Chapter 4

# Diseases of Scleractinian Corals

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## 4.1 Introduction

There is a large diversity of coral species, with over 1,300 extant species in the order Scleractinia (phylum Cnidaria, class Anthozoa; World Register of Marine Species (WoRMS)). The Scleractinia (stony corals) represent the ecological framework builders of modern coral reefs, providing habitat and refuge for countless other marine species that inhabit coral reef ecosystems As ecosystem engineers, corals provide important goods and services that are both ecologically and economically important, including sustaining high biodiversity, protecting coastlines, supporting fisheries, and contributing an estimated US$ 36 billion to the global economy directly from tourism-based industries (Spalding et al. 2017).

### 4.1.1 Coral biology, ecology, and microbiology

Corals build colonies by modular additions of single polyps to achieve complex morphologies. Within the Scleractinia, polyps are monomorphic (with the exception of the genus *Acropora*), and all perform the same functions, including deposition of calcium carbonate, feeding, and reproduction. Modular colonial organisation of corals allows for the unique capability of sharing resources among polyps through the connective tissue (coenosarc), responding to environmental cues across a colony, and allowing a coral animal to experience partial mortality. Within the Scleractinia, symbiosis with unicellular photosynthetic dinoflagellates belonging to the family Symbiodinaceae is a common characteristic (LaJeunesse et al. 2018) and underpins the coral animal's success in oligotrophic waters.

Symbiodiniaceae cells are situated within the coral gastrodermal layer and are particularly abundant in gastrodermal cells adjacent the free body wall epidermis. Photosynthesis by these symbionts contributes to coral metabolism by translocating fixed carbon to coral animal cells, providing a significant proportion of their nutritional needs. Additionally, algal photosynthesis requires sunlight, and therefore this symbiosis plays an important role in determining the depth distribution of coral species.

An array of other microbial communities has been demonstrated to be associated with corals, including bacteria, Archaea, fungi, and viruses (reviewed in Bourne et al. 2016b). Collectively, this consortium of host and microbial cells has been termed the coral holobiont, with the stability of the microbiome linked to whole organism health. In addition to the coral host's immune defences (i.e. antioxidant production and melanisation processes; see Chapter 1 for further details), coral-associated microbial communities are likely involved in coral immunity either directly through production of antimicrobial compounds (Ritchie 2006) or indirectly through niche exclusion of opportunistic or pathogenic organisms (Rosenberg et al. 2007; Shnit- Orland and Kushmaro 2009). While some microbial taxa are directly linked to disease onset (Sweet and Bulling 2017), disturbance of the coral host's normal microbial community composition (i.e. dysbiosis) can induce disease or disease-like signs (Egan and Gardiner 2016; Sweet and Bulling 2017).

The coral holobiont is well studied, and in particular the delicate symbiosis between the coral animal and Symbiodiniaceae, with environmental stress (particularly temperature increases) resulting in a breakdown of this partnership and ejection of Symbiodiniaceae cells from the coral tissues (termed bleaching). Climate driven ocean warming is the biggest threat to coral reefs globally (Hughes et al. 2017a), pushing corals and their relationship with Symbiodiniaceae above their thermal threshold, leading to sub-optimal coral health and increased incidence of bleaching and disease (Hoegh-Guldberg et al. 2017). Severe mass bleaching events can result in mass coral mortality, and subsequent extensive impacts on reef ecosystems, with these impacts predicted to be exacerbated under future climate scenarios (Hughes et al. 2017b). Synergy between heat stress, bleaching, and disease has been repeatedly demonstrated, leading to further concerning reduction in coral cover globally (Brodnicke et al. 2019). Combined with localised impacts including eutrophication, overfishing, and coastal development, reefs globally are in a precarious predicament.

### 4.1.2 Coral disease background

Black band disease (BBD) was identified in the early 1970's in the Caribbean through the work of Antonius (1973). BBD is often described as the first coral disease to be identified, though descriptions of growth anomalies (GA) on corals were reported a decade earlier (Squires 1965). Since those early studies of rare occurrences of diseased colonies (Antonius 1973), coral disease has increased in terms of prevalence, diversity of disease types, and impacts on coral communities and reefs. Initial studies of coral disease focussed on Caribbean corals, in part

due to the detection of novel diseases and significant disease outbreaks in this region (Gladfelter 1982; McClanahan and Muthiga 1998; Williams et al. 1999). Disease mediated declines in *Acropora palmata* and *Acropora cervicornis* have been so dramatic throughout their Caribbean range that these species were nominated for inclusion in the United States' endangered species register (Diaz-Soltera 1999). In part due to disease outbreaks, Caribbean acroporid corals are now rare on reefs on which they had previously been the dominant coral taxa for at least 95,000 years (Pandolfi and Jackson 2006).

Until more recently, coral disease was thought to occur only rarely and have little impact on the function of Indo-Pacific corals and coral reefs (reviewed in Sutherland et al. 2004). Significant disease outbreaks have, however, now been recorded from numerous Indo-Pacific regions (Antonius 1999; Willis et al. 2004; Aeby 2005; Williams et al. 2011; Richards and Newman 2019). It is unclear whether the recent emergence of novel coral diseases and outbreaks on Indo-Pacific reefs represent a real increase in coral disease, or an increase in disease-focussed research in this region. Nonetheless, disease is now ubiquitous though generally low in prevalence outside of outbreak conditions on reefs throughout the Indo-Pacific (Willis et al. 2004; Page et al. 2009; Onton et al. 2011; Aeby et al. 2011).

Despite over 50 years of research which has characterised an extensive array of coral syndromes, the causative agents of most have remained largely unidentified (Montilla et al. 2019). Currently, there are over 40 different coral disease syndromes reported in the literature that detail compromised coral health, though many have poor macroscopic and diagnostic descriptions with little epizootic and aetiologic information. In addition, many reported diseases lack wide distributions, being reported only from few localised reefs. As a result, many of the names associated with coral disease syndromes (i.e. WP Type I and Type II, white plague-like, WB type I, type II, type III etc.) are imprecise and lack clear definitions that discriminate the individual syndromes (Bruckner 2016b).

## 4.2 Principal diseases

There are nine major scleractinian diseases reported from the Caribbean, including growth anomalies (GA), black band disease (BBD), white plague (WP), white band disease (WBD), white pox (WPX), yellow band disease (YBD), dark spot syndrome (DSD), Caribbean ciliate infestations, and Caribbean stony coral tissue loss disease (SCTLD), and six in the Indo-Pacific Region including black band disease (BBD), white syndromes (WSs), brown band disease (BrB), skeletal eroding band (SEB), ulcerative white syndrome (UWS), and growth anomalies (GA). These diseases reported for corals are summarised in Table 4.1. While several other diseases have been detailed, these main diseases have a broad geographical footprint and repeated observations. Coral bleaching, representing the loss of the endosymbiotic dinoflagellates (Symbiodinaceae) is by definition also a disease (i.e. impairment of normal function). Thermally induced bleaching is a physiological response to environmental stress and is investigated extensively elsewhere, hence is not presented in this chapter. Comparatively less research has been undertaken to understand diseases of octocorals compared to those affecting scleractinians, with the exception of Aspergillosis infection of gorgonians. Diseases such as BBD and GA have also been documented within octocorals (Weil et al. 2015; Kim 2016), however, this chapter specifically focusses on diseases of scleractinian corals. The diseases are presented in rough chronological order of when they were first reported in the literature (see Sutherland et al. 2004), though all white diseases are grouped for consistency.

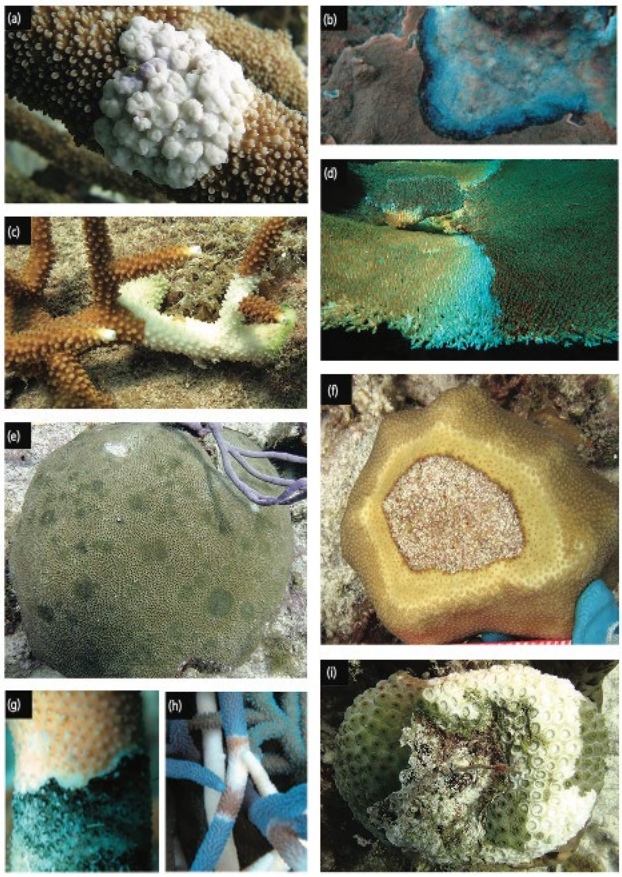

Figure 4.1 Images of common coral diseases. (a) Acroporid from on the Great Barrier Reef displaying growth anomaly. (b) *Montipora* sp. on the Great Barrier Reef displaying black band disease. (c) *Acropora cervicornis* from Florida with white band disease. (d) *Acropora hyacinthus* from the Great Barrier Reef displaying white syndrome. (e) *Siderastrea* sp. from the Caribbean with dark spot disease. (f) *Orbicella* sp. from Belize with yellow band disease. (g) *Acropora muricata* from the Indo-Pacific region displaying skeletal eroding band (h) *Acropora muricata* from the Great Barrier Reef displaying brown band disease. (i) *Montastrea* sp. from the Caribbean with stony coral tissue loss disease. Source: images from the Great Barrier Reef and Indo-Pacific supplied by Cathie Page, images from the Caribbean supplied by Greta Aeby.

### 4.2.1 Growth anomalies (GAs)

GAs were the first (Squires 1965), and still are one of the most commonly reported syndromes globally (Work et al. 2015). These present as exuberant distinct tissue and skeletal growths on coral colonies, having grown at a faster rate than surrounding areas (see Figure 4.1a). Characteristics include aberrant corallite and coenosarc shapes, often as a result of rapid skeletal accretion (Peters et al. 1986; Work et al. 2008a). They have been reported from a large number of coral genera, with prevalence ranging from low (< 5%) up to 70% in some reef regions (Aeby et al. 2011; Work et al. 2015). They are most commonly reported for corals in the families Acroporidae and Poritidae (Aeby et al. 2011). The classical appearance of GAs in acroporids is described by smooth to rugose, variably sized skeletal masses with reduced or absent calices. The tissue overlaying the abnormal growth is often pale or translucent due to the mass of aragonite skeleton underlying the tissue and reduced densities of Symbiodiniaceae. Plating acroporids often have GAs on the upper surfaces, though in branching colonies they can be found randomly (Work et al. 2008b). Across all acroporids, the abnormal development of the gastrovascular canals and excessive accretion of the coenosteum (i.e. skeletal material secreted by the coenosarc) is consistently observed (Preston and Richards 2020). Visually different GAs have been described for *Porites* spp., including a skeletal growth resulting in a raised appearance demarcated by paler tissues, while a second type displays very rough surfaces with pale or white patches and occasional pink pigmentation (Kaczmarsky 2006). The aetiology of GAs is unknown, with previous studies proposing environmental factors, genetic predisposition, and infectious agents including bacteria, fungi, and viruses (Loya et al. 1984; Peters et al. 1986; Domart-Coulon et al. 2006; Kaczmarsky 2006; Kaczmarsky and Richardson 2007; Aeby et al. 2011). Ageing and senescence leading to inadequate cell repair have also been proposed (Hanahan and Weinberg 2000; Work et al. 2015). Elevated activity of the enzyme phenoloxidase in GAs and the healthy tissues of GA-affected colonies, compared to colonies having no GAs, suggests an immune response in affected colonies (Palmer and Baird 2018). The impacts of GAs on corals appear to differ depending on species impacted and may reflect the previously described investment in immunity. In acroporids, GAs impact the host negatively as they can progress and spread, therefore reducing fitness through reduced growth and reproductive output. GAs have been categorised as neoplasia conditions (cancerous) and some aspects of the lesions support this. However, diagnosis of neoplasia in invertebrates is challenging. The nature of GAs indicates aberrant cell division, though further work

is required to appropriately classify these lesions and Work et al. (2015) argue the classification of GAs as true cancers in other coral genera to be premature.

### 4.2.2 Black band disease (BBD)

BBD represents arguably the most comprehensively understood coral disease. First reported in the 1970s, it has a global distribution that infects a wide range of scleractinian taxa (Richardson 2004; Page and Willis 2006; Sato et al. 2016; Spalding et al. 2017). BBD is often reported to infect dominant coral taxa on reefs, irrespective of morphology, with at least 42 Caribbean and 57 Indo-Pacific taxa being susceptible. The prevalence of the disease is generally low (< 1%), though localised outbreaks have been reported that can impact coral population demographics (Edmunds 1991; Kuta and Richardson 1996; Green and Bruckner 2000; Sato et al. 2009). The lesion presents as a darkly pigmented band that migrates across corals (see Figure 4.1b), killing the underlying tissues and leaving behind dead and denuded coral skeleton that is quickly overgrown by algae and other fouling organisms. Progression rates are, on average 3 mm $day^{-1}$ though can range from 1 mm $day^{-1}$ up to 2 cm $day^{-1}$ in some case studies (Richardson 2004), with higher progression rates resulting in whole colony mortality in days to weeks. Water-borne transmission of BBD is supported by spatiotemporal patterns in the spread of the disease to other colonies often following the direction of predominant current and waves (Bruckner et al. 1997; Zverlov et al. 2005). Gastropods, polychaetes, and reef fishes may also act as vectors, or may facilitate transmission through physical injury to the coral host (Aeby and Santavy 2006; Chong-Seng et al. 2011; Nicolet et al. 2018).

BBD is characterised as a polymicrobial disease, whereby a consortium of microorganisms forms a microbial mat that creates and maintains anoxic and sulfidic biochemical conditions that are toxic to the underlying coral tissues. The microbial communities associated with BBD lesions have been well characterised and are remarkably consistent across global case studies (reviewed in Sato et al. 2016). Filamentous cyanobacteria affiliated to *Roseofilum reptotaenium* (Casamatta et al. 2012) (Figures 4.2 a,b), represent the largest biomass in the microbial mat, though highly diverse communities of heterotrophic bacteria (Sekar et al. 2008; Sato et al. 2010; Meyer et al. 2017; Sato et al. 2017), a phylogenetically novel lineage of Archaea (Sato et al. 2013), plus a high abundance of sulphur-oxidising and sulphate- reducing bacteria have been characterised from BBD lesions (Bourne et al. 2011; Bourne et al. 2013). Histopathology of BBD demonstrates the incursion of cyanobacterial filaments into the tissues at the lesion interface, with cyanobacterial toxins implicated in contributing to tissue necrosis in some studies (Richardson et al. 2007). The integrated metabolic pathways that support the microbial consortium in the lesion have been characterised through metagenomic and meta-transcriptomic approaches, with cyanobacterial-derived photosynthetically fixed $CO_2$ enhancing productivity and promoting sulphide production within the lesion (Meyer et al. 2017; Sato et al. 2017). A putative sulphide tolerance metabolic pathway exists in the dominant *Roseofilum reptotaenium* cyanobacterium that explains its success and persistence in the lesion (Sato et al. 2017).

### 4.2.3 White syndromes (WSs)

Within the literature, there is a historical legacy of different coral diseases being reported that lack clear and unambiguous descriptions of the gross lesions. This has resulted in descriptions of coral diseases that are open to subjective interpretation, leading to a proliferation of coral disease names that display similar visible signs of tissue loss. This is particularly evident for many of the 'white' diseases reported in the Western Atlantic, for which names such as WP, WB, and WPX are frequently reported. Despite varying names, all of these 'white' diseases display a tissue loss pattern characterised by a distinct separation of apparently healthy tissue and freshly exposed white coral skeleton and the absence of visible causative agents at the tissue-skeleton interface. Distinction between diseases have been made based on taxa affected, rates of tissue loss, slight variations in pattern of appearance, and lesion progression, locations of the lesions, and if a zone of bleached tissue is present between healthy and necrotic coral tissues (Bruckner 2016b). Without the standardised and systematic framework for describing coral lesions (Work and Aeby 2006), and with little definitive identification of the underlying causation of the diseases, these various disease names have proliferated in the literature and are often used interchangeably, making it very difficult to compare diseases between different case studies. As a result of the limited understanding of the epizoology and aetiology of many white disease case studies, and to avoid confusion, here we discuss the pathology of individual reported case studies using the original disease nomenclature allocated to disease signs.

#### 4.2.3.1 White plague (WP)

WP was first described from the Florida Reef Tract in the mid-1970s and characterised by macroscopic signs of an advancing distinct margin between apparently healthy coral tissue and newly exposed white skeleton, often resulting in whole colony mortality (Dustan 1977; Bythell et al. 2004). A subsequent outbreak of WP was reported in 1995 on the same reefs, though it was named WP type II and distinguished from the first reported outbreak (WP type I) based on the more rapid rate of lesion progression, higher prevalence and greater number of susceptible coral species (Richardson 1998). Work and Aeby (2006) provide a definitive gross description of WP-Type II as diffuse, peripherally and basally situated large, irregular, and distinct areas of tissue loss revealing intact bare white skeleton. An additional type of WP, WP type III was reported in 1999 on reefs in Florida and characterised by very rapid rates of lesion progression (Richardson et al. 2001). WP type II and type III have been reported to have spread throughout the wider Caribbean (Nugues 2002; Borger 2003; Croquer et al. 2003) and other reef systems across the Indo-Pacific and Red Sea (Barash et al. 2005). Confusion in descriptions of gross

lesion characteristics combined with poor understanding of the underlying aetiologies have resulted in more recent naming of lesions displaying these signs as WP-like disease (Pratte and Richardson 2016), similar to the grouping of white syndromes of Indo-Pacific corals (see Section 4.2.3.4), until aetiologies of distinct diseases can be established.

The aetiologic diagnosis of WP-like diseases are reported for some case studies. The bacterium *Aurantimonas coralicidia* was identified as the causative agent of WP type II based on isolation of this strain from diseased colonies of *Dichocoenia stokesi* followed by inoculation of healthy colonies that subsequently displayed the same disease signs (Denner et al. 2003). However, later studies highlighted that apparently healthy colonies are not susceptible to the original or subsequently isolated bacterial strains (Lesser et al. 2007). Another bacterial agent, *Thalassomonas loyana* (Barash et al. 2005; Thompson et al. 2006), has been implicated in disease causation for WP in Red Sea corals (*Favia favus*), with inoculation of the bacterium supplemented with seawater filtrate containing an unknown factor from the aquarium water of diseased colonies resulting in disease onset on apparently healthy colonies (Barash et al. 2005). Microbial community profiling of WP-like diseased tissues of *Montastrea annularis* colonies from the US Virgin Islands found a high abundance of sequences related to *Roseovarius crassostreae*, a previously identified bacterium involved in juvenile oyster disease, which was suggested to have a role in WP-like disease causation (Pantos et al. 2003). In all these cases the aetiological agent was not unequivocally confirmed and therefore definitive causation is still lacking. It is possible that different pathogens or bacterial consortia produce similar disease phenotypes in different coral species across broad geographic regions (Sweet and Bulling 2017).

**4.2.3.2 White band disease (WBD)**

The general distinction between WBD and WP diseases is that WBD is restricted to Caribbean acroporid species (see Figure 4.1c), while WP occurs on massive and encrusting non-*Acropora* growth forms, though this distinction can be argued to be historically arbitrary (Bythell et al. 2004). Similar to WP, two forms of WBD have been reported in the literature. White band disease (type I) was first reported in the 1970s in the US Virgin Islands (Gladfelter et al. 1977; Gladfelter 1982). Over the ensuing decades, the disease spread throughout the Caribbean basin (now reported from more than 27 countries), severely impacting the populations of two of the dominant framework corals of Caribbean reefs, *Acropora palmata* and *A. cervicornis* (Green and Bruckner 2000; Bruckner et al. 2002). At some sites, the abundance and cover of these corals declined by > 90%, leading to a designation of these two species as critically endangered (The International Union for Conservation of Nature (IUCN) Red List of Threatened species; Hogarth 2006). WBD type II was first identified in San Salvador, Bahamas, and contrasts to WB type I as it affects only *A. cervicornis*. The gross lesions of both type I and type II are described by a distinct band of white exposed skeleton that separates live tissue and algal colonised dead skeleton behind the lesion front (Bruckner 2009). The two types are distinguished based on the rates of tissue loss, which is faster in WBD type II (up to 10 cm $day^{-1}$) compared to WBD type I (average 5.5 mm $day^{-1}$). Type II can be further distinguished by the presence of a bleached tissue region at the interface of apparently normal tissue and denuded skeleton (Ritchie and Smith 1998). Like WP, there is a lack of clear distinctions between type I and type II, plus additional poorly characterised syndromes of acroporids in the Caribbean are reported (i.e. shut-down reaction; Antonius 1977; rapid tissue loss; Williams and Miller 2005). Hence, the general term WBD is now used to describe any visible white band that results from tissue death and loss that is not related to bleaching, predation or other band diseases (e.g. BBD or ciliate infections). The unifying characteristics of WBD describe a diffuse, basally situated lesion with distinct areas of tissue loss that reveal intact, bare skeleton that is well differentiated from the distal skeleton, which is discoloured and overgrown with algae (Work and Aeby 2006).

Identification of the causative agents of WBD have remained elusive. Transmission studies have variably indicated an infectious biotic agent, with direct contact, biological vectors, and the water column as possible modes of spread of the disease (Vollmer and Kline 2008; Gignoux-Wolfsohn et al. 2012; Certner et al. 2017). Histopathology of the disease lesion demonstrates atrophy, necrosis, and lysing of the surface and basal body wall and polyp structures at the tissue-lesion margin (Gignoux- Wolfsohn et al. 2020). Early studies also identified bacterial aggregates in higher abundance in tissue regions adjacent to WBD type I lesions, though bacterial aggregates are also generally found in healthy coral tissues (Peters 1984; Santavy and Peters 1997; Work and Aeby 2014). Earlier studies of WBD-type II identified a higher abundance of *Vibrio* spp. (most closely related to *V. carchariae*; synonym *V. harveyi*) in diseased tissue relative to healthy tissues, though causation was not demonstrated (Ritchie and Smith 1998; Gil-Agudelo et al. 2006). Other bacterial agents are associated with WBD diseased tissues including *Bacillus* sp., *Lactobacillus* sp. and a *Rickettsiales*- like organism (Casas et al. 2004; Sweet et al. 2014), though the latter are consistently observed in both visibly healthy and diseased tissues of WBD infected colonies (Gignoux-Wolfsohn et al. 2020). Recent studies have suggested that shifts in the microbial consortia associated with the host coral are linked to gross lesion signs and compromised host health (Sweet and Bulling 2017). Hence, rather than identifying a single biotic causative agent, it is proposed that dysbiosis of the associated microbiome results in a transition toward a pathobiome that is characteristic of the disease.

**4.2.3.3 White pox (WPX)**

The first report of WPX disease was in 1996 on reefs off Key West in Florida (Patterson et al. 2002), though in following years the disease was also reported more widely across the Caribbean (Porter et al. 2001; Rodriguez-Martinez et al. 2001; Patterson et al. 2002; Sutherland and Ritchie 2004). The disease affects *Acropora palmata*

corals and manifests as variable sized, irregular white patches devoid of coral tissues that can develop simultaneously on different regions of the same colony. Lesions are characterised as focal to multifocal, basal to apically distributed, small to medium in size, and varying shapes from circular, oblong or pyriform with extensive tissue loss leaving intact bare white skeleton (Work and Aeby 2006). The lesions progress at an average of 2.5 cm $day^{-1}$, with progression greatest at elevated temperatures (Patterson et al. 2002). Lesions vary in size from generally a few cm in area to > 80 $cm^2$ and can coalesce, resulting in whole colony mortality (Sutherland et al. 2004). Additional case studies have reported syndromes with similar gross lesion characteristics at sites across the Caribbean, with various names including white- patch disease, patchy necrosis, and necrotic patches (Bruckner and Bruckner 1997; Rodriguez-Martinez et al. 2001), though these are now generally grouped under WPX since no comparative pathology studies were conducted.

Early reports of WPX highlighted it was highly contagious, spreading to neighbouring colonies and rapidly being transmitted between reefs in the Florida Keys National Marine Park Sanctuary. It is estimated that 88% of remaining *A. palmata* corals were lost in this region between 1996 to 2002 (Porter et al. 2001; Patterson et al. 2002; Sutherland et al. 2004). In other regions such as the United States Virgin Islands, Puerto Rico, and Mexico, mortality rates were variable and patterns in disease outbreaks followed seasonal drivers (Bruckner 2016a). More recent studies assessing WPX outbreaks highlight that disease severity and colony mortality was high between 1994–2004 and low in the period between 2008–2014, suggesting that changes in host, causative agent, and environmental dynamics influence the disease aetiology and complicate diagnosis (Sutherland et al. 2016a).

The causative agent of the disease was originally identified and confirmed by Koch's postulates as the bacterium *Serratia marcescens* and was linked to possible human sewage pollution (Patterson et al. 2002; Sutherland et al. 2010). Subsequent studies failed to recover *S. marcescens* from coral with WPX disease signs and questioned its role as the aetiological agent of the disease (Lesser and Jarett 2014; Joyner et al. 2015). WPX is still characterised on gross disease signs, though one form of WPX is termed acroporid serratiosis and is diagnosed if the classic lesion signs on the *A. palmata* host co- occur with the presence of the established pathogen *S. marcescens* (Sutherland et al. 2016a). However, WPX does not always co-occur with *S. marcescens*, and hence the same gross signs may be caused by more than one aetiological agent (Sutherland et al. 2016a).

Histopathology of apparently healthy tissue (1 to 10 cm away from the gross lesion margin) demonstrate tissue and cellular degeneration characterised by rounding of gland cells in mesenterial filaments and epidermis of the pharynx, potentially indicating involvement of bacterial derived toxins (for acroporid serratiosis; Sutherland 2015). Atrophy and necrosis in coenenchyme tissues and disruption of the epithelia of the gastrovascular cavity were also observed in apparently healthy tissues. Bacteria were not directly evident in diseased tissues, though rickettsia-like bacteria have been observed (Sutherland et al. 2016b). Histopathology of the apparently healthy tissues and disease lesion tissues of WPX colonies was similar, indicating a potential systemic, whole- colony response, which may partially explain the patchy distribution of lesions (Sutherland et al. 2016b).

**4.2.3.4 White syndromes (WSs) of Indo-Pacific corals**

Willis et al. (2004) highlighted the difficulties of assigning causative agents and causal relationships to diseases that display similar signs. Therefore, it was recommended to group diseases in the Indo-Pacific for which the underlying disease aetiology is unknown, but with macroscopic signs of irregular white bands or patches as a consequence of tissue loss, collectively as White Syndromes (WSs). Similar to the Caribbean, there are likely to be many diseases with varying underlying causative agents that result in gross WS signs in Indo-Pacific corals. However, this grouping prevents the emergence of multiple disease names which have few distinguishing diagnostic features (Willis et al. 2004). Once the underlying aetiologies are determined, then more definitive descriptions using established frameworks can be made (Work and Aeby 2006; Work et al. 2008b; Beeden et al. 2012). Until then, this grouping prevents the erection of distinct disease names that can result in confusion for researchers and managers.

WS gross lesions are characterised by a diffuse linear (or annular) band or irregular patch comprised of recently exposed coral skeleton adjacent to healthy tissues (see Figure 4.1d). In some cases, a region of bleached tissue may precede the advancing lesion, though more commonly there is no transition zone between healthy coral tissues and freshly denuded coral skeleton (Bourne et al. 2015; Bourne et al. 2016a). WSs were first recorded from the Great Barrier Reef in 1998/1999, affecting 17 species or growth forms of corals, though disease signs are particularly prevalent in the fast-growing tabular and branching species of *Acropor*a (Willis et al. 2004). It is noted, however, that earlier reports of lesions consistent with WSs were observed in the Philippines (Antonius 1985). Multiple localised reports of tissue loss consistent with WS signs were quickly reported from regions across the Indo-Pacific. The signs were reportedly affecting tabulate acroporids from the North- Western Hawaiian Islands (Aeby 2005), Marshall Islands (Jacobson et al. 2006), Pilbara region reefs, and Christmas and Cocos Islands, North Western Australia (Hobbs and Frisch 2010; Page and Stoddart 2010) and the US remote Pacific Islands (Vargas-Angel 2009; Aeby et al. 2011). WSs were also reported in other coral genera across this region including *Pachyseris*, *Montipora*, *Pocillopora*, *Goniastrea*, and *Platygyra* (Sussman et al. 2008; Page et al. 2009; Vargas-Angel 2009; Aeby et al. 2011).

Consistent with descriptive frameworks, additional information has been introduced for many WSs, including *Montipora* white syndrome, which displays both acute and chronic lesion progression rates in Hawaii (Aeby et al. 2010; Work et al. 2012). A number of diseases have been reported with signs consistent with WSs in massive

*Porites* corals, and alternative names have been suggested, including *Porites* white patch syndrome (Séré et al. 2012), *Porites* tissue loss (Williams et al. 2010), and *Porites* bleaching with tissue loss (Lawrence et al. 2004; Sudek et al. 2012). However, no underlying aetiology is provided to support alternative naming, and therefore it is recommended that they should be categorised under WSs, and more specifically *Porites* white syndrome.
The challenges associated with assigning causation to WSs have been detailed previously in Bourne et al. (2015). At the gross level, there are generally no visual signs of microbial communities at the lesion interface. In some case studies, however, ciliates have been observed at the lesion boundary, and hence ciliates have been suggested to be one causative agent (Sweet and Bythell 2012), noting that visible ciliate bands are characteristic of BrB (presented in more detail in Section 4.2.7). Not surprisingly, considering that this grouping of diseases likely encompasses a range of causative agents, evidence for disease causation at the cellular level has been varied. Histologically, a range of cellular patterns has been observed for WS lesion tissues. Work and Rameyer (2005) observed cell necrosis associated with filamentous algae, fungi, and ciliates in histological sections from a range of corals including tabular acroporids, *Montipora*, *Porites*, and *Echinopora* genera. On the other hand, other case studies displayed no microbial cells associated with diseased tissue, but instead observed tissue necrosis characterised by fragmentation, dissolution, or swelling of cell nuclei (Work and Rameyer 2005). Ainsworth et al. (2007b) investigated WS-infected *Acropora* corals from Heron Island and did not detect bacteria in histological sections, nor through florescence *in situ* hybridisation (FISH) microscopy at the lesion border or in healthy tissue up to 3 cm away from the lesion (Ainsworth et al. 2007b). Similarly, investigations of *Acropora* WSs from three disperse geographic locations, Lizard Island, Western Australia, and Palmyra Atoll, observed no signs of necrosis, fragmentation, tissue swelling, ciliates, or cyanobacteria in the healthy tissues immediately preceding the disease lesion (Pollock et al. 2017; Smith et al. 2020). Helminths and fungi were observed in a minority of samples, though these organisms were also observed in healthy tissues with no gross WS signs. In contrast, high levels of necrosis and tissue fragmentation characterised the lesion front of samples subjected to histological investigations (Pollock et al. 2017). FISH also detected no bacteria in healthy tissues (less than 1 cm ahead of WS lesion fronts), though bacteria were detected in all lesion tissues both at and immediately behind the WS lesion front (Pollock et al. 2017; Smith et al. 2020). In other coral species (*Hydnophora* sp. and *Stylophora pistillata*), extensive tissue necrosis was partnered with extensive bacterial proliferation penetrating the healthy tissue layers (Ainsworth et al. 2007a), further highlighting likely differing underlying aetiologies for Indo-Pacific WSs. Studies on WS of the dominant Hawaiian coral species *Montipora capitata* demonstrated that at the cellular level, different microorganisms were associated with a rapidly progressing acute phase (i.e. ciliates) compared to a slow progressing chronic phase (i.e. helminths and chimeric parasites) (Aeby et al. 2010; Work et al. 2012). The variety of observations at a cellular level highlights the complexity of disease causation for WSs, which have a number of potential multiple causes, as well as varying host responses (Work et al. 2012; Aeby et al. 2016).
A number of studies have detected an increase in Rhodobacteraceae-affiliated sequences in compromised WS tissues (Sunagawa et al. 2009; Cárdenas et al. 2012; Roder et al. 2014; Pollock et al. 2017). This bacterial family is emerging as a potential indicator of compromised tissue health, though its direct role in disease onset or progression is unknown (Smith et al. 2020). A number of other studies have identified *Vibrio* affiliated bacteria as potential causative agents in WS diseases. Ben-Haim et al. (2003) isolated *Vibrio coralliilyticus* from necrotic *Pocillopora damicornis* tissues sampled from reefs in the Red Sea. Sussman et al. (2008), satisfying Henle-Koch's postulates, similarly reported *V. coralliilyticus* strains associated with WS lesions from multiple disease outbreaks in the Great Barrier Reef (*Montipora aequituberculata),* Palau (*Pachyseris speciosa*), and the Marshall Islands (tabulate acroporids). *V. coralliilyticus* possessed high metalloprotease activity, which bleached and lysed the Symbiodiniaceae cells within the coral gastrodermal tissues and resulted in cleavage of coral connective tissues and paracellular perturbations (Ben-Haim et al. 2003; Sussman et al. 2008; Sussman et al. 2009). *Vibrio harveyi* was also implicated in WSs in Indonesian coral studies (Luna et al. 2010). Two pathogenic vibrios have also been implicated in inducing disease signs consistent with *Montipora* WS in Hawaii. *Vibrio owensii* (strain OCN002) was identified as a bacterial pathogen linked to the chronic phase characterised by diffuse tissue loss (chronic *Montipora* WS) and *V. coralliilyticus* (strain OCN088) was identified as inducing acute *Montipora* WS characterised by faster progressive tissue loss (Ushijima et al. 2012; Ushijima et al. 2014). However, vibrios were not detected in high abundance using FISH and 16S rRNA gene amplicon sequencing in WSs across three Indo-Pacific sites (Smith et al. 2020). These disparate patterns highlight the complexity of the involvement of this group in WS causation, suggesting that it may have a role in some, but not all, WSs. More recently, a bacterium, *Pseudoalteromonas piratica* (strain OCN003) was reported as another aetiological agent of acute *Montipora* WS, inducing a switch from the chronic to the acute form of the disease and suggested that similar disease signs (acute *Montipora* WS on *M. capitata*) is caused by multiple bacterial pathogens (Beurmann et al. 2017). The variety of microbial taxa identified in WS tissues highlights the possibility that dysbiosis caused by many detrimental taxa may lead to disease signs, rather than a single bacterial agent. Novel studies have applied microscale tracking combining microfluidics with stable isotopes to view high resolution interactions of putative bacterial pathogens and host coral tissues (Shapiro et al. 2016; Gibbin et al. 2018). In these studies, the penetration and dispersal of the coral pathogen *V. coralliilyticus*, inoculated onto individual *Pocillopora damicornis* polyps were visualised, with most pathogen cells located in the oral epidermis (Gibbin et al. 2018).

In addition to microbial-mediated pathways, programmed cell death, and virus-like particles have been implicated in some WS case studies. Programmed cell death can be instigated by biotic or abiotic factors in other organisms and can be an effective method for removing pathogens from a host. Ainsworth et al. (2007b) reported apoptotic cell nuclei within epithelial and gastrodermal tissues at the lesion borders, with transmission electron microscopy images supporting this. However, Pollock et al. (2017), using the same approach, did not detect programmed cell death in WS lesion tissues for corals sampled at Lizard Island on the Great Barrier Reef. Patten et al. (2008) observed virus like particles in WS lesions, though there was no correlation of such particles with diseased versus healthy tissues (Patten et al. 2008). In contrast, Pollock et al. (2014) reported 65% higher virus like particle numbers in acroporid tissues displaying WS at Lizard Island.

**4.2.3.5 Ulcerative white syndromes (UWS)**

Another disease consistent with WSs for Indo- Pacific corals is reported as ulcerative white spots (UWS). First reported from *Porites* sp. in the Philippines, the name originally erected was *Porites* ulcerative white spot disease (Raymundo et al. 2003). Reports of similar lesions on other coral genera including *Montipora*, massive morphologies, and the octocoral *Heliopora* resulted in the more general nomenclature to accommodate the increasing range of hosts displaying characteristic lesions for which the underlying aetiology remains unknown. UWS lesions are distinct from WSs by displaying multifocal patterns of bleached tissue (3 to 5 mm in diameter) which manifest as small circular or oblong areas that can either regress or progress to full tissue-thickness ulcerations, resulting in patches of bare white coral skeleton. The small lesions can occasionally coalesce, resulting in whole colony mortality (Raymundo et al. 2003). Reports from reefs in the Philippines highlight high prevalence during outbreaks (72% on some reefs; Raymundo et al. 2005), though generally levels are low but widely distributed across other reef areas including the Wakatobi Marine National Park, Indonesia (Haapkyla et al. 2007), Zanzibar and Kenya (Harvell et al. 2007), Guam (Myers and Raymundo 2009), Palau (Page et al. 2009), Maldives (Montano et al. 2016), and the Great Barrier Reef (Willis et al. 2004). Little is known of causative agents of the lesions, though *Vibrio* affiliated bacteria have been implicated through isolation and inoculation studies attempting to satisfy Henle-Koch's postulates, though no direct characterisation of microorganisms within active lesions was conducted (Arboleda and Reichardt 2010).

### 4.2.4 Dark spot syndrome (DSD)

Dark spot syndrome (or dark spot disease; DSD) was first reported in association with a bleaching event in the 1990s on Colombian Reefs (Solano et al. 1993; Gil-Agudelo et al. 2004; Borger 2005). Subsequently, it has been widely reported across the entire Caribbean region. It has been found predominantly affecting three coral species (*Montastraea annularis, Siderastrea siderea*, and *Stephanocoenia intersepta*) (Gil-Agudelo et al. 2004; Weil 2004), though further studies identified possible wider species susceptibility (Garzón-Ferreira et al. 2001). On Floridian reefs, the disease was highly prevalent, infecting more than 70% of corals surveyed, highlighting its potential impact on coral populations (Porter et al. 2011).

The disease lesion manifests as dark spots (brown, purple or black), that subsequently result in tissue loss, exposing skeleton that is colonised by algae or other fouling invertebrates (see Figure 4.1e); (Cervino et al. 2001; Borger 2005). The aetiology of DSD is unknown, though Borger (2005) suggested that lesions may represent a stress response in the coral. This response is proposed to cause disruption to the endosymbiotic dinoflagellates, with the Symbiodiniaceae cells appearing pigmented and swollen, many with disruption of their organelles (Renegar et al., 2008). Both the Symbiodiniaceae populations primarily, and the host tissues secondarily, have been suggested to be compromised through an unknown aetiological agent (Cervino et al. 2001). Histological analysis identified fungi associated with disease tissues, similar to *Aspergillus sydowii*, the pathogen linked to aspergillosis in sea fans (Renegar et al. 2008; Sweet et al. 2013). Studies have also profiled microbial communities associated with infected tissues and linked putative pathogens *Vibrio carchariae*, a cyanobacterium *Oscillatoria* (associated with BBD), and a fungal plant pathogen, *Rhytisma acerinum*, as potential causative agents (Gil-Agudelo et al. 2007; Sweet et al. 2013). These studies only used molecular profiling and no studies have demonstrated direct causation or microbial pathogens directly linked with diseased tissues.

### 4.2.5 Yellow-Band disease (YBD)

YBD has been reported extensively throughout the Caribbean, however diseases with similar gross descriptions have been found on corals from other regions including Pacific and Arabian Gulf reefs (Bruckner and Riegl 2016). These yellow diseases have been termed Pacific YBD and Arabian YBD to avoid confusion with the originally described YBD affecting Caribbean corals. Most studies, including the most thoroughly described disease lesions, have emerged from the Caribbean and are focused upon here.

First reported to be affecting *Montastrea annularis* and *M. faveolata* colonies in 1994 on Florida reefs (Reeves 1994), Caribbean yellow-band disease is characterised by a band or patch of pale yellow tissue that radiates outwards from the central lesion (see Figure 4.1f; Cervino et al. 2001; Bruckner and Riegl 2016). Central areas of the lesion may suffer tissue mortality, with the lesion boundary forming annular bands. Multiple lesions can form on a single colony and may coalesce, resulting in extensive partial colony mortality. Typical reported rates of lesion progression are < 1 cm per month, though lesions can be persistent and therefore have extensive accumulated impacts on coral colonies. There are also seasonal differences in lesion progression, with warmer conditions promoting the disease prevalence and rates of progression (Cervino et al. 2001; Bruckner and Bruckner 2006). The disease can have a high prevalence in the *M. annularis* complex (> 90%) and therefore has contributed to

significant mortality of these corals on Caribbean reefs in the 2000s (Bruckner and Bruckner 2006; Bruckner and Hill 2009), with longer term impacts on reproductive output also impacting coral populations (Weil et al. 2009). Original outbreaks of Caribbean yellow-band disease occurred following coral bleaching events, and both temperature and light have been correlated with the prevalence and virulence of the disease (Bruckner and Bruckner 2006; Harvell et al. 2009). Experimentally increased nutrients have also been demonstrated to cause increases in lesion progression rates (Bruno et al. 2003).

*Vibrio* spp. infecting the endosymbiotic Symbiodinaceae cells have been implicated in the early stages of Caribbean yellow-band disease onset, with histological studies showing progressive degeneration of dinoflagellate cells, including swelling, vacuolisation, fragmentation, and loss of cellular integrity (Cervino et al. 2004). This results in breakdown of the symbiotic association between the coral host and Symbiodiniaceae, leading Cervino et al. (2004) to suggest the disease is principally a disease of the symbiont. Four *Vibrio* strains which were recovered from the mucus of diseased corals, reproduced disease signs when healthy corals were inoculated with all four *Vibrio* strains, but failed to cause disease when inoculated as individual isolates (Cervino et al. 2008). Later studies found these vibrios in both diseased and healthy tissues of affected corals (Cunning et al. 2009), so the specific causative agent (vibrios or other biotic and abiotic agents) remains to be elucidated.

### 4.2.6 Skeletal eroding band (SEB) and Caribbean ciliate infections (CCI)

SEB is associated with the folliculid ciliate *Halofolliculina corallasia* and was the first disease described from the Indo-Pacific (Antonius 1999). The disease presents as a dark band 1–10 cm wide resulting from high densities of the *H. corallasia* ciliate (Figure 4.1g). The band is located at the interface of recently denuded skeleton and apparently healthy coral tissues (Figure 4.2c). This condition is most commonly associated with acroporid and pocilloporid coral genera, though it has been recorded afflicting over 80 coral species found on reefs across the Indo-Pacific and the Red Sea (Antonius 1999; Page et al. 2016). Cróquer et al. (2006a) reported a similar ciliate infection on a number of coral species in the Caribbean, with the disease named Caribbean ciliate infection (CCI) due to potential different aetiologies of this condition and the Indo-Pacific skeletal eroding band (Cróquer et al. 2006; Rodríguez et al. 2009; Weil and Rogers 2011). However, recent morpho-molecular studies confirmed that both of these two conditions display similar macroscopic signs and fine scale skeletal erosion patterns derived from a common ciliate phenotype unequivocally identified as *H. corallasia* (Montano et al. 2020). Though a species complex may exist between Indo-Pacific and Caribbean *H. corallasia* populations, both disease names should be synonymised to avoid confusion in reporting of these two diseases (Montano et al. 2020).

The ciliate *H. corallasia* has a free-living form (see Figure 4.2d) that migrates onto or immediately adjacent to living coral tissue before transitioning to a sessile form. In its sessile form, the ciliate penetrates living coral tissues and attaches to the coral skeleton, forming a lorica (sac-like housing) with a rounded posterior and cylindrical neck. The ciliate and its associated lorica has an average length of 220 μm and width of 95 μm, with the ciliate housed within the lorica and possessing two conspicuous retractable pericytostomial wings bearing feeding cilia. Often, only the neck of the lorica is visible above the coral skeletal surface. The presence of the ciliate compromises healthy coral tissues potentially through spinning and chemical secretions, but it also damages and erodes the coral skeleton (Cróquer et al. 2006; Page and Willis 2008; Page et al. 2016). The migration of the ciliates across the colony surface leaves empty lorica visible behind the advancing front of live ciliates. Injury of coral tissues facilitates colonisation by *H. corallasia*, though studies have shown that intact healthy coral tissues challenged with the ciliate fail to manifest disease signs or tissue loss (Page and Willis 2008). Hence, while *H. corallasia* is characteristic of the disease, additional factors that increase ciliate virulence or compromise host coral tissues may be required to promote halofolliculinid infestations that result in pathogenesis and coral tissue loss. SEB can sometimes be confused in field observations with BBD when the density of the invading ciliates is high (Page and Willis 2008). Lesions in SEB are often associated with other potential causative agents including cyanobacteria, and the contribution of these other agents is unclear in cases where ciliates occur at varying densities (Page et al. 2016).

### 4.2.7 Brown band disease (BrB)

BrB was first reported in 2003 from the Great Barrier Reef, though since has been recorded across the Indo-Pacific (Harvell et al. 2007; Nugues and Bak 2009; Page et al. 2009; Qiu et al. 2010; Onton et al. 2011; Weil et al. 2012) with similar disease signs also being reported from Caribbean reef systems (Randall et al. 2015). BrB is distinctively characterised by a brown band of variable width which separates apparently healthy tissues from exposed white coral skeleton (Figure 4.1h). There may also be a narrow zone of bleached tissue or denuded coral skeleton between the brown band and live apparently healthy tissue (Figure 4.2e). The brown band is comprised of a dense population of ciliates, which can consist of mixed populations, though generally is dominated by a protozoan scuticociliate of the class Oligohymenophorea (Bourne et al. 2008). Morphological work further identified the dominant ciliate as *Porpostoma guamense*, which was characterised from infected *Acropora* colonies from Guam (Lobban et al. 2011). Ciliates within the band can reach densities of ~ 120 cells $ml^{-1}$ and actively feed on coral tissues, progressing at rates > 2 cm $day^{-1}$ (Lobban et al. 2011). The ability to feed on living tissue means *P. guamense* is an ectoparasite of coral polyps and ingests Symbiodiniaceae cells along with the coral tissues (Figure 4.2f). These Symbiodinaceae cells remain actively photosynthesising, thereby benefiting the ciliate through a mixotrophic energy acquisition (Ulstrup et al. 2007). The corallivorous gastropod *Drupella* sp. was

demonstrated to be an effective vector for BrB to spread between colonies (Nicolet et al. 2013). Additionally, predation by marine fishes and other invertebrates increased the occurrence of BrB through feeding scars, which create wounds sufficiently extensive to facilitate colonisation of coral tissues by the ciliates (Chong-Seng et al. 2011; Katz et al. 2014).

Ciliate species consistent with those found in BrB have been identified at the lesion interface of other diseases including WS (Indo-Pacific) and WBD (Caribbean) and are implicated in conferring the macroscopic visible signs of these diseases (Sweet and Bythell 2012; Sweet et al. 2014). However, *Philaster* sp. ciliates appear to be secondary colonisers within lesions resulting from alternate aetiologies. Other broad studies on WS have not consistently observed ciliates at the lesion interface (Pollock et al. 2017; Smith et al. 2020). Hence, while ciliates are linked to some WS cases, these are unlikely the primary causative agents, instead being histophagic, feeding on damaged tissues and endosymbionts. However, at high densities ciliates may play a role in pathogenesis through removal of coral tissues by their feeding activities resulting in denuded skeleton. Nicolet et al. (2013) reported visual differences in WS and BrB disease with the role of ectoparasite *Porpostoma guamense* and other distinct histophagic ciliates potentially contributing to these gross differences.

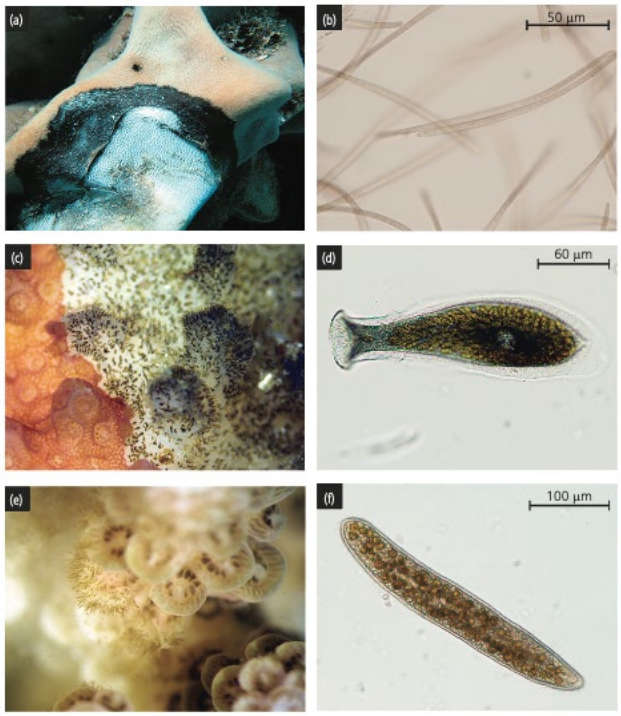


Figure 4.2. Images of common coral diseases and photomicrographs of microorganisms implicated in disease causation. (a) Macroscopic appearance of black band disease. (b) Photomicrograph of the dominant cyanobacterium (*Roseofilum reptotaenium*) associated with the black band disease microbial mat. (c) *Halofolliculina* bands associated with skeletal eroding band bordering healthy coral tissues. (d) Photomicrograph of a motile swarmer folliculind ciliate *Halofolliculina corallasia* associated with skeletal eroding band. (e) Image of *Acropora tenuis* from the GBR with ciliates associated with brown band disease bordering healthy coral tissue. (f) Photomicrograph of the dominant protozoan scuticociliate (Class Oligohymenophorea; Genus *Porpostoma*) found in brown band disease lesions. Source: images supplied by Cathie Page and David Bourne.

### 4.2.8 Stony coral tissue loss disease (SCTLD)

SCTLD was first reported in reefs off Florida in 2014, and subsequently spread through almost the entirety of the Florida Reef Tract (Precht et al. 2016; Walton et al. 2018) and is now also reported in many other regions of the wider Caribbean (Jamaica, Mexico, US Virgin Islands, Dominican Republic, Turks & Caicos Islands, Belize, Puerto Rico, and Grand Bahama (Alvarez-Filip et al. 2019; Weil et al. 2019)). The disease causes extensive coral mortality on already degraded reefs, compounded by observations that SCTLD disease signs have been reported for a large number (~ 24) of important reef-building coral genera (Muller et al. 2020). The environmental and ecological drivers of the disease outbreak are poorly understood, though the first reports coincided with a summer bleaching event across the Florida Reef Tract, combined with localised dredging operations which increased sedimentation deposition onto reefs in the vicinity of the Port of Miami, Florida (Miller et al. 2016; Walton et al. 2018). Disease transmission can occur by direct contact between coral colonies or through the water column (Aeby et al. 2019), with modelling studies reporting the epizootic followed a contagion model with spread up to 100 m day$^{-1}$ and potentially facilitated by water currents (Muller et al. 2020).

Signs of SCTLD vary within and among affected coral species (Aeby et al. 2019), displaying focal or multifocal diffuse areas of tissue loss, and lesion boundaries adjacent to bleached tissues in some case studies (see Figure 4.1i). The rate of tissue loss can vary from acute (3–4 cm day$^{-1}$) to sub- acute, influenced by host species,

individual host genotype, region, and time of year. A detailed case definition for SCTLD is available (NOAA 2018), with gross morphology of tissue loss distributed basally, peripherally, or both. Tissues bordering the lesions have indistinct bands (1–5 cm) of pallor, progressing to normal pigmentation away from denuded skeleton. Histological investigations report that tissue lesion pathology first affects the gastrodermal basal body wall, displaying signs of degradation, fragmentation, and swelling associated with disintegration of the mesoglea and subsequently progresses towards the oral surface, manifesting as tissue necrosis. Landsberg et al. (2020) histologically characterised SCTLD lesions from eight coral species, with all displaying lytic necrosis originating in the gastrodermis of the basal body wall, which progresses to the surface body wall as the lesions advance. The host cells display degenerative changes including disintegration of the mesoglea layers, degradation and fragmentation of the gastrodermal cells, plus mucocyte hypertrophy. In addition, endosymbiotic Symbiodiniaceae cells displayed a range of changes including necrosis, peripheral nuclear chromatin condensation, cytoplasmic vacuolation, deformation and degradation of chloroplasts, highlighting that SCTLD lesions result as a consequence of the disruption to the coral host and symbiont physiology leading to tissue sloughing from the underlying skeleton (Landsberg et al. 2020).

The aetiologic diagnosis of SCTLD is currently unknown, with studies showing the application of antibiotics or human wound treatment patches containing antiseptics and natural antioxidants can slow or halt lesion progression, suggesting some involvement of bacteria in the disease (Neely et al. 2020; Contradi et al. 2020). Higher relative abundance of sequences affiliated with the bacterial orders Rhodobacterales and Rhizobiales (Rosales et al. 2020) and an unclassified genus of the Flavobacteriales (Meyer et al. 2019) have been detected in disease lesions, though it is unknown if these taxa have a direct role in lesion progression or are secondary colonisers of compromised tissues. An obvious host-cell inflammatory response was not observed in histopathology studies, which may indicate that bacteria, fungi and parasites are not primary causes of the disease (Landsberg et al. 2020). Other aetiological causes under investigation include viral pathogens, toxicants, metabolic dysfunction and other environmental factors. Due to the ecological impact of the SCTLD disease outbreak across such a broad geographic and taxonomic range, and its occurrence on coral reefs already under intense pressures, significant research efforts are currently focussed on understanding this disease. However, a number of management failures in the early stage of the outbreak may have prevented effective management to stop spread and mitigate its impacts (Precht 2019).

## 4.3 Control and treatment of coral diseases

Control and treatment of coral diseases in open reef environments in which there are few physical barriers to disease spread is challenging, with prevention of outbreaks the best long-term option. This is best achieved through mitigation of anthropogenic stressors on coral reef ecosystems, which, if unchecked, may result in widespread disease outbreaks impacting coral community assemblages (Harvell et al. 1999, 2002, 2007). The biggest threat currently facing coral reefs is the global anthropogenic warming of seawater that is likely to contribute to the increased virulence of coral pathogens, and/or decreased coral host immunity, and ultimately deterioration of the functional coral holobiont, resulting in coral bleaching, disease outbreaks, and ultimately high coral mortality (Bruno et al. 2007; Muller et al. 2008; Heron et al. 2010; Brodnicke et al. 2019). Unfortunately, given current climate modelling projections, global seawater temperatures will continue to rise, driving further coral disease outbreaks. Difficulty in unambiguously identifying the causative agents of many coral diseases has hindered the development of potential control and treatment strategies. However, there have been a number of approaches trialled at different scales, and current global concern regarding declining reef ecosystem health is driving exploration of new approaches for mitigating coral diseases and building resilience in coral populations (Bostrӧm-Einarsson et al. 2018; National Academies of Sciences 2018, 2019).

The first approach to treat and manage a coral disease was conducted on BBD-infected colonies in the 1980s (Hudson 2000). The partially successful treatment involved using an aspirator device to remove the microbial mat infecting the colony and the pressing of modelling clay into the coral skeleton at the site post-aspiration to seal the wound and reduce reinfection (Hudson 2000). Epoxy resin has similarly been used to mechanically block progression of coral lesions (Miller et al. 2014), with chemical treatments such as chlorine also included in the resin (Aeby et al. 2015). Randall et al. (2018) explored three mitigation strategies for YBD, including shading, underwater aspiration of the disease tissue followed by sealing with modelling clay, and creating a firebreak through chiselling a trench between the lesion and adjacent apparently healthy tissues. The firebreak method was identified as the best for slowing the spread of the disease, though long-term benefits were unclear (Randall et al. 2018). Removal of the region or branch of a coral colony that displays disease signs or removal of whole colonies from the population can also be undertaken to reduce disease spread (National Academies of Sciences 2018). In aquarium settings, the screening of corals for disease agents prior to their introduction to aquaria, and the removal of any colony displaying disease signs is the best recommended approach to prevent transmission through the closed system (Sweet et al. 2011). Antibiotic treatments have also been trialled successfully in aquarium settings to both control disease and help identify if bacteria are implicated as biotic agents of the disease (Sheridan et al. 2013; Sweet et al. 2014). All these approaches, however, are small scale, labour intensive, and expensive, resulting in limited applicability at broader reef ecosystem scales.

Phage therapy has been trialled to control coral disease progression and transmission in both closed experimental systems and open reef environments. The concept of phage therapy is based upon the principle

that every bacterium has one or many bacteriophages that have evolved (or coevolved) to infect and/or lyse that bacterium (Keen 2015). If a coral bacterial pathogen is known, then a phage can be isolated, grown in high abundance, and added to control the pathogen and prevent disease progression and/or transmission. The approach has been used widely in both human and agricultural systems (Doss et al. 2017). Bacteriophages targeting the coral pathogen *V. coralliilyticus* have been isolated and used effectively in small-scale experimental aquarium systems to stop progression of WP-like lesions on *Favia favus* in the Red Sea (Efrony et al. 2007, 2009; Cohen et al. 2013). A proof-of-concept field study was also conducted in the Red Sea and was shown to be effective in mitigating disease impacts (Atad et al. 2012). While the approach offers promise, there are many challenges to applying phage therapy to control coral diseases in open reef ecosystems, with an extensive risk/benefit analyses required for each application to ensure the benefits of disease control are not offset by other deleterious impacts to coral reef ecosystems (National Academies of Sciences 2018).

Manipulation of the coral microbiome, essentially through addition of probiotics is emerging as another potential option to increase coral resilience to environmental stress and disease. The addition of beneficial microorganisms for corals may enhance nutrient cycling (including acquisition of heterotrophic nutrients), biological control of potential pathogens, supply essential trace nutrients, metals or vitamins, and mitigate the effects of reactive oxygen species (Peixoto et al. 2017). Rosado et al. (2018) demonstrated the potential for these microbes to minimise the impacts of environmental stressors. A range of bacterial species displaying potential beneficial traits were isolated and applied as a cocktail to corals in aquaria. These were subsequently subjected to bacterial challenge with the coral pathogen *V. coralliilyticus* and heat stress to simulate a bleaching event. Inoculated corals displayed improved health compared to controls, measured as lower bleaching metrics (Rosado et al. 2018). Heterotrophic feeds may provide an efficient route to deliver probiotics to corals, with recent studies demonstrating rotifers ingested beneficial microbes, which were subsequently ingested by *Pocillopora damicornis* corals (Assis et al. 2020). This approach could be applicable to coral aquaculture facilities, which are becoming more numerous and of increased size in response to increased reef restoration efforts (Barton et al. 2017).

Manipulation of the cell-to-cell chemical signalling (quorum sensing) of the coral microbiome may also hold promise for disease treatment. Quorum sensing through acyl homoserine lactones (AHLs) in bacterial communities can control the coordinated expression of virulence genes (Teplitski and Ritchie 2009), and hence disrupting (or 'quenching') AHL signals may allow the host to prevent pathogenesis. Interference of quorum sensing as disease biocontrol has been investigated in agriculture and other model systems (reviewed in Teplitski and Ritchie 2009). BBD microbial communities have demonstrated AHL-based quorum sensing activities, and hence may play a role in pathogenesis (Zimmer et al. 2014). A proof-of-concept study in corals conducted by Certner and Vollmer (2017) showed that microbial communities isolated from WBD-infected corals that were exposed to a quorum sensing inhibitor (i.e. antagonist of AHLs) were unable to establish disease signs on *A. cervicornis* (Certner and Vollmer 2018). The same microbial communities without the inhibitor treatment established WBD signs within 2 days. While the application of quorum quenching to disease biocontrol *ex situ* may be promising, the application *in situ* in open ocean systems remains a challenge.

## 4.4 Future directions

Diagnosis of coral diseases and the identification of their causative agents has proved challenging since the first reported cases emerged in reef ecosystems over 50 years ago (Montilla et al. 2019). The limited success in conclusively assigning causative agents to many coral diseases highlights the complex interactions that occur between the coral host, its diverse and complex microbiome, and the surrounding environment (Bourne et al. 2016b). There remains a critical need for systematic morphological descriptions of coral diseases at the gross and cellular levels to enable comparative studies across large geographical regions (Work and Aeby 2006; Bourne et al. 2009). In addition, the links between host immunity, homeostasis of the microbial symbiont community, primary *vs.* opportunistic pathogens, the role of dysbiosis in disease onset, and how all these factors are influenced by environmental pressures, requires further elucidation (Vega Thurber et al. 2020). Genomic tools offer new ways to explore these questions as well as the interactions between holobiont members and their surrounding environment. However, genomics is only part of the toolkit to help elucidate disease causation through a deductive approach and should not be the focus at the expense of classical biomedical approaches to standardise disease case definitions (see Chapter 3 for more detailed discussion of this point).

## 4.5 Summary

- Novel coral diseases continue to be reported from coral reefs globally, however inconsistencies in disease nomenclature and the failure to apply systematic morphological descriptions of diseases at both the gross and cellular levels results in proliferation of diseases assumed to have narrow geographic distributions.
- The causation of most coral diseases remains poorly understood and remains an urgent research priority considering the increasingly emerging links between environmental stress and disease outbreaks.
- Dysbiosis is increasingly linked to many coral diseases through a shift in the symbiotic microbiome allowing proliferation of opportunistic bacteria/pathogens.

- Reefs globally are declining at an alarming rate and disease outbreaks have historically, and will continue to, contribute to this loss of coral cover and coral reef ecosystem functioning.
- Ongoing coral declines have led to research focussed on methods to mitigate further anthropogenic contributions to environmental impacts on coral reefs, build coral resilience, and increase disease resistance in the face of a rapidly changing environment.

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## References

Aeby, G. S. 2005. Outbreak of coral disease in the Northwestern Hawaiian Islands. *Coral Reefs,* 24: 481-481.
Aeby, G. S. and Santavy, D. L. 2006. Factors affecting susceptibility of the coral *Montastraea faveolata* to black-band disease. *Marine Ecology Progress Series,* 318: 103-110.
Aeby, G. S., Ross, M., Williams, G. J., Lewis, T. D. and Work, T. M. 2010. Disease dynamics of *Monitopra* white syndrome within Kaneohe Bay, Oahu, Hawaii: distribution, seasonality, virulence, and transmissibility. *Diseases of Aquatic Organisms,* 91: 1-8.
Aeby, G. S., Williams, G. J., Franklin, E. C., Kenyon, J., Cox, E. F., Coles, S. and Work, T. M. 2011. Patterns of coral disease across the Hawaiian archipelago: relating disease to environment. *PloS One,* 6: e20370.
Aeby, G. S., Work, T. M., Runyon, C. M., Shore-Maggio, A., Ushijima, B., Videau, P., Beurmann, S. and Callahan, S. M. 2015. First record of black band disease in the Hawaiian archipelago: response, outbreak status, virulence, and a method of treatment. *PLoS One,* 10: e0120853.
Aeby, G. S., Callahan, S., Cox, E. F., Runyon, C., Smith, A., Stanton, F. G., Ushijima, B. and Work, T. M. 2016. Emerging coral diseases in Kāneohe Bay, O ahu, Hawai i (USA): two major disease outbreaks of acute *Montipora* white syndrome. *Diseases of Aquatic Organisms,* 119: 189-198.
Aeby, G. S., Ushijima, B., Campbell, J. E., Jones, S., Williams, G., Meyer, J. L., Hase, C. and Paul, V. 2019. Pathogenesis of a tissue loss disease affecting multiple species of corals along the Florida Reef Tract. *Frontiers in Marine Science,* 6: 678.
Ainsworth, T. D., Kramasky-Winter, E., Loya, Y., Hoegh-Guldberg, O. and Fine, M. 2007a. Coral disease diagnostics: What's between a plague and a band? *Applied and Environmental Microbiology,* 73: 981-992.
Ainsworth, T. D., Kvennefors, E. C., Blackall, L. L., Fine, M. and Hoegh-Guldberg, O. 2007b. Disease and cell death in white syndrome of Acroporid corals on the Great Barrier Reef. *Marine Biology,* 151: 19-29.
Alvarez-Filip, L., Estrada-Saldívar, N., Pérez-Cervantes, E., Molina-Hernández, A. and González-Barrios, F. J. 2019. A rapid spread of the stony coral tissue loss disease outbreak in the Mexican Caribbean. *PeerJ,* 7: e8069.
American Association for the Advancement of Science. 1996. Coral disease hot spot in Florida Keys. *Science.* pp. 2017.
Antonius, A. 1973. New observations on coral destruction in reefs. 10th Meeting of the Association of Island Marine Laboratories of the Caribbean, University of Puerto Rico. 3 pp.
Antonius, A. 1985. Coral diseases in the Indo-Pacific: A first record. *Marine Ecology,* 6: 197-218.
Antonius, A. 1999. *Halofolliculina corallasia*, a new coral-killing ciliate on Indo-Pacific reefs. *Coral Reefs,* 18: 300-300.

Arboleda, M. D. and Reichardt, W. T. 2010. *Vibrio sp*. causing *Porites* ulcerative white spot disease. *Diseases of Aquatic Organisms,* 90: 93-104.
Assis, J., Abreu, F., Villela, H., Barno, A., Franco, R., Vieira, R., Taveira, I., Duarte, G., Bourne, D. G., Høj, L. and Peixoto, R. S. 2020. Delivering beneficial microorganisms for corals: Rotifers as carriers of probiotic bacteria. *Frontiers in Microbiology,* 11:608506.
Atad, I., Zvuloni, A., Loya, Y. and Rosenberg, E. 2012. Phage therapy of the white plague-like disease of *Favia favus* in the Red Sea. *Coral Reefs,* 31: 665-670.
Barash, Y., Sulam, R., Loya, Y. and Rosenberg, E. 2005. Bacterial strain BA-3 and a filterable factor cause a white plague-like disease in corals from the Eilat coral reef. *Aquatic Microbial Ecology,* 40: 183-189.
Barton, J. A., Willis, B. L. and Hutson, K. S. 2017. Coral propagation: a review of techniques for ornamental trade and reef restoration. *Reviews in Aquaculture,* 9: 238-256.
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.
Ben-Haim, Y., Thompson, F. L., Thompson, C. C., Cnockaert, M. C., Hoste, B., Swings, J. and Rosenberg, E. 2003. *Vibrio coralliilyticus* sp. nov., a temperature-dependent pathogen of the coral *Pocillopora damicornis*. *International Journal of Systematic and Evolutionary Microbiology,* 53: 309-15.
Beurmann, S., Ushijima, B., Videau, P., Svoboda, C. M., Smith, A. M., Rivers, O. S., Aeby, G. S. and Callahan, S. M. 2017. *Pseudoalteromonas piratica* strain OCN003 is a coral pathogen that causes a switch from chronic to acute *Montipora* white syndrome in *Montipora capitata*. *PLoS One,* 12: e0188319.
Borger, J. L. 2003. Three scleractinian coral diseases in Dominica, West Indies: Distribution, infection patterns and contribution to coral tissue mortality. *Revista de Biologia Tropical,* 51: 25-38.
Borger, J. L. 2005. Dark spot syndrome: a scleractinian coral disease or a general stress response? *Coral Reefs,* 24: 139-144.
Boström-Einarsson, L., Ceccarelli, D., Babcock, R. C., Bayraktarov, E., Cook, N., Harrison, P., Hein, M., Shaver, E., Smith, A., Stewart-Sinclair, P. J., Vardi, T. and Mcleod, I. M. 2018. Coral restoration in a changing world - A global synthesis of methods and techniques. A report for the Reef Restoration and Adaptation Program, Subproject 1a - Review of existing technologies, pilots and new initiatives. 85 pp.
Bourne, D. G., Boyett, H. V., Henderson, M. E., Muirhead, A. and Willis, B. L. 2008. Identification of a ciliate (Oligohymenophorea : Scuticociliatia) associated with brown band disease on corals of the Great Barrier Reef. *Applied and Environmental Microbiology,* 74: 883-888.
Bourne, D. G., Garren, M., Work, T. M., Rosenberg, E., Smith, G. and Harvell, C. D. 2009. Microbial disease and the coral holobiont. *Trends in Microbiology,* 17: 554-562.
Bourne, D. G., Muirhead, A. and Sato, Y. 2011. Changes in sulfate-reducing bacterial populations during the onset of black band disease. *The ISME Journal,* 5: 559-564.
Bourne, D. G., Van Der Zee, M. J., Botté, E. S. and Sato, Y. 2013. Sulfur-oxidizing bacterial populations within cyanobacterial dominated coral disease lesions. *Environmental Microbiology Reports,* 5: 518-524.
Bourne, D. G., Ainsworth, T. D., Pollock, F. J. and Willis, B. L. 2015. Towards a better understanding of white syndromes and their causes on Indo-Pacific coral reefs. *Coral Reefs,* 34: 233-242.
Bourne, D. G., Ainsworth, T. D. and Willis, B. L. 2016a. White syndromes of Indo-Pacific corals. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. &

GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken, New Jersey: WILEY Blackwell. pp. 300-315.
Bourne, D. G., Morrow, K. M. and Webster, N. S. 2016b. Insights into the coral microbiome: underpinning the health and resilience of reef ecosystems. *Annual Review of Microbiology,* 70: 317-340.
Brodnicke, O., Bourne, D., Heron, S., Pears, R., Stella, J., Smith, H. and Willis, B. 2019. Unravelling the links between heat stress, bleaching and disease: fate of tabular corals following a combined disease and bleaching event. *Coral Reefs,* 38: 591-603.
Bruckner, A. and Bruckner, R. 1997. Outbreak of coral disease in Puerto Rico. *Coral Reefs,* 16: 260-260.
Bruckner, A. W., Bruckner, R. J. and Williams Jr, E. H. 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.
Bruckner, A. W., Aronson, R. B., Bruckner, R. J. and Precht, W. F. 2002. Endangered acroporid corals of the Caribbean: Large-scale dynamics of coral reef systems. *Coral Reefs,* 21: 41-42.
Bruckner, A. W. and Bruckner, R. J. 2006. Consequences of yellow band disease (YBD) on *Montastraea annularis* (species complex) populations on remote reefs off Mona Island, Puerto Rico. *Diseases of Aquatic Organisms,* 69: 67-73.
Bruckner, A. W. 2009. Progress in understanding coral diseases in the Caribbean. *Coral Health and Disease in the Pacific: Vision for Action.* pp. 126.
Bruckner, A. W. and Hill, R. L. 2009. Ten years of change to coral communities off Mona and Desecheo Islands, Puerto Rico, from disease and bleaching. *Diseases of Aquatic Organisms,* 87: 19-31.
Bruckner, A. W. 2016a. White syndromes of western Atlantic reef-building corals. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken, New Jersey: WILEY Blackwell. 316-332.
Bruckner, A. W. 2016b. History of coral disease research. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A., PORTER, J. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken, New Jersey: WILEY Blackwell. 52-84.
Bruckner, A. W. and Riegl, B. 2016. Yellow-Band Diseases. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken, New Jersey: WILEY Blackwell. 376-386.
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., 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 Biology,* 5: 1220-1227.
Bythell, J. C., Pantos, O. and Richardson, L. 2004. White plague, white band, and other "white" diseases. *In:* ROSENBERG, E. & LOYA, Y. (eds.) *Coral Health and Disease.* Heildelberg: Springer-Verlag. 351-364.
Casamatta, D., Stanić, D., Gantar, M. and Richardson, L. L. 2012. Characterization of *Roseofilum reptotaenium* (Oscillatoriales, Cyanobacteria) gen. et sp. nov. isolated from Caribbean black band disease. *Phycologia,* 51: 489-499.
Casas, V., Kline, D. I., Wegley, L., Yu, Y., Breitbart, M. and Rohwer, F. 2004. Widespread association of a Rickettsiales-like bacterium with reef-building corals. *Environmental Microbiology,* 6: 1137-1148.

Certner, R. H., Dwyer, A. M., Patterson, M. R. and Vollmer, S. V. 2017. Zooplankton as a potential vector for white band disease transmission in the endangered coral, *Acropora cervicornis*. *PeerJ,* 5: e3502.
Cervino, J., Goreau, T. J., Nagelkerken, I., Smith, G. W. and Hayes, R. 2001. Yellow band and dark spot syndromes in Caribbean corals: distribution, rate of spread, cytology, and effects on abundance and division rate of zooxanthellae. *Hydrobiologia,* 460: 53-63.
Cervino, J. M., Hayes, R. L., Polson, S. W., Polson, S. C., Goreau, T. J., Martinez, R. J. and Smith, G. W. 2004. Relationship of *Vibrio* species infection and elevated temperatures to yellow blotch/band disease in Caribbean corals. *Applied and Environmental Microbiology,* 70: 6855-6864.
Cervino, J. M., Thompson, F. L., Gomez-Gil, B., Lorence, E. A., Goreau, T. J., Hayes, R. L., Winiarski-Cervino, K. B., Smith, G. W., Hughen, K. and Bartels, E. 2008. The *Vibrio* core group induces yellow band disease in Caribbean and Indo-Pacific reef-building corals. *Journal of Applied Microbiology,* 105: 1658-1671.
Chong-Seng, K., Cole, A., Pratchett, M. and Willis, B. 2011. Selective feeding by coral reef fishes on coral lesions associated with brown band and black band disease. *Coral Reefs,* 30: 473-481.
Cohen, Y., Joseph Pollock, F., Rosenberg, E. and Bourne, D. G. 2013. Phage therapy treatment of the coral pathogen *Vibrio coralliilyticus*. *Microbiology Open,* 2: 64-74.
Croquer, A., Pauls, S. M. and Zubillaga, A. L. 2003. White plague disease outbreak in a coral reef at Los Roques National Park, Venezuela. *Revista de Biologia Tropical,* 51: 39-45.
Cróquer, A., Bastidas, C. and Lipscomb, D. 2006. Folliculinid ciliates: a new threat to Caribbean corals? *Diseases of Aquatic Organisms,* 69: 75-78.
Cunning, J., Thurmond, J., Smith, G., Weil, E. and Ritchie, K. 2009. A survey of vibrios associated with healthy and yellow band diseased *Montastraea faveolata*. Proceedings of the 11th international coral reef symposium. pp. 206-210.
Denner, E. B. M., Smith, G. W., Busse, H. J., Schumann, P., Narzt, T., Polson, S. W., Lubitz, W. and Richardson, L. L. 2003. *Aurantimonas coralicida* gen. nov., sp nov., the causative agent of white plague type II on Caribbean scleractinian corals. *International Journal of Systematic and Evolutionary Microbiology,* 53: 1115-1122.
Diaz-Soltera, H. 1999. Endangered and threatened species: a revision of candidate species list under the Endangered Species Act. Fed Register. *Fed Register,* 64: 33466-33468.
Domart-Coulon, I. J., Traylor-Knowles, N., Peters, E., Elbert, D., Downs, C. A., Price, K., Stubbs, J., Mclaughlin, S., Cox, E. and Aeby, G. 2006. Comprehensive characterization of skeletal tissue growth anomalies of the finger coral *Porites compressa*. *Coral Reefs,* 25: 531-543.
Doss, J., Culbertson, K., Hahn, D., Camacho, J. and Barekzi, N. 2017. A review of phage therapy against bacterial pathogens of aquatic and terrestrial organisms. *Viruses,* 9: 50.
Dustan, P. 1977. Vitality of reef coral populations off Key Largo, Florida: recruitment and mortality. *Environmental Geology,* 2: 51-58.
Edmunds, P. J. 1991. Extent and effect of black band disease on a Caribbean reef. *Coral Reefs,* 10: 161-165.
Efrony, R., Loya, Y., Bacharach, E. and Rosenberg, E. 2007. Phage therapy of coral disease. *Coral Reefs,* 26: 7-13.
Efrony, R., Atad, I. and Rosenberg, E. 2009. Phage therapy of coral white plague disease: Properties of phage BA3. *Current Microbiology,* 58: 139-145.
Egan, S. and Gardiner, M. 2016. Microbial dysbiosis: rethinking disease in marine ecosystems. *Frontiers in Microbiology,* 7: 991.
Garzón-Ferreira, J., Gil-Agudelo, D., Barrios, L. and Zea, S. 2001. Stony coral diseases observed in southwestern Caribbean reefs. *Hydrobiologia,* 460: 65-69.

Gibbin, E., Gavish, A., Domart-Coulon, I., Kramarsky-Winter, E., Shapiro, O., Meibom, A. and Vardi, A. 2018. Using NanoSIMS coupled with microfluidics to visualize the early stages of coral infection by *Vibrio coralliilyticus*. *BMC Microbiology,* 18: 1-10.
Gignoux-Wolfsohn, S., Marks, C. J. and Vollmer, S. V. 2012. White band disease transmission in the threatened coral, *Acropora cervicornis*. *Scientific Reports,* 2: 804.
Gignoux-Wolfsohn, S. A., Precht, W. F., Peters, E. C., Gintert, B. E. and Kaufman, L. S. 2020. Ecology, histopathology, and microbial ecology of a white-band disease outbreak in the threatened staghorn coral *Acropora cervicornis*. *Diseases of Aquatic Organisms,* 137: 217-237.
Gil-Agudelo, D., Smith, G. and Weil, E. 2006. The white band disease type II pathogen in Puerto Rico. *Revista de Biologia Tropical,* 54: 59-67.
Gil-Agudelo, D. L., Smith, G. W., Garzón-Ferreira, J., Weil, E. and Petersen, D. 2004. Dark spots disease and yellow band disease, two poorly known coral diseases with high incidence in Caribbean reefs. *In:* ROSENBERG, E. & LOYA, Y. (eds.) *Coral Health and Disease.* Heildelberg: Springer-Verlag. 337-349.
Gil-Agudelo, D. L., Fonseca, D. P., Weil, E., Garzon-Ferreira, J. and Smith, G. W. 2007. Bacterial communities associated with the mucopolysaccharide layers of three coral species affected and unaffected with dark spots disease. *Canadian Journal of Microbiology,* 53: 465-471.
Gladfelter, W. B., Gladfelter, E. H., Monahan, R. K., Ogden, J. C. and Dill, R. F. 1977. Environmental studies of Buck Island Reef National Monument. US National Park Service Report. 144 pp.
Gladfelter, W. B. 1982. White-band disease in *Acropora palmata*: Implications for the structure and growth of shallow reefs. *Bulletin of Marine Science,* 32: 639-643.
Green, E. P. and Bruckner, A. W. 2000. The significance of coral disease epizootiology for coral reef conservation. *Biological Conservation,* 96: 347-361.
Haapkyla, 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. *Journal of the Marine Biological Association of the United Kingdom,* 87: 403-414.
Hanahan, D. and Weinberg, R. A. 2000. The hallmarks of cancer. *Cell,* 100: 57-70.
Harvell, C. D., Kim, K., Burkholder, J. M., Colwell, R. R., Epstein, P. R., Grimes, D. J., Hofmann, E. E., Lipp, E. K., Osterhaus, A., Overstreet, R. M., Porter, J. W., Smith, G. W. and Vasta, G. R. 1999. Emerging marine diseases - Climate links and anthropogenic factors. *Science,* 285: 1505-1510.
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: 2158-62.
Harvell, 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. *Oceanography,* 20: 172-195.
Harvell, 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.
Heron, S. F., Willis, B. L., Skirving, W. J., Eakin, C. M., Page, C. A. and Miller, I. R. 2010. Summer hot snaps and winter conditions: Modelling white syndrome outbreaks on Great Barrier Reef corals. *PLoS One,* 5: e12210: 1-11.
Hobbs, J.-P., A. and Frisch, A. J. 2010. Coral disease in the Indian Ocean: taxonomic susceptibility, spatial distribution and the role of host density on the prevalence of white syndrome *Diseases of Aquatic Organisms*: 1-8.

Hoegh-Guldberg, O., Poloczanska, E. S., Skirving, W. and Dove, S. 2017. Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science,* 4: 158.
Hogarth, W. 2006. Endangered and threatened species: final listing determinations for elkhorn coral and staghorn coral. *Federal Register,* 71: 26852-61.
Hudson, H. 2000. First aid for massive corals infected with black band disease: an underwater aspirator and post-treatment sealant to curtail re-infection. *In:* HALLOCK P & FRENCH L (eds.) *Diving for Science in the 21st Century.* Portland: : The American Academy of Underwater Sciences. pp. 10–11.
Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B., Kleypas, J., Van De Leemput, I. A., Lough, J. M. and Morrison, T. H. 2017a. Coral reefs in the Anthropocene. *Nature,* 546: 82-90.
Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R. and Berkelmans, R. 2017b. Global warming and recurrent mass bleaching of corals. *Nature,* 543: 373-377.
Jacobson, D. M., Smith, L. W., Dailer, M. L., Smith, J. E., Herzfeld, I., Smith, C. M., Sansone, F., Whelan, K. R., Miller, J. and Warra, R. 2006. Fine scale temporal and spatial dynamics of a Marshall Islands coral disease outbreak: Evidence for temperature forcing. *EOS, Transactions, American Geophysical Union,* 87: (36)
Joyner, J. L., Sutherland, K. P., Kemp, D. W., Berry, B., Griffin, A., Porter, J. W., Amador, M. H., Noren, H. K. and Lipp, E. K. 2015. Systematic analysis of white pox disease in *Acropora palmata* of the Florida Keys and role of *Serratia marcescens*. *Applied and Environmental Microbiology,* 81: 4451-4457.
Kaczmarsky, L. T. 2006. Coral disease dynamics in the central Philippines. *Diseases of Aquatic Organisms,* 69: 9-21.
Kaczmarsky, L. T. and Richardson, L. L. 2007. Transmission of growth anomalies between Indo-Pacific Porites corals. *Journal of Invertebrate Pathology,* 94: 218-221.
Katz, S. M., Pollock, F. J., Bourne, D. G. and Willis, B. L. 2014. Crown-of-thorns starfish predation and physical injuries promote brown band disease on corals. *Coral Reefs,* 33: 705-716.
Keen, E. C. 2015. A century of phage research: Bacteriophages and the shaping of modern biology. *BioEssays* 37: 6-9.
Kim, K. 2016. Diseases of Octocorals. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken: WILEY Blackwell. 410-415.
Kuta, K. G. and Richardson, L. L. 1996. Abundance and distribution of black band disesase on coral reefs in the northern Florida Keys. *Coral Reefs,* 15: 219-223.
Lajeunesse, T. C., Parkinson, J. E., Gabrielson, P. W., Jeong, H. J., Reimer, J. D., Voolstra, C. R. and Santos, S. R. 2018. Systematic revision of Symbiodiniaceae highlights the antiquity and diversity of coral endosymbionts. *Current Biology,* 28: 2570-2580. e6.
Landsberg, J. H., Kiryu, Y., Peters, E. C., Wilson, P. W., Perry, N., Waters, Y., Maxwell, K. E., Huebner, L. K. and Work, T. M. 2020. Stony coral tissue loss disease in Florida is associated with disruption of host–zooxanthellae physiology. *Frontiers in Marine Science*.
Lawrence, J. R., Chenier, M. R., Roy, R., Beaumier, D., Fortin, N., Swerhone, G. D., Neu, T. R. and Greer, C. W. 2004. Microscale and molecular assessment of impacts of nickel, nutrients, and oxygen level on structure and function of river biofilm communities. *Applied and Environmental Microbiology,* 70: 4326-39.
Lesser, M. P., Bythell, J. C., Gates, R. D., Johnstone, R. W. and Hoegh-Guldberg, O. 2007. Are infectious diseases really killing corals? Alternative interpretations of the experimental and ecological data. *Journal of Experimental Marine Biology and Ecology,* 346: 36-44.

Lesser, M. P. and Jarett, J. K. 2014. Culture-dependent and culture-independent analyses reveal no prokaryotic community shifts or recovery of *Serratia marcescens* in *Acropora palmata* with white pox disease. *FEMS Microbiology Ecology,* 88: 457-467.
Lobban, C. S., Raymundo, L. M. and Montagnes, D. J. S. 2011. *Porpostoma guamensis* n. sp., a Philasterine Scuticociliate associated with brown-band disease of corals. *Journal of Eukaryotic Microbiology,* 58: 103-113.
Loya, Y., Bull, G. and Pichon, M. 1984. Tumor formations in scleractinian corals. *Helgolander Meersuntersuchungen,,* 37: 138-151.
Luna, G. M., Bongiorni, L., Gili, C., Biavasco, F. and Danovaro, R. 2010. *Vibrio harveyi* as a causative agent of the white syndrome in tropical stony corals. *Environmental Microbiology Reports* 2: 120-127.
Meyer, J. L., Paul, V. J., Raymundo, L. J. and Teplitski, M. 2017. Comparative metagenomics of the polymicrobial black band disease of corals. *Frontiers in Microbiology,* 8: 618.
Meyer, J. L., Castellanos-Gell, J., Aeby, G. S., Häse, C. C., Ushijima, B. and Paul, V. J. 2019. Microbial community shifts associated with the ongoing stony coral tissue loss disease outbreak on the Florida Reef Tract. *Frontiers in Microbiology,* 10: 2244.
Miller, M. W., Lohr, K. E., Cameron, C. M., Williams, D. E. and Peters, E. C. 2014. Disease dynamics and potential mitigation among restored and wild staghorn coral, *Acropora cervicornis*. *PeerJ,* 2: e541.
Miller, M. W., Karazsia, J., Groves, C. E., Griffin, S., Moore, T., Wilber, P. and Gregg, K. 2016. Detecting sedimentation impacts to coral reefs resulting from dredging the Port of Miami, Florida USA. *PeerJ,* 4: e2711.
Montano, S., Strona, G., Seveso, D., Maggioni, D. and Galli, P. 2016. Widespread occurrence of coral diseases in the central Maldives. *Marine and Freshwater Research,* 67: 1253-1262.
Montano, S., Maggioni, D., Liguori, G., Arrigoni, R., Berumen, M. L., Seveso, D., Galli, P. and Hoeksema, B. W. 2020. Morpho-molecular traits of Indo-Pacific and Caribbean Halofolliculina ciliate infections. *Coral Reefs*: 1-12.
Montilla, L. M., Ascanio, A., Verde, A. and Croquer, A. 2019. Systematic review and meta-analysis of 50 years of coral disease research visualized through the scope of network theory. *PeerJ,* 7: e7041.
Muller, E., Rogers, C. S., Spitzack, A. S. and Van Woesik, R. 2008. Bleaching increases likelihood of disease on *Acropora palmat*a (Lamarck) in Hawksnest Bay, St John, US Virgin Islands. *Coral Reefs,* 27: 191-195.
Muller, E. M., Sartor, C., Alcaraz, N. I. and Van Woesik, R. 2020. Spatial epidemiology of the stony-coral-tissue-loss disease in Florida. *Frontiers in Marine Science,* 7: 163.
Myers, R. L. and Raymundo, L. J. 2009. Coral disease in Micronesian reefs: a link between disease prevalence and host abundance. *Diseases of Aquatic Organisms,* 87: 97-104.
National Academies of Sciences, E., And Medicine 2018. A research review of interventions to increase the persistence and resilience of coral reefs. The National Academies Press. Washington, DC. pp. 230.
National Academies of Sciences, E., And Medicine 2019 2019. A decision framework for interventions to increase the persistence and resilience of coral reefs. The National Academies Press. Washington, DC. pp. 200.
Nicolet, K., Hoogenboom, M. O., Gardiner, N., Pratchett, M. and Willis, B. 2013. The corallivorous invertebrate Drupella aids in transmission of brown band disease on the Great Barrier Reef. *Coral Reefs,* 32: 585-595.
Nicolet, K., Chong-Seng, K., Pratchett, M., Willis, B. and Hoogenboom, M. 2018. Predation scars may influence host susceptibility to pathogens: evaluating the role of corallivores as vectors of coral disease. *Scientific Reports,* 8: 1-10.

Nugues, M. M. 2002. Impact of a coral disease outbreak on coral communities in St. Lucia: What and how much has been lost? *Marine Ecology Progress Series,* 229: 61-71.
Nugues, M. M. and Bak, R. P. M. 2009. Brown-band syndrome on feeding scars of the crown-of-thorn starfish *Acanthaster planci*. *Coral Reefs,* 28: 507-510.
Onton, K., Page, C. A., Wilson, S. K., Neale, S. and Armstrong, S. 2011. Distribution and drivers of coral disease at Ningaloo reef, Indian Ocean. *Marine Ecology Progress Series,* 433: 75-84.
Page, C. A. and Willis, B. L. 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 Willis, B. L. 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.
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. *Diseases of Aquatic Organisms,* 87: 135-150.
Page, C. A. and Stoddart, J. A. 2010. New records of five coral diseases from the Pilbara Region of Western Australia. *Coral Reefs,* 29: 987-987.
Page, C. A., Cróquer, A., Bastidas, C., Rodríguez, S., Neale, S. J., Weil, E. and Willis, B. L. 2016. Halofolliculina ciliate infections on corals (skeletal eroding disease). *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* . Hoboken, New Jersey: WILEY Blackwell. 361-375.
Pandolfi, J. M. and Jackson, J. B. C. 2006. Ecological persistence interrupted in Caribbean coral reefs. *Ecology Letters,* 9: 818-826.
Pantos, O., Cooney, R. P., Le Tissier, M. D., Barer, M. R., O'donnell, A. G. and Bythell, J. C. 2003. The bacterial ecology of a plague-like disease affecting the Caribbean coral *Montastrea annularis*. *Environmental Microbiology,* 5: 370-82.
Patten, N. L., Harrison, P. L. and Mitchell, J. G. 2008. Prevalence of virus-like particles within a staghorn scleractinian coral (*Acropora muricata*) from the Great Barrier Reef. *Coral Reefs,* 27: 569-580.
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*. *Proceedings of the National Academy of Sciences of the United States of America,* 99: 8725-30.
Peixoto, R. S., Rosado, P. M., Leite, D. C. D. A., Rosado, A. S. and Bourne, D. G. 2017. Beneficial microorganisms for corals (BMC): proposed mechanisms for coral health and resilience. *Frontiers in Microbiology,* 8: 341.
Peters, E. C. 1984. A survey of cellular reactions to environmental stress and disease in Caribbean scleractinian corals. *Helgolander Meersuntersuchungen,* 37: 113-137.
Peters, E. C., Halas, J. C. and Mccarty, H. B. 1986. Calicoblastic neoplasms in *Acropora palmata*, with a review of reports on anomalies of growth and form in corals. *Journal of the National Cancer Institute,* 76: 895-912.
Pollock, F. J., Wood-Charlson, E. M., Van Oppen, M. J. H., Bourne, D. G., Willis, B. L. and Weynberg, K. D. 2014. Abundance and morphology of virus-like particles associated with the coral *Acropora hyacinthus* differ between healthy and white syndrome-infected states. *Marine Ecology Progress Series,* 510: 39-43.
Pollock, F. J., Wada, N., Torda, G., Willis, B. L. and Bourne, D. G. 2017. White syndrome-affected corals have a distinct microbiome at disease lesion fronts. *Applied and Environmental Microbiology,* 83.

Porter, J. W., Dustan, P., Jaap, W. C., Patterson, K. L., Kosmynin, V., Meier, O. W., Patterson, M. E. and Parsons, M. 2001. Patterns of spread of coral disease in the Florida Keys. *Hydrobiologia,* 460: 1-24.
Porter, J. W., Torres, C., Sutherland, K. P., Meyers, M. K., Callahan, M. K., Ruzicka, R. and Colella, M. 2011. Prevalence, severity, lethality, and recovery of dark spots syndrome among three Floridian reef-building corals. *Journal of Experimental Marine Biology and Ecology,* 408: 79-87.
Pratte, Z. A. and Richardson, L. L. 2016. Possible links between white plague-like disease, scleractinian corals, and a cryptochirid gall crab. *Diseases of Aquatic Organisms,* 122: 153-161.
Precht, W. F., Gintert, B. E., Robbart, M. L., Fura, R. and Van Woesik, R. 2016. Unprecedented disease-related coral mortality in Southeastern Florida. *Scientific Reports,* 6: 31374.
Precht, W. F. 2019. Failure to respond to a coral disease outbreak: potential costs and consequences. PeerJ Preprints.
Preston, S. and Richards, Z. 2020. Biological consequences of an outbreak of growth anomalies on Isopora palifera at the Cocos (Keeling) Islands. *Coral Reefs*: 1-13.
Qiu, D., Huang, L., Huang, H., Yang, J. and Lin, S. 2010. Two functionally distinct ciliates dwelling in *Acropora* corals in the South China Sea near Sanya, Hainan Province, China. *Applied and Environmental Microbiology,* 76: 5639-5643.
Randall, C. J., Jordán-Garza, A. G. and Van Woesik, R. 2015. Ciliates associated with signs of disease on two Caribbean corals. *Coral Reefs,* 34: 243-247.
Randall, C. J., Whitcher, E. M., Code, T., Pollock, C., Lundgren, I., Hillis-Starr, Z. and Muller, E. M. 2018. Testing methods to mitigate Caribbean yellow-band disease on Orbicella faveolata. *PeerJ,* 6: e4800.
Raymundo, L. J., Harvell, C. D. and Reynolds, T. L. 2003. *Porites* ulcerative white spot disease: description, prevalence, and host range of a new coral disease affecting Indo-Pacific reefs. *Diseases of Aquatic Organisms,* 56: 95-104.
Raymundo, L. J., Rosell, K. B., Reboton, C. T. and Kaczmarsky, L. 2005. Coral diseases on Philippine reefs: genus *Porites* is a dominant host. *Diseases of Aquatic Organisms,* 64: 181-191.
Reeves, L. 1994. Newly discovered: yellow band disease strikes keys reefs. *Underwater USA,* 11: 16.
Renegar, D.-E. A., Blackwelder, P., Miller, J., Gochfeld, D. and Moulding, A. L. 2008. Ultrastructural and histological analysis of dark spot syndrome in *Siderastrea siderea* and *Agaricia agaricites*. Proceedings of the 11th International Coral Reef Symposium, Ft Lauderdale, Florida 7.
Richardson, L. L. 1998. Coral diseases: what is really known? *Trends in Ecology & Evolution,* 13: 438-443.
Richardson, L. L., Smith, G. W., Ritchie, K. B. and Carlton, R. G. 2001. Integrating microbiological, microsensor, molecular, and physiologic techniques in the study of coral disease pathogenesis. *Hydrobiologia,* 460: 71-89.
Richardson, L. L. 2004. Black Band Disease. *In:* ROSENBERG, E. & LOYA, Y. (eds.) *Coral Health and Disease.* Berlin: Springer-Verlag. 325-336.
Richardson, L. L., Sekar, R., Myers, J. L., Gantar, M., Voss, J. D., Kaczmarsky, L., Remily, E. R., Boyer, G. L. and Zimba, P. V. 2007. The presence of the cyanobacterial toxin microcystin in black band disease of corals. *FEMS Microbiology Letters,* 272: 182-187.
Ritchie, K. B. and Smith, G. W. 1998. Type II white-band disease. *Revista De Biologia Tropical,* 46: 199-203.

Ritchie, K. B. 2006. Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. *Marine Ecology-Progress Series,* 322: 1-14.
Rodriguez-Martinez, R., Banaszak, A. and Jordan-Dahlgren, E. 2001. Necrotic patches affect *Acropora palmata* (Scleractinia: acroporidae) in the Mexican Caribbean. *Diseases of Aquatic Organisms,* 47: 229-234.
Rodríguez, S., Croquer, A., Guzmán, H. M. and Bastidas, C. 2009. A mechanism of transmission and factors affecting coral susceptibility to *Halofolliculina sp*. infection. *Coral Reefs,* 28: 67-77.
Rosado, P. M., Leite, D. C., Duarte, G. A., Chaloub, R. M., Jospin, G., Da Rocha, U. N., Saraiva, J. P., Dini-Andreote, F., Eisen, J. A. and Bourne, D. G. 2018. Marine probiotics: increasing coral resistance to bleaching through microbiome manipulation. *The ISME Journal*: 1.
Rosales, S. M., Clark, A. S., Huebner, L. K., Ruzicka, R. R. and Muller, E. M. 2020. *Rhodobacterales* and *Rhizobiales* are associated with stony coral tissue loss disease and its suspected sources of transmission. *Frontiers in Microbiology,* 11: 681.
Rosenberg, E., Koren, O., Reshef, L., Efrony, R. and Zilber-Rosenberg, I. 2007. The role of microorganisms in coral health, disease and evolution. *Nature Reviews Microbiology,* 5.
Santavy, D. L. and Peters, E. C. 1997. Microbial pests: coral disease in the Western Atlantic. Proceedings of the 8th International Coral Reef Symposium. 607-612.
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). *Proceedings of the Royal Society B: Biological Sciences,* 276: 2795-2803.
Sato, Y., Willis, B. L. and Bourne, D. G. 2010. Successional changes in bacterial communities during the development of black band disease on the reef coral, *Montipora hispida The ISME Journal* 4: 203-214.
Sato, Y., Willis, B. L. and Bourne, D. G. 2013. Pyrosequencing-based profiling of archaeal and bacterial 16S rRNA genes identifies a novel archaeon associated with black band disease in corals. *Environmental Microbiology,* 15: 2994-3007.
Sato, Y., Civiello, M., Bell, S. C., Willis, B. L. and Bourne, D. G. 2016. Integrated approach to understanding the onset and pathogenesis of black band disease in corals. *Environmental Microbiology,* 18: 752-765.
Sato, Y., Ling, E. Y., Turaev, D., Laffy, P., Weynberg, K. D., Rattei, T., Willis, B. L. and Bourne, D. G. 2017. Unraveling the microbial processes of black band disease in corals through integrated genomics. *Scientific Reports,* 7: 1-14.
Sekar, R., Kaczmarsky, L. T. and Richardson, L. L. 2008. Microbial community composition of black band disease on the coral host *Siderastrea siderea* from three regions of the wider Caribbean. *Marine Ecology-Progress Series,* 362: 85-98.
Séré, M. G., Schleyer, M. H., Quod, J. P. and Chabanet, P. C. R.-. 2012. *Porites* white patch syndrome: an unreported coral disease on Western Indian Ocean reefs. *Coral Reefs,* 31: 739.
Shapiro, O. H., Kramarsky-Winter, E., Gavish, A. R., Stocker, R. and Vardi, A. 2016. A coral-on-a-chip microfluidic platform enabling live-imaging microscopy of reef-building corals. *Nature Communications,* 7: 1-10.
Sheridan, C., Kramarsky-Winter, E., Sweet, M., Kushmaro, A. and Leal, M. C. 2013. Diseases in coral aquaculture: causes, implications and preventions. *Aquaculture,* 396-399: 124-135.
Shnit-Orland, M. and Kushmaro, A. 2009. Coral mucus-associated bacteria: a possible first line of defense. *FEMS Microbiology Ecology,* 67: 371-380.
Smith, H. A., Conlan, J. A., Pollock, F. J., Wada, N., Shore, A., Hung, J. Y.-H., Aeby, G. S., Willis, B. L., Francis, D. S. and Bourne, D. G. 2020. Energy depletion and opportunistic

microbial colonisation in white syndrome lesions from corals across the Indo-Pacific. *Scientific Reports,* 10: 1-14.
Solano, O. D., Navas Suárez, G. and Moreno-Forero, S. K. 1993. Blanqueamiento coralino de 1990 en el Parque Nacional Natural Corales del Rosario (Caribe, colombiano). *Boletín de Investigaciones Marinas y Costeras-INVEMAR,* 22: 97-111.
Spalding, M., Burke, L., Wood, S. A., Ashpole, J., Hutchison, J. and Zu Ermgassen, P. 2017. Mapping the global value and distribution of coral reef tourism. *Marine Policy,* 82: 104-113.
Squires, D. F. 1965. Neoplasia in a Coral? *Science,* 148: 503-505.
Sudek, M., Work, T. M., Aeby, G. and Davy, S. 2012. Histological observations in the Hawaiian reef coral, *Porites compressa*, affected by *Porites* bleaching with tissue loss. *Journal of Invertebrate Pathology,* 111: 121-125.
Sussman, M., Willis, B. L., Victor, S. and Bourne, D. G. 2008. Coral pathogens identified for white syndrome (WS) epizootics in the Indo-Pacific. *PLoS One,* 3: e2393.
Sussman, M., Mieog, J. C., Doyle, J., Victor, S., Willis, B. L. and Bourne, D. G. 2009. *Vibrio* zinc-metalloprotease causes photoinactivation of coral endosymbionts and coral tissue lesions. *PLoS One,* 4: e4511.
Sutherland, K. P., Porter, J. W. and Torres, C. 2004. Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals. *Marine Ecology-Progress Series,* 266: 273-302.
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. 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*. *Environmental Microbiology,* 12: 1122-1131.
Sutherland, K. P., Berry, B., Park, A., Kemp, D. W., Kemp, K. M., Lipp, E. K. and Porter, J. W. 2016a. Shifting white pox aetiologies affecting *Acropora palmata* in the Florida Keys, 1994–2014. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 371: 20150205.
Sutherland, K. P., Lipp, E. K. and Porter, J. W. 2016b. Acroporid Serratiosis. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken, New Jersey: WILEY-Blackwell. 221-230.
Sweet, M., Jones, R. and Bythell, J. 2011. Coral diseases in aquaria and in nature. *Journal of the Marine Biological Association of the United Kingdom,* 92: 791-801.
Sweet, M. and Bythell, J. 2012. Ciliate and bacterial communities associated with white syndrome and brown band disease in reef-building corals. *Environmental Microbiology,* 14: 2184-2199.
Sweet, M., Burn, D., Croquer, A. and Leary, P. 2013. Characterisation of the bacterial and fungal communities associated with different lesion sizes of dark spot syndrome occurring in the coral *Stephanocoenia intersepta*. *PLoS One,* 8: e62580.
Sweet, M. J., Croquer, A. and Bythell, J. C. 2014. Experimental antibiotic treatment identifies potential pathogens of white band disease in the endangered Caribbean coral *Acropora cervicornis*. *Proceedings of the Royal Society B: Biological Sciences,* 281: 20140094.
Sweet, M. J. and Bulling, M. T. 2017. On the importance of the microbiome and pathobiome in coral health and disease. *Frontiers in Marine Science,* 4: 9.
Thompson, F. L., Barash, Y., Sawabe, T., Sharon, G., Swings, J. and Rosenberg, E. 2006. *Thalassomonas loyana sp* nov, a causative agent of the white plague-like disease of corals on the Eilat coral reef. *International Journal of Systematic and Evolutionary Microbiology,* 56: 365-368.

Ulstrup, K. E., Kuhl, M. and Bourne, D. G. 2007. Zooxanthellae harvested by ciliates associated with brown band syndrome of corals remain photosynthetically competent. *Applied and Environmental Microbiology,* 73: 1968-1975.
Ushijima, B., Smith, A., Aeby, G. S. and Callahan, S. M. 2012. *Vibrio owensii* induces the tissue loss disease *Montipora* white syndrome in the Hawaiian Reef Coral *Montipora capitata*. *PLoS One,* 7: e46717.
Ushijima, B., Videau, P., Burger, A. H., Shore-Maggio, A., Runyon, C. M., Sudek, M., Aeby, G. S. and Callahan, S. M. 2014. *Vibrio coralliilyticus* strain OCN008 is an etiological agent of acute *Montipora* white syndrome. *Applied and Environmental Microbiology,* 80: 2102-2109.
Vargas-Angel, B. 2009. Coral health and disease assessment in the US Pacific Remote Islands Areas. *Bulletin of Marine Science,* 84: 211-227.
Vega Thurber, R. L., Mydlarz, L. D., Brandt, M., Harvell, C. D., Weil, E., Raymundo, L., Willis, B., Langevin, S., Tracy, A. M. and Littman, R. 2020. Deciphering coral disease dynamics: integrating host, microbiome, and the changing environment. *Frontiers in Ecology and Evolution,* 8: 402.
Vollmer, S. V. and Kline, D. I. 2008. Natural disease resistance in threatened staghorn corals. *PLoS One,* 3: e3718.
Walton, C. J., Hayes, N. K. and Gilliam, D. S. 2018. Impacts of a regional, multi-year, multi-species coral disease outbreak in Southeast Florida. *Frontiers in Marine Science,* 5: 323.
Weil, E. 2004. Coral Diseases in the wider Caribbean. *In:* ROSENBERG, E. & LOYA, Y. (eds.) *Coral Health and Disease.* Berlin: Springer-Verlag. 35-68.
Weil, E., Cróquer, A. and Urreiztieta, I. 2009. Yellow band disease compromises the reproductive output of the Caribbean reef-building coral *Montastraea faveolata* (Anthozoa, Scleractinia). *Diseases of Aquatic Organisms,* 87: 45-55.
Weil, E. and Rogers, C. S. 2011. Coral reef diseases in the Atlantic-Caribbean. *Coral reefs: an ecosystem in transition.* Springer. 465-491.
Weil, E., Irikawa, A., Casareto, B. and Suzuki, Y. 2012. Extended geographic distribution of several Indo-Pacific coral reef diseases. *Diseases of Aquatic Organisms,* 98: 163-170.
Weil, E., Rogers, C. S. and Croquer, A. 2015. Octocoral diseases in a changing ocean. *In:* ROSSI, S., BRAMANTI, L., GORI, A. & OREJAS SACO DEL VALLE, C. (eds.) *Marine Animal Forests: The Ecology of Benthic Biodiversity Hotspots.* Cham: Springer International Publishing. 1-55.
Weil, E., Hernández-Delgado, E., Gonzalez, M., Williams, S., Suleimán-Ramos, S., Figuerola, M. and Metz-Estrella, T. 2019. Spread of the new coral disease "SCTLD" into the Caribbean: implications for Puerto Rico. *Reef Encounter,* 34: 38-43.
Williams, G. J., Aeby, G. S., Cowie, R. O. and Davy, S. K. 2010. Predictive modeling of coral disease distribution within a reef system. *PLoS One,* 5: e9264.
Willis, B. L., Page, C. A. and Dinsdale, E. A. 2004. Corals disease on the Great Barrier Reef. *In:* ROSENBERG, E. & LOYA, Y. (eds.) *Coral Health and Disease.* Heildelberg: Springer-Verlag 69-104.
Work, T. M. and Rameyer, R. A. 2005. Characterizing lesions in corals from American Samoa. *Coral Reefs,* 24: 384-390.
Work, T. M. and Aeby, G. S. 2006. Systematically describing gross lesions in corals. *Diseases of Aquatic Organisms,* 70: 155-160.
Work, T. M., Aeby, G. S. and Coles, S. L. 2008a. Distribution and morphology of growth anomalies in *Acropora* from the Indo-Pacific. *Diseases of Aquatic Organisms,* 78: 255-264.
Work, T. M., Richardson, L. L., Reynolds, T. L. and Willis, B. L. 2008b. Biomedical and veterinary science can increase our understanding of coral disease. *Journal of Experimental Marine Biology and Ecology,* 362: 63-70.

Work, T. M., Russell, R. and Aeby, G. S. 2012. Tissue loss (white syndrome) in the coral *Montipora capitata* is a dynamic disease with multiple host responses and potential causes. *Proceedings of the Royal Society B: Biological Sciences,* 279: 4334-4341.
Work, T. M. and Aeby, G. S. 2014. Microbial aggregates within tissues infect a diversity of corals throughout the Indo-Pacific. *Marine Ecology Progress Series,* 500: 1-9.
Work, T. M., Kaczmarsky, L. T. and Peters, E. C. 2015. Skeletal growth anomalies in corals. *In:* WOODLEY, C. M., DOWNS, C. A., BRUCKNER, A. W., PORTER, J. W. & GALLOWAY, S. B. (eds.) *Diseases of Coral.* Hoboken, New Jersey: WILEY-blackwell. 291-299.
Worms Editorial Board: 2019 World Register of Marine Species.
Zverlov, V., Klein, M., Lücker, S., Friedrich, M. W., Kellermann, J., Stahl, D., Loy, A. and Wagner, M. 2005. Lateral gene transfer of dissimilatory (bi)sulfite reductase revisited *Journal of Bacteriology,* 187: 2203-2208.