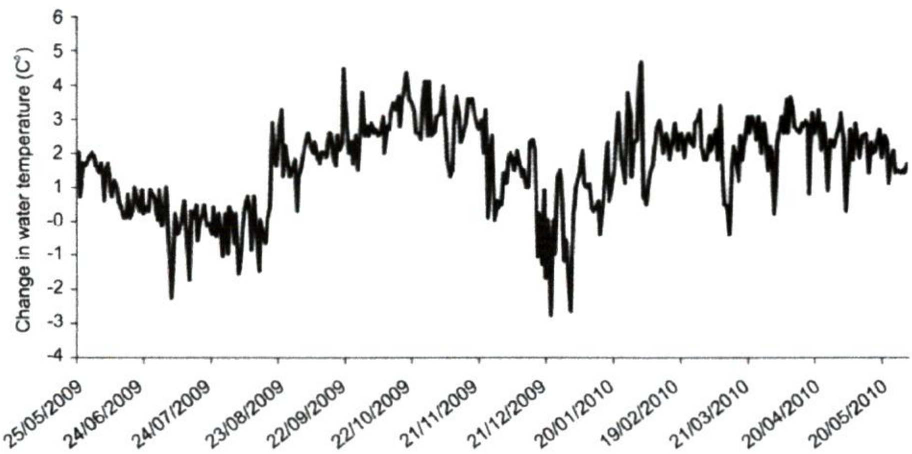

Fig 8. Annual pattern in the difference between daily seawater temperatures from 2009–2010 and average seawater temperatures taken over the past 15 years (1995–2010) in the Spermonde Archipelago (daily temperatures measured manually at Badi Island, Spermonde Archipelago; Yusuf et al., 2010).

increasing inputs of terrestrial bacteria, viruses and other potential pathogens (for example from aquaculture, Garren et al., 2009) may activate emerging diseases in organisms in the marine environment that were previously unexposed to these microorganisms (Mydlarz et al., 2006). In a clean, healthy environment, progression and severity of disease within host colonies, and transmissibility of disease to nearby susceptible hosts, is predicted to be lower than on reefs with similar coral communities where water quality is declining. By improving conditions at sites where coral cover has been greatly reduced by poor water quality, corals may show improved survival and recruitment. Well-constructed studies to test this hypothesis are needed to determine the efficacy of this approach as a management strategy for coral disease.

Another strategy which provides hope for managing coral diseases is the establishment of Marine Protected Areas. New studies suggest that functioning and enforced no-take MPAs, with an intact complement of fish, are associated with lower levels of coral disease (Raymundo et al., 2009; Page et al., 2009). In both the Philippines and Palau, low prevalence of coral disease was associated with high fish diversity (both functional and taxonomic diversity). In the Philippines, levels of coral diseases were lower in MPAs than their paired fished counterpart reefs. At each of these surveyed reefs, low abundance of corallivorous butterflyfishes was most strongly associated with both high fish diversity and low coral disease prevalence (Raymundo et al., 2009). The mechanisms by which this effect may operate are still under study, but likely involve both direct and indirect interactions between corals, potential vectors of disease, and microbes that cause disease. Reefs that are not harvested have intact communities with innate population-regulating mechanisms; on heavily fished reefs, some fish functional groups are completely eliminated, leaving certain community functions unfilled. Other organisms may undergo rapid increases, such as certain algal groups that are no longer kept in check via herbivory or smaller fish or invertebrates that are not controlled via predation. Sweatman (2008), for instance, found fewer outbreaks of the crown-of-thorns starfish (*Acanthaster planci*) within Australian MPAs. Again, the mechanism was not elucidated, but the author speculated that this effect of MPAs may be due to a cascade effect, which begins with protection of large predatory fish and results in increased predation on juvenile COTS by benthic invertebrates. It is likely that the overall effect of functionally complete marine communities on coral health will have multiple mechanisms, depending on the unique etiology of each disease. These mechanisms may involve a variety of organisms, including microbial communities (e.g. Dinsdale et al., 2008), which may interact with corals as pathogens, food sources or habitat, and the effects are likely to be indirect and complex. However, while elucidating these mechanisms is necessary for understanding and managing individual diseases, establishing and maintaining MPAs is a feasible management strategy for promoting overall coral health and limiting disease impacts. The newly established MPAs as part of the Coral Reef Rehabilitation and Management Program (COREMAP) may well increase coral health and resilience, as well as allowing fish populations to recover from over-fishing.

CONCLUSION

The preliminary data from this study show that levels of coral disease prevalence at the sites surveyed in Sulawesi were relatively low. However, surveys in WNP over several years indicate that the number of coral diseases may be increasing and that progression rates of diseases are comparable to rates found in the Caribbean and on the GBR. Furthermore, as the oceans continue to warm and pollution to the marine environment increases, coral diseases will likely become more prevalent. More comprehensive baseline surveys of coral health are needed to provide data on coral disease increases in cases of declining environmental quality, as well as coral disease decreases in response to improved management practices. Indonesia, with its extensive reefs of high biodiversity, coupled with high population densities and intensive harvesting of marine resources, should be a primary focus for disease research efforts in the future.

Acknowledgements

We would like to thank COREMAP, Jamaluddin Jompa, Muhammad Lukman, Marea Hatziolis and all of the participants in the first Indonesia coral disease workshop, especially those that helped collect the data presented in this manuscript including Muhammad Abrar, Beginer Subhan, Sadarun, Ofri Johan, Dondy Arafat, Awaludinnoer, Ranalse Patiung, Suharto, Erwin Murdiyanto, Dedi Parenden, Nurliah Buhari, Radhiyah, Arniati Massinai, Pieter Manihin, Syamsul, Nirwan, and Aidah A. A. Husain. CDH, LJR and EMM were funded by NSF Int Programs OCE-1145070. EMM was also funded by a Mote Postdoctoral Fellowship.

REFERENCES

Aeby, G.S. and Santavy, D.L. 2006. Factors affecting susceptibility of the coral *Montastraea faveolata* to black-band disease. Mar. Ecol. Prog. Ser., 318: 103–110.

Aronson, R.B. and Precht, W.F. 2001. White-band disease and the changing face of Caribbean coral reefs. Hydrobiologia, 460: 25–38.

Beeden, R., Maynard, J.A., Marshall, P.A., Heron, S.F., and Willis, B.L. 2012. A framework for responding to coral disease outbreaks that facilitates adaptive management. Environmental Management, 49: 1–13.

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

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

Bruno, J.F. and Selig, E.R. 2007. Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. PloS ONE, 2(8): e711. doi:10.1371/ journal. pone.0000711.

Bruno, J.F., Selig, E.R., Casey, K.S., Page, C.A., Willis, B.L., Harvell, C.D., Sweatman, H., and Melendy, A.M. 2007. Thermal stress and coral cover as drivers of coral disease outbreaks. PLoS Biol., 5(6): e124. doi:10.1371/journal.pbio.0050124.

Bryant, D., Burke, L., McManus, J., and Spalding, M. 1998. Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs. World Resources Institute, Washington, DC. 56 p.

Burke, L., Reytar, K., Spalding, M., and Perry, A. 2011. Reefs at Risk Revisited. World Resources Institute, Washington, DC. 116 p.

Dinsdale, E.A., Pantos, O., Smirga, S., Edwards, R.A., Angly, F., Wegley, L., Hatay, M., Hall, D., Brown, E., Haynes, M., Krause, L., Sala, E., Sandin, S.A., Thurber, R.V., Willis, B.L., Azam, F., Knowlton, N., and Rohwer, F. 2008. Microbial ecology of four coral atolls in the Northern Line Islands. PloS ONE, 3(2): e1584. doi:10.1371/journal.pone.0001584.

Efrony, R., Loya, Y., Bacharach, E., and Rosenberg, E. 2007. Phage therapy of coral disease. Coral Reefs, 26: 7–16.

Garren, M., Raymundo, L., Guest, J., Harvell, C.D., and Azam, F. 2009. Resilience of coral-associated bacterial communities exposed to fish farm effluent. PLoS ONE, 4(10): e7319. doi:10.1371/journal.pone.0007319.

Haapkylä, J., Seymour, A.S., Trebilco, J., and Smith, D. 2007. Coral disease prevalence and coral health in the Wakatobi Marine Park, South-East Sulawesi, Indonesia. J. Mar. Biol. Ass. UK, 87: 403–414.

Haapkylä, J., Unsworth, R.K.F., Seymour, A.S., Melbourne-Thomas, J., Flavell, M., Willis, B.L., and Smith, D.J. 2009. Spatio-temporal coral disease dynamics in the Wakatobi National Park, South-East Sulawesi, Indonesia. Dis. Aquat. Org., 87: 105–115.

Haapkylä, J., Melbourne-Thomas, J., Flavell, M., and Willis, B. 2010. Spatiotemporal patterns of coral disease prevalence on Heron Island, Great Barrier Reef, Australia. Coral Reefs, 29(4): 1035–1045.

Haapkylä, J., Unsworth, R.K.F., Flavell, M., Bourne, D., Schaffelke, B., and Willis, B.L. 2011. Seasonal rainfall and runoff promote coral disease on an inshore reef. PLoS ONE, 6(2): 1–10.

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

Harvell, C.D., Jordan-Dahlgren, E., Merkel, S., Rosenberg, E., Raymundo, L., Smith, G., Weil, E., and Willis, B. 2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. Oceanograpy, 20: 172–195.

Harvell, C.D., Altizer, S., Cattadori, I.M., Harrington, L., and Weil, E. 2009. Climate change and wildlife diseases: When does the host matter the most? Ecology, 90: 912–920.

Hughes, T.P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science, 265: 1547–1551.

Jompa, J. and Yusuf, S. 2010. First record of relatively severe coral bleaching in the Spermonde Archipelago, South Sulawesi, Indonesia: Potential consequences and management challenges. International of Small Island and Coral Reef Symposium, Ambon Indonesia, August 2010.

Kaczmarsky, L.T., Draud, M., and Williams, E.H. 2005. Is there a relationship between proximity to sewage effluent and the prevalence of coral disease? Caribb. J. Sci., 41: 124–137.

Kaczmarsky, L. 2006. Coral disease dynamics in the central Philippines. Diseases of Aquatic Organisms, 69: 9–21.

Lamb, J.B. and Willis, B.L. 2011. Using coral disease prevalence to assess the effects of concentrating tourism activities on offshore reefs in a tropical marine park. Conservation Biology, 5: 1044–1052.

Lesser, M.P., Bythell, J.C., Gates, R.D., Johnstone, R.W., Hoegh-Guldberg, O. 2007. Are infectious diseases really killing corals? Alternative interpretations of the experimental and ecological data. J. Exp. Mar. Biol. Ecol., 346: 36–44.

Maynard, J.A., Anthony, K.R.N., Harvell, C.D., Burgman, M.A., Beeden, R., Sweatman, H., Heron, S.F., Lamb, B., and Willis, B.L. 2011. Predicting outbreaks of a climate-driven coral disease in the Great Barrier Reef. Coral Reefs, 30: 485–495.

McClanahan, T.R. 2004. Coral bleaching, diseases and mortality in the western Indian Ocean, in: Rosenberg, E. and Loya, Y. (Eds.), Coral Health and Disease. Springer-Verlag, Berlin-Heidelberg-New York. Pp. 157–176.

Miller, J., Waara, R., Muller, E., and Rogers, C. 2006. Coral bleaching and disease combine to cause extensive mortality on reefs in US Virgin Islands. Coral Reefs, 25: 418.

Morrow, K.M., Paul, V.J., Liles, M.R., and Chadwick, N.E. 2011. Allelochemical produced by Caribbean macroalgae and cyanobacteria have species-specific effects of reef coral microorganisms. Coral Reefs, 30: 309–320.

Muller, E.M., Rogers, C.S., Spitzack, A.S., and van Woesik, R. 2008. Bleaching increases likelihood of disease on *Acropora palmata*

(Lamarck) in Hawksnest Bay, St. John, US Virgin Islands. Coral Reefs, 27: 191–195.

Mydlarz, L.D., Jones, L.E., and Harvell, C.D. 2006. Innate immunity, environmental drivers, and disease ecology of marine and freshwater invertebrates. Annu. Rev. Ecol. Syst., 37: 251–288.

Myers, R.L. and Raymundo, L.J. 2009. Coral disease in Micronesian reefs: a link between disease prevalence and host abundance. Dis. Aquat. Org., 87: 97–104.

Nugues, M.M., Smith, G.W., Hooidonk, R.J., Seabra, M.I., and Bak, R.P.M. 2004. Algal contact as a trigger for coral disease. Ecol. Lett., 7: 919–923.

Page, C.A., Baker, D.M., Harvell, C.D., Golbuu, Y., Raymundo, L., Neale, S.J., Rosell, K.B., Rypien, K.L., Andras, J.P., and Willis, B.L. 2009. Influence of marine reserves on coral disease prevalence. Dis. Aquat. Org., 87: 135–150.

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

Raymundo, L., Rosell, K., and Reboton, C. 2005. Coral diseases on Philippine reefs: genus *Porites* is a dominant host. Diseases of Aquatic Organisms, 64: 181–191.

Raymundo, L., Couch, C., and Harvell, C. (Eds). 2008. Coral Disease Handbook: Guidelines for Assessment, Monitoring and Management. Currie Communications, Melbourne, Australia.

Raymundo, L., Halford, A., Maypa, A., and Kerr, A. 2009. Functionally-diverse reef fish communities ameliorate coral disease. PNAS, 106: 1767–1770.

Richardson, L.L. 1998. Coral diseases: what is really known? Trends Ecol. Evol., 13: 438–443.

Ritchie, K. 2006. Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. Mar. Ecol. Prog. Ser., 322: 1–14.

Rogers, C., Muller, E., Spitzack, A., and Miller, J. 2009. The future of coral reefs in the US Virgin Islands: Is *Acropora palmata* more likely to recover than Montastraea annularis complex? Proc. 11th Int. Coral Reef Symp., 1: 226–230.

Ruiz-Moreno, D., Willis, B.L., Page, C.A., Weil, E., Croquer, A., Vargas-Angel, B., Jordan-Garza, A.G., Jordán-Dahlgren, E., Raymundo, L., and Harvell, C.D. In review. Global coral disease prevalence associated with sea temperature anomalies and local factors. Dis. Aquat. Org.

Sato, Y., Bourne, D.G., and Willis, B.L. 2009. Dynamics of seasonal outbreaks of black band disease in an assemblage of *Montipora* species at Pelorus Island (Great Barrier Reef, Australia). P. Roy. Soc. Lond. B. Bio., 276: 2795–2803.

Sato, Y., Bourne, D.G., and Willis, B.L. 2011. Effects of temperature and light on the progression of black band disease of the reef coral, *Montipora hispida*. Coral Reefs, 30: 753–761.

Selig, E.R., Harvell, C.D., Bruno, J.F., Willis, B.L., Page, C.A., Casey, K., and Sweatman, H. 2006. Analyzing the relationship between ocean temperature anomalies and coral disease outbreaks at broad spatial scales, in: Phinney, J., Hoegh-Guldberg, O., Kleypas, J., Skirving, W., Strong, A. (Eds.), Coral Reefs and Climate Change: Science and Management. American Geophysical Union, Washington DC. Pp. 111–128.

Smith, J.E., Shaw, M., Edwards, R.A., Obura, D., Pantos, O., Sala, E., Sandin, S.A., Smriga, S., Hatay, M., and Rohwer, F.L. 2006. Indirect effects of algae on coral: algae-mediated, microbe-induced coral mortality. Ecol. Lett., 9: 835–845.

Sutherland, K.P. and Ritchie, K.B. 2004. White pox disease of the Caribbean elkhorn coral, *Acropora palmata*, in: Rosenberg, E., Loya, Y. (Eds.), Coral Health and Disease. Springer-Verlag, Berlin-Heidelberg-New York. Pp. 289–300.

Sutherland, K.P., Porter, J.W., Turner, J.W., Thomas, B.J., Looney, E.E., Luna, T.P., Meyers, M.K., Futch, J.C., and Lipp, E.K. 2010. Human sewage identified as likely source of white pox disease of the threatened Caribbean elkhorn coral, *Acropora palmata*. Environ. Microbiol., 12: 1122–1131.

Sutherland, K.P., Shaban, S., Joyner, J.L., Porter, J.W., and Lipp, E.K. 2011. Human pathogen shown to cause disease in the threatened elkhorn coral *Acropora palmata*. PLoS ONE, 6(8): e23468. doi:10.1371/journal.pone.0023468

Sweatman, H. 2008. No-take reserves protect coral reefs from predatory starfish. Current Biology, 18: R598–R599.

Toren, A., Landau, L., Kushmaro, A., Loya, Y., and Rosenburg, E. 1998. Effect of temperature on adhesion of *Vibrio* strain AK-1 to *Oculina patagonica* and on coral bleaching. Appl. Environ. Microbiol., 64: 1379–1384.

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

Weil, E. 2004. Coral diseases of the wider Caribbean, in: Rosenburg, E., Loya, E. (Eds.), Coral Health and Disease. Springer-Verlag, Berlin-Heidelberg-New York. Pp. 35–68.

Weil, E., Smith, G., and Gil-Agudelo, D.L. 2006. Status and progress in coral reef disease research. Dis. Aquat. Org., 69: 1–7.

Weil, E., Croquer, A., and Urreiztieta, I. 2009. Temporal variability and impact of coral diseases and bleaching in La Parguera, Puerto Rico from 2003-2007. Carib. J. Sci., 45: 221–246.

Weil, E., Irikawa, A., Casareto, B., and Suzuki, Y. In press. Extended geographic distribution of several Indo-Pacific coral diseases. Dis. Aquat. Org.

Willis, B.L., Page, C.A., and Dinsdale, E.A. 2004. Coral disease on the Great Barrier Reef, in: Rosenberg, E., Loya, Y. (Eds.), Coral Health and Disease. Springer-Verlag, Berlin-Heidelberg-New York. Pp. 69–104.

Yusuf, S., Rani, C., and Jompa, J. 2010. Coral bleaching phenomenon on 2009 in Badi Island reef, Makassar Strait. Indonesian Fisheries and Marine Science Meeting and Seminar VII, Gajahmada University, Yogyakarta, 24 July 2010.