CORAL DISEASES

CORDAP R&D TECHNOLOGY ROADMAP

cordap
G20 Coral Research & Development Accelerator Platform

CORALIUM

Universidad Nacional Autónoma de México

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

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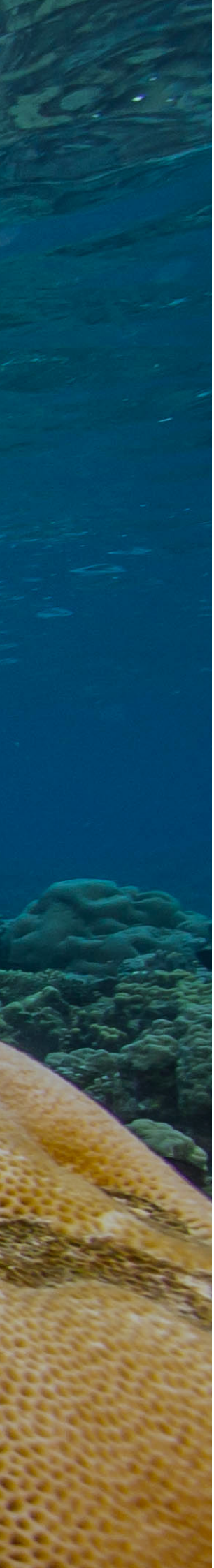

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Scope of work

From the 29th to the 31st of October 2024, an in-person workshop was held in the Riviera Maya, Mexico to bring together 25 experts researching different aspects of infectious diseases and coral reef ecology around the globe, as well as those working on diseases in other marine and terrestrial environments from which to draw knowledge that could be applied in coral ecosystems. Each day of the three-day workshop had a different theme. On day 1, the theme was "Current State of Knowledge of Coral Disease" with the objective to understand what is known about diseases in coral and to identify knowledge gaps. Day 2 was devoted to understanding the "Current State of Knowledge of Diseases in Other Organisms" and the objective was to determine whether the techniques used in other kinds of disease outbreaks could be applied to corals. On day 3, the theme was "Future Directions: Approaches to Combating Coral Diseases" to determine the paths forward. Each day, the workshop started with presentations by experts about the theme of the day, with a question and answer at the end of the expert´s interventions. To end the day, panel sessions were held to discuss how best to overcome the identified knowledge gaps and apply what we learned during the morning sessions.

This workshop was timely, particularly given the increased interest in ecological restoration, biobanking and cryopreservation, the quality of which could be compromised in the presence of diseases.

1. Executive summary

Coral reefs worldwide are facing an unprecedented crisis. Large-scale bleaching events, exacerbated by declining water quality due to inadequate sewage treatment, sedimentation, and pollution from river discharges, have drastically reduced coral cover. Infectious diseases and other stressors have further contributed to coral loss, disrupting reproductive connectivity and natural recruitment, which are essential for reef resilience.

The goals of the workshop were to review the current state of knowledge about coral diseases (day 1), diseases in other groups (day 2), and future directions in combating coral diseases (day 3), as well as to identify critical knowledge gaps and suggest paths to move forward. This gathering of experts also served to motivate knowledge sharing and collaboration among researchers from different geographical regions, given the problems that diseases cause and the possibility of new diseases in the future.

One of the key takeaways was the shift in focus from traditional infection control to microbiome management strategies. The preservation of coral genetic diversity through biobanking, restoration, and cryopreservation was also highlighted as a necessary precaution in the face of escalating disease threats. Additionally, establishing a coral disease biobank was identified as a priority to enable retrospective analyses and comparisons with potential future outbreaks.

A fundamental limitation in coral disease research has been the lack of centralized, long-term datasets that integrate ecological, environmental, and molecular data. To address this, there is a pressing need for a Global Platform for Scientific Networking and Data Integration — a centralized repository that consolidates disease monitoring records, facilitates real-time data sharing, and provides open-access resources such as best practices manuals, standardized protocols, and training materials. Such a platform would enhance early detection, improve outbreak response, and streamline the development of science-based interventions for coral disease containment and treatment.

The increasing reliance on coral reef restoration as a conservation strategy makes disease management an urgent priority. Without proactive disease mitigation, restoration efforts risk being undermined by recurring outbreaks. A globally accessible data infrastructure would not only support restoration practitioners with up-to-date disease management tools but also enable predictive modeling to anticipate emerging threats. Additionally, substantial investment in research and development is crucial to accelerating scientific advancements in coral resilience and disease intervention strategies. Programs such as the G20 Coral Research & Development Accelerator Platform (CORDAP) serve as exemplary models for fostering interdisciplinary research and technological innovation in coral conservation.

Effectively addressing coral disease necessitates a comprehensive and integrative approach that integrates ecology, microbiology, medicine, predictive modeling, and strategic investment in research. This multidisciplinary framework is essential for safeguarding the future of coral reef ecosystems amid accelerating environmental change. In this context, the development of a roadmap is critical to aligning efforts across disciplines, ensuring that restoration strategies are informed by the latest scientific advancements in disease prevention and coral resilience.

Credits: Greta Aaby

2. CORDAP R&D roadmap for coral diseases

2.1 Coral diseases: what we know

In recent decades, coral diseases have emerged as one of the primary global threats to the health and functionality of coral reefs (Vega-Thurber *et al.*, 2024). The increasing frequency and intensity of disease outbreaks have triggered mass mortality events and drastically reduced live coral cover, resulting in significant biodiversity loss and the widespread degradation of these ecosystems (Alvarez-Filip *et al.*, 2022). Since their emergence, coral disease outbreaks have proven to be complex phenomena influenced by multiple biotic and abiotic factors (Figure 1). Generally, coral diseases are characterized by changes in coral coloration, rapid tissue loss, and disruption of the symbiotic relationship with Symbiodiniaceae, often culminating in coral mortality (Richardson, 1998; Miller *et al.*, 2009). Various pathogens, including bacteria, fungi, protozoa, and viruses, have been associated with coral diseases, with significant contributors being *Vibrio* spp., and *Roseofilum* spp., among other bacterial groups (Sutherland *et al.*, 2004; Sato *et al.*, 2016). Based on their pathological manifestations, coral diseases can be broadly classified into three major categories: growth anomalies, pigmentation disorders, and tissue-loss diseases.

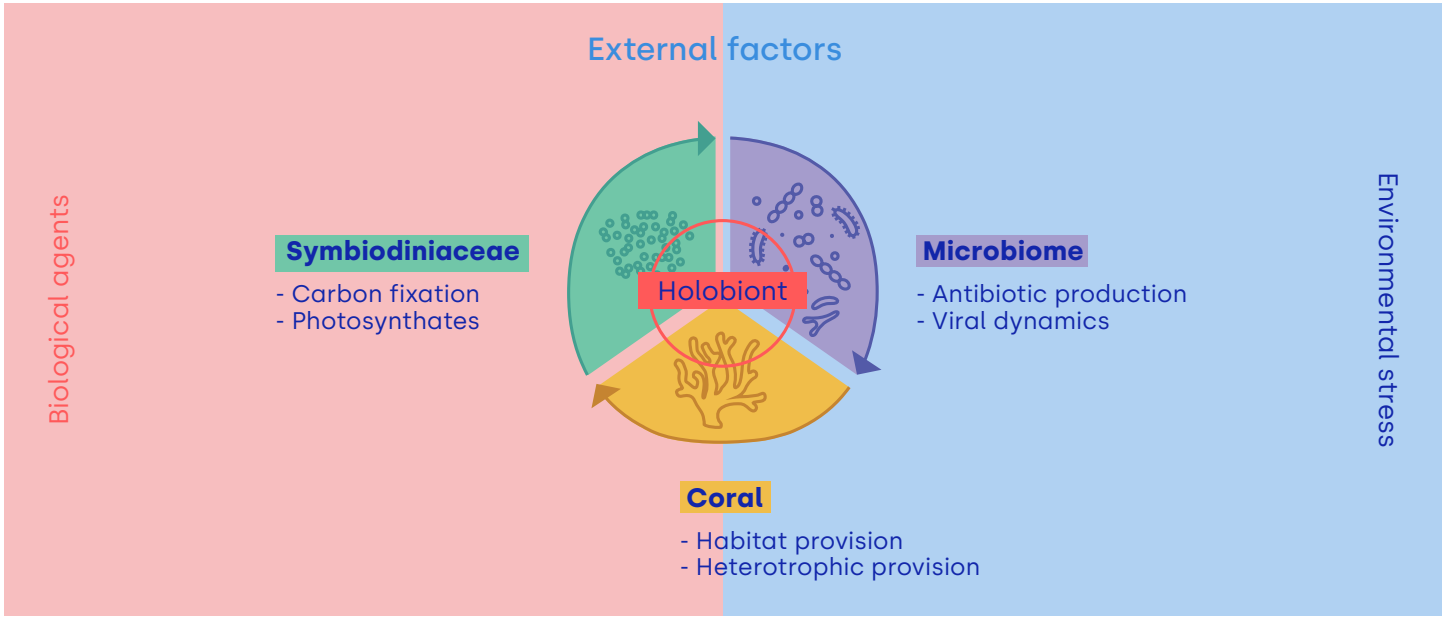


Figure 1. Conceptual model of the holobiont components and their interactions with external factors and biological agents in the development of coral diseases.
The coral holobiont comprises three main components: the coral host, the dinoflagellate symbiont of the order Symbiodiniaceae, and the associated microbiome. This system interacts dynamically with external factors and biological agents that influence coral health and the prevalence of diseases. **Coral:** The fundamental structure forming the reef, which is produced by scleractinian corals and other organisms, providing a physical habitat and energy through carbon fixation carried out by its symbionts. It is highly susceptible to environmental stress, such as elevated sea surface temperatures. **Symbiodiniaceae:** Symbiotic microalgae that perform photosynthesis, supplying essential energy products to the coral. Environmental disturbances, such as elevated sea surface temperature (SST), lead to coral bleaching due to the disruption of this symbiotic association. **Microbiome:** A diverse microbial community including bacteria, archaea, fungi, viruses, and protozoa and their interactions within the holobiont. It plays a crucial role in regulating coral health but can also include pathogens such as *Vibrio* spp. and *Roseofilum reptotaenium*. **Environmental stress:** Elevated sea surface temperatures (SST) and eutrophication are key triggers that exacerbate coral susceptibility to diseases. These factors disrupt the holobiont's homeostasis, weakening coral immune defenses and favoring pathogen proliferation. Biological factors: Associated biotic pathogenic agents, including bacteria, fungi, and viruses, interact with environmental conditions to promote disease emergence and transmission. **Coral disease dynamics:** Changes in coral coloration, rapid tissue loss, and disruption of the symbiosis, often culminating in coral mortality.

Growth anomalies

Credits: Greta Aeby

Growth anomalies (GAs) are a coral disease characterized by abnormal proliferation of coral tissue, leading to macroscopically visible structures with diverse morphologies, including nodular, exophytic, and umbonate formations (Peters *et al.*, 1986; Ricci, 2022). Due to their appearance, early observations of some GAs were mistakenly classified as different species of coral or as neoplasms or tumors (Tarin, 2023). These anomalies have been reported across tropical reef regions and affect multiple genera of scleractinian corals, with particularly high prevalence in species of the genera *Acropora* spp., *Montipora* spp., and *Porites* spp. (Work *et al.*, 2015).

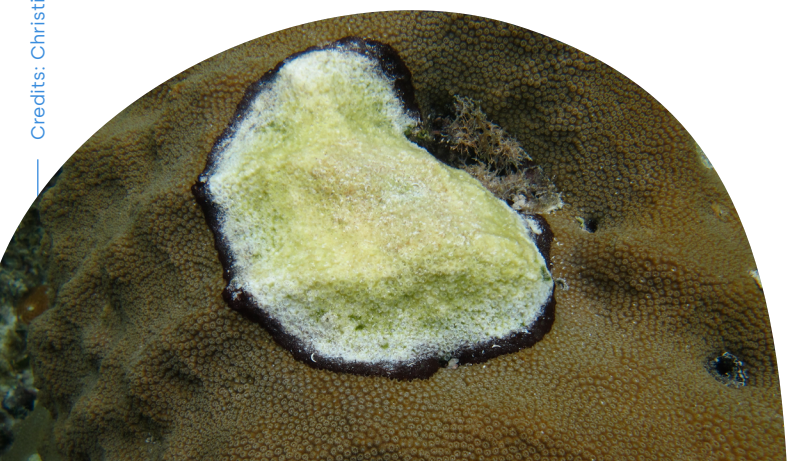
The etiology of GAs remains unclear, though a multifactorial origin has been proposed. Bacterial and viral pathogens have been suggested as potential contributors to these anomalies. Additionally, studies have identified significant correlations between GA incidence and abiotic environmental factors such as rising ocean temperatures, anthropogenic pollution, and parasitic infections (Aeby *et al.*, 2011). The proximity to areas of high human density has been linked to a higher prevalence of the disease, suggesting that GAs could serve as a bioindicator of Anthropocene-driven impacts on coral reef ecosystems.

Histologically, GAs are characterized by exacerbated cellular proliferation and alterations in calcium carbonate deposition, compromising the structural integrity and functionality of the coral host (Work *et al.*, 2015). Affected tissue often exhibits localized necrosis, reduced reproductive capacity, and skeletal fragility, diminishing resilience to environmental stressors and increasing susceptibility to secondary diseases (Burns & Takabayashi, 2011). Transcriptomic analyses have revealed the overexpression of genes associated with morphogenesis, osteogenesis, and organogenesis, drawing parallels to tumorigenic processes observed in vertebrates (Domart-Coulon *et al.*, 2006). Tarin (2023) confirmed that the GAs of *Acropora palmata*, termed calicoblastic epitheliomas, are an example of neoplasia in coral.

Furthermore, GAs disrupt the homeostasis of the coral holobiont by altering its symbiotic relationship with *Symbiodiniaceae*. A decline in symbiont density has been documented in affected tissues in some GAs, leading to reduced photosynthetic activity and, consequently, diminished energy production for the coral (Bak, 1983; Shore-Maggio *et al.*, 2018). While GAs generally progress at a slower rate than acute tissue loss diseases, their chronic nature and long-term debilitating effects underscore the urgent need for further research into their pathogenesis and mitigation strategies. Future studies should focus on the interplay between genetic and environmental factors in GA development, as well as the implementation of monitoring tools and conservation strategies to mitigate their impact within the context of accelerating climate change.

Pigmentation disorders

Discoloration Diseases (DDs) in corals represent a significant yet poorly understood threat to reef ecosystems. These diseases, first documented in the late 20th century, are characterized by abnormal pigmentation changes in coral tissues, often manifesting as dark spots, yellow bands, or diffuse discoloration (Goreau *et al.*, 1998; Cervino *et al.* 2001). Affected corals exhibit irregularly shaped lesions in shades of purple, black, or brown, which may spread across the coral-algal boundary or remain localized. Although DDs do not always lead to immediate tissue mortality, severe cases can result in necrosis progressing at rates of up to 4 cm per month, compromising coral health and structural integrity (Cervino *et al.*, 2001). These diseases are prevalent in multiple coral species, particularly *Orbicella annularis*, *Siderastrea siderea*, and *Stephanocoenia intersepta*, which play key roles in reef stability and biodiversity (Garzón-Ferreira *et al.*, 2001).



Credits: Christina A. Kellogg

The etiology of DDs remains unresolved, with multiple potential causative agents implicated. Studies suggest that both fungi and bacteria contribute to disease progression, yet no definitive pathogen has been identified (Renegar *et al.*, 2008; Sweet *et al.*, 2013). Environmental stressors (abiotic factors), particularly elevated sea surface temperatures, are strongly associated with disease outbreaks, with

peak prevalence occurring during summer months (Weil, 2004). Additionally, large-scale climatic events such as El Niño-Southern Oscillation have been linked to increased incidence, indicating a complex interplay between pathogens and environmental conditions (Randall & van Woesik, 2017). The physiological mechanisms driving tissue discoloration are not fully understood but may involve microbial dysbiosis, immune responses, or disruptions in coral-symbiont interactions (Gil-Agudelo *et al.*, 2007).

Discoloration diseases pose significant challenges for coral resilience by disrupting symbiotic relationships and altering coral physiology. Affected corals often experience a decline in Symbiodiniaceae density or shifts in symbiont community composition, potentially reducing photosynthetic efficiency and energy production (Gil-Agudelo *et al.*, 2007; Work & Weil, 2015). This weakened physiological state may lower coral resistance to additional stressors, such as ocean acidification, pollution, and other diseases.

Tissue-loss diseases

Tissue-loss diseases are among the most widespread and destructive coral pathologies. These diseases result in progressive tissue necrosis, exposing the underlying skeleton and often leading to colony mortality (Richardson, 1998). Black band disease (BBD) was the first documented coral disease, initially observed in the Belize reefs in 1973 and later spreading throughout the Caribbean, the Indo-Pacific, and the Red Sea (Antonius, 1973; Edmunds, 1991). BBD is caused by a complex microbial consortium, including the cyanobacterium *Roseofilum reptotaenium*, sulfur-reducing bacteria, and other associated microbes (Sato *et al.*, 2016). Other notable tissue-loss diseases include white plague, which primarily affects *Acropora* spp. in the Caribbean and has been linked to *Vibrio* spp. and environmental stressors such as rising sea surface temperatures (SST) and eutrophication (Dustan, 1977; Burge *et al.*, 2014). White plague is characterized by rapid tissue necrosis and high mortality rates among affected colonies (Heron *et al.*, 2010). Additional tissue-loss diseases include white band disease, ciliatosis, and other emerging white syndromes affecting reef-building corals (Ainsworth *et al.*, 2007).

The most recent and alarming outbreak is stony coral tissue loss disease (SCTLD), first identified in 2014 on Florida's reefs (Precht *et al.*, 2016; Papke *et al.*, 2024). SCTLD has caused mass mortality in multiple coral species, particularly in Florida and the Mexican Caribbean, where mortality reached up to 58% of affected colonies between 2018 and 2019 (Estrada-Saldívar *et al.*, 2020). SCTLD is characterized by rapid tissue loss progressing within weeks and has rapidly spread across the region, impacting *Orbicella* spp. and other species critical to reef structural complexity (Alvarez-Filip *et al.*, 2019). Despite efforts to identify its causative pathogen, the etiological agent remains uncertain, though research suggests a bacterial component (Aeby *et al.*, 2019; Ushijima *et al.*, 2020), and has also shown strong correlations with elevated SST, and host coral physiological stress (Kenkel *et al.*, 2020). Additionally, SCTLD is proposed to result from a disruption in the physiology of the coral holobiont, specifically in the host-symbiont relationship (Landsberg *et al.*, 2020). Recent evidence suggests that viral infection of the symbionts could be a critical factor in the disease's pathogenesis, triggering the detachment and loss of coral tissue (Work *et al.*, 2021; Klein *et al.*, 2024).

Credits: Lorenzo Alvarez-Filip

Diseases dynamics

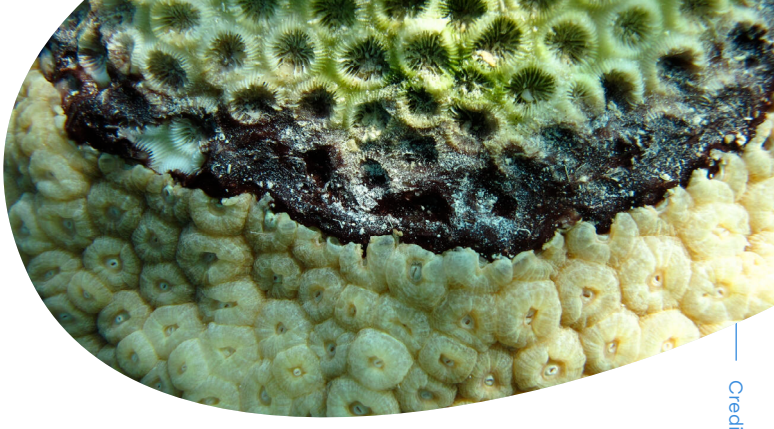
The dynamics of coral diseases are complex, with each disease exhibiting unique transmission patterns influenced by pathogen biology, host susceptibility, and environmental conditions during outbreaks (Vega-Thurber *et al.*, 2020). Consequently, factors such as vectors, transmission rates, prevalence percentages, and mortality rates vary among diseases.

Disease transmission (transmission of microbial pathogen(s) that infect healthy corals and result in disease), in corals primarily occurs through three mechanisms: direct transmission, waterborne transmission, and biological vector transmission (Shore & Caldwell, 2019). Direct transmission is limited due to the tendency of corals to avoid contact with

other colonies by ceasing growth or redirecting their extension (Sutherland *et al.* 2004). However, aggressive interactions such as the exudation of chemical compounds, the use of stinging tentacles, and the extension of mesenterial filaments to attack neighboring tissues can facilitate pathogen transfer, particularly in reef environments with high colony density. Additionally, flexible corals such as gorgonians may enhance disease transmission by moving with ocean currents, increasing physical contact between colonies (Shore & Caldwell, 2019). Although direct transmission through fragmentation has not been documented in scleractinian corals, it has been suggested that the detachment of infected fragments may facilitate disease spread (Brandt *et al.*, 2013).

Waterborne transmission plays a crucial role in the dispersal of coral diseases (Aeby *et al.*, 2019). This mechanism allows the spread of pathogenic microorganisms through biological debris, such as algal aggregates or coral mucus, as well as abiotic particles, including resuspended sediments and plastic debris (Sheridan *et al.*, 2014). These aggregates can concentrate pathogens such as *Vibrio* spp., at significantly higher levels than the surrounding water, thereby increasing infection probability (Studivan *et al.*, 2022). Maritime traffic also contributes to pathogen dispersal through ballast water and biofouling on ship hulls (Rosenau *et al.*, 2021). Pathogens responsible for white-band disease and white pox have been detected in ballast water from vessels in the Gulf of Mexico, although their epidemiological impact on maritime routes remains poorly understood (Aguirre-Macedo *et al.*, 2008). Additionally, terrestrial runoff carrying untreated wastewater can introduce potentially pathogenic microorganisms into reef systems, promoting disease outbreaks (Sutherland *et al.*, 2011).

Biological vectors also play a major role in coral disease transmission. Corallivorous fish, such as species from the genus *Chaetodon* (butterflyfish), have been associated with the spread of coral diseases due to their selective feeding on infected colonies, which may facilitate pathogen transmission through sequential feeding on healthy corals (Aeby & Santavy, 2006; Titus *et al.*, 2022). Fecal excretion has also been proposed as a potential transmission mechanism by depositing pathogens onto other colonies (Shore & Caldwell, 2019). Among invertebrates, corallivorous snails such as *Coralliophila abbreviata* and *Drupella* spp., have been implicated in the transmission of white pox disease (WPD), and white band disease (WBD) (Williams & Miller, 2005; Nicolet *et al.*, 2018). Other organisms, such as the fireworm *Hermodice carunculata*, can act as reservoirs and vectors of pathogens like *Vibrio shiloi*, which has been linked to White Pox Disease outbreaks in the Caribbean (Miller & Williams, 2007). Overall, the interaction between biological vectors and disease propagation depends



Credits: Christina A. Kellogg

on pathogen virulence and the density of the vector organisms within a given reef ecosystem.

Over time, epizootics of various coral diseases have shown dispersal patterns linked to the prevailing environmental conditions in specific reef regions (Harvell *et al.*, 2002; Meron *et al.*, 2011; Maynard *et al.*, 2015). One of the most prominent factors is elevated SST, associated with climate change. Higher SST are a key trigger for the emergence and intensification of coral diseases, as they disrupt the symbiotic relationship between corals (hosts) and dinoflagellate microalgae of the order Symbiodiniaceae (symbionts). This phenomenon, known as bleaching, reduces coral energy capacity by depleting photosynthetic products produced by the symbionts, weakening immune responses and facilitating pathogen invasion and proliferation.

In addition to thermal stress, other environmental factors, such as eutrophication from nutrient runoff, exacerbate coral susceptibility to bacterial and fungal infections (Vega Thurber *et al.*, 2013). This process increases organic matter concentrations in reef environments, favoring microbial pathogen growth and virulence. The combination of thermal stress and eutrophication creates ideal conditions for disease spread, further compromising reef resilience (Dougan *et al.*, 2020).

Each coral disease possesses unique characteristics in terms of virulence, pathology, and transmission (see Box 1) (Vega-Thurber *et al.*, 2020). For instance, BBD outbreaks are associated with high bacterial loads in affected reefs, particularly in areas with high turbidity and human activity (Voss & Richardson, 2006). Conversely, SCTLD appears more influenced by thermal variability and physiological stress induced by extreme temperatures (Chaves-Fonnegra *et al.*, 2021). Coral diseases are complex and emerging phenomena that affect various coral species worldwide, particularly in tropical and subtropical regions. Despite advances in understanding coral disease dynamics, significant gaps remain, including interactions between the microbiome and pathogens, transmission pathways, and environmental drivers that promote outbreaks and enhance disease virulence. Addressing these gaps is crucial to predicting, preventing, and managing future coral disease outbreaks, especially in regions with limited baseline data (e.g., developing countries).

Box 1: Timeline of coral disease emergence and progression (1965–2014)

Coral diseases have been increasingly documented worldwide, with more than **40 diseases affecting more than 200 species of reef-building corals** (Vega-Thurber *et al.*, 2024).

Some diseases, due to their high frequency of outbreaks, elevated prevalence, rapid transmission rates, broad host range, and severe ecological consequences, have been identified as the most significant threats to coral reef ecosystems.

These diseases account for approximately 77% of all coral disease reports globally (Morais *et al.*, 2022). The following timeline presents the most impactful coral diseases, detailing their etiology, clinical manifestations, affected species, geographic distribution, and ecological consequences (Figure 2).

Growth anomalies (GA) *1965*

Credits: Greta Aeby

Etiology and symptoms:

First reported in 1965 (Squires, 1965), growth anomalies in coral tissue affect everything from skeletal structure and arrangement to essential biological functions such as growth and gamete reproduction. More than 14 types of anomalies include umbonate, bosselated, nodular, exophytic, fimbriated, and vermiform (Ricci *et al.*, 2022). These anomalies can be caused by parasitic infections, pollution, temperature changes, and opportunistic pathogens.

Main affected species and locations:

Documented in over 30 families of corals, including *Acropora* spp., *Montipora* spp., and *Porites* spp. (Ricci *et al.* 2022). GA occurrences have been reported worldwide, with notable presence in reefs across the Indo-Pacific and the Caribbean (Aeby *et al.*, 2011).

Ecological consequences:

Growth anomalies can alter colony morphology and functionality, reducing reproductive capacity and increasing vulnerability to other diseases and environmental disturbances.

Black band disease (BBD) *1973*

Etiology and symptoms:

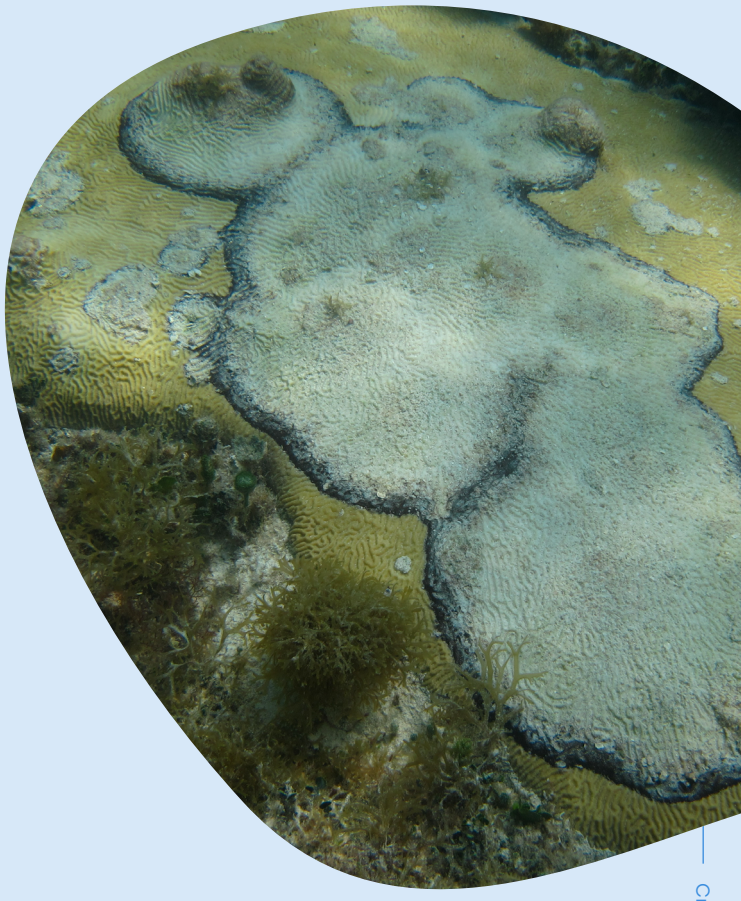
First described by Antonius (1973) and formally characterized by Rützler *et al.*, (1983), BBD is caused by a microbial consortium dominated by cyanobacteria (*Roseofilum reptotaenium*, *Phormidium corallyticum*), sulfate-reducing bacteria (*Desulfovibrio* spp.), and sulfide-oxidizing bacteria (*Beggiatoa* spp.) (Richardson, 1998). It manifests as a dark, migrating band on the surface of the coral. The pathogenic bacteria completely degrade the coral tissue, leaving behind bare skeletons (Richardson, 2012).

Main affected species and locations:

BBD primarily affects massive reef-building corals, including species of *Orbicella* spp., *Diploria* spp., and *Colpophyllia* spp. It was first observed in the Caribbean and has since been documented in the Indo-Pacific, indicating a broad geographical distribution (Aeby *et al.*, 2015).

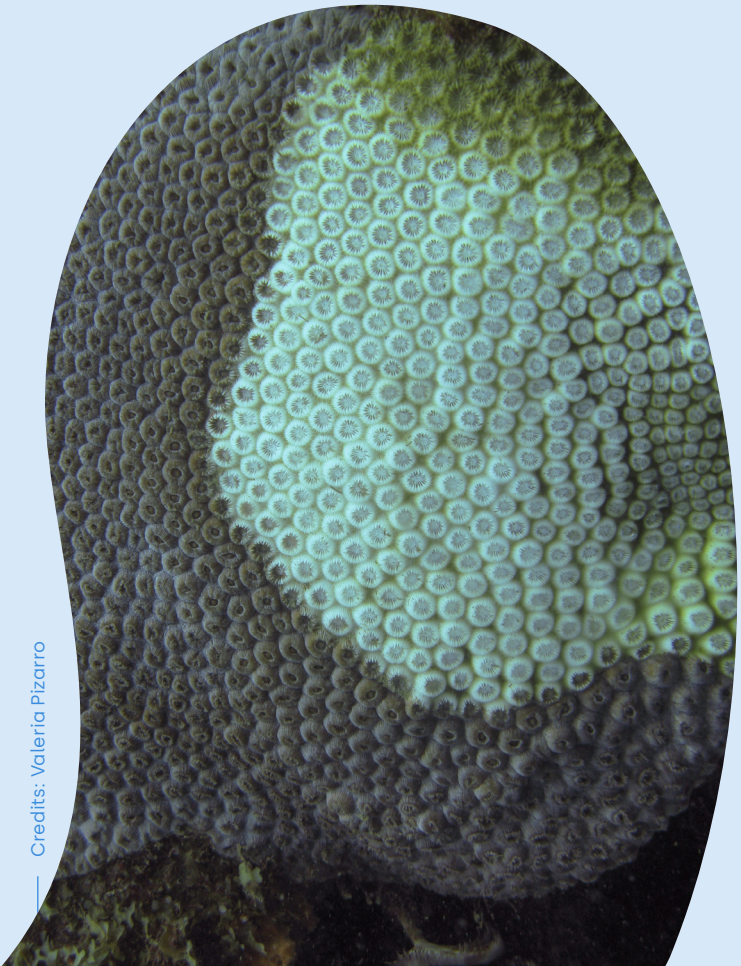
Ecological consequences:

BBD can cause up to 3 cm of tissue loss per day (Buerger *et al.*, 2016), leading to significant reductions in live coral cover and compromising the structural integrity of affected reefs (Carlton & Richardson, 1995).



Credits: Christina A. Kellogg

White plague (WP) *1977*



Credits: Valeria Pizarro

Etiology and symptoms:

Originally described by Dustan (1977), WP causes rapid tissue loss and manifests as an advancing white band of denuded skeleton. Three types of WP have been identified (WP-I, WP-II, and WP-III), with *Aurantimonas coralicida* implicated as the primary pathogen for WP-II (Richardson *et al.*, 1998). However, the etiological agents for WP-I and WP-III remain unidentified.

Main affected species and locations:

WP affects over 40 species of scleractinian corals, including *Colpophyllia natans*, *Pseudodiploria strigosa*, and *Orbicella annularis*. Initially reported in the Florida Keys, WP has since spread throughout all Caribbean reefs (Richardson *et al.*, 1998, Weil *et al.*, 2006).

Ecological consequences:

WP outbreaks have led to severe declines in coral cover, with tissue loss rates of up to 4 cm per day. These events have significantly altered community structures and reduced the biodiversity of affected reefs (Miller *et al.*, 2009).

White band disease (WBD) *1980*

Etiology and symptoms:

WBD is associated with an unidentified bacterial pathogen (gram-negative bacterium). It manifests as a distinct white band of necrotic tissue that progresses from the base to the branch tips, eventually leading to total colony mortality (Gladfelter, 1977, 1982).

Main affected species and locations:

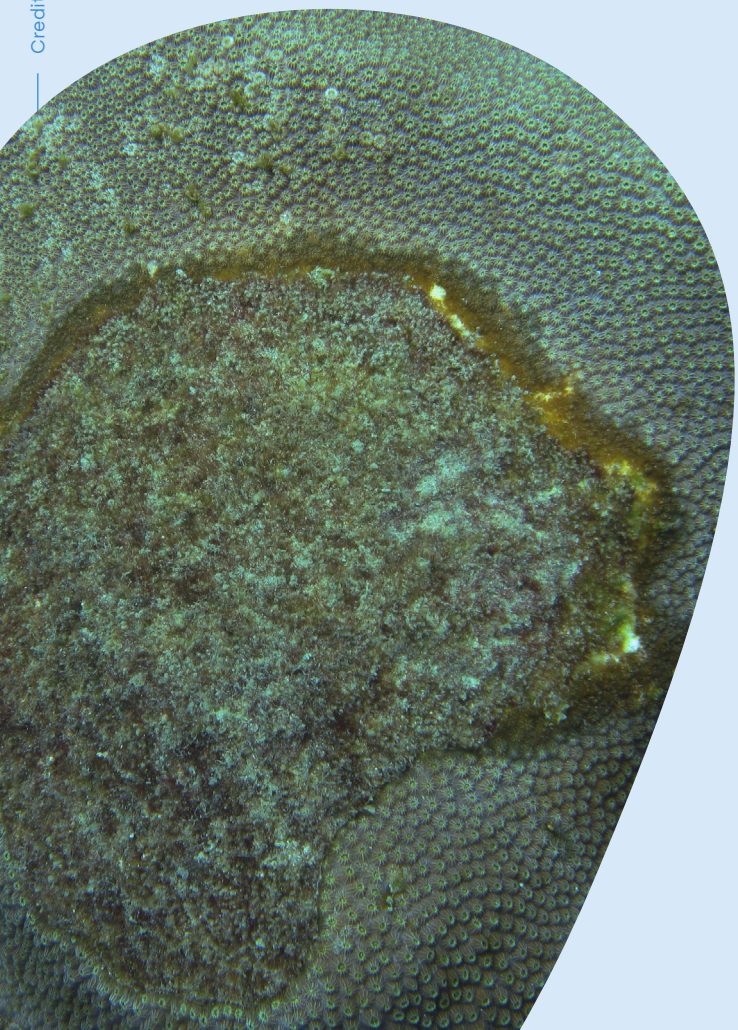
This disease primarily affects the Caribbean *Acropora species*, *A. palmata* and *A. cervicornis*. and their hybrids. It was first observed in the Caribbean and remains largely restricted to this region (Aronson & Precht, 2001).

Ecological consequences:

Although WBD has a slow tissue loss rate at 0.5 cm per day (Gladfelter, 1982), it has caused extensive population declines of *Acropora* spp. (~90%), contributing to their classification as critically endangered species. The resulting loss of structural complexity has diminished habitat availability and reduced fish biodiversity (Aronson & Precht, 2001).

Credits: Valeria Pizarro

Yellow band disease (YBD) *1994*



Credits: Valeria Pizarro

Etiology and symptoms:

Characterized by pale yellow lesions that expand gradually, YBD affects the symbiotic dinoflagellates, impairing photosynthesis and leading to tissue mortality. *Vibrio alginolyticus* and other *Vibrio* species have been identified as the primary pathogens (Cervino *et al.*, 2004).

Main affected species and locations:

YBD primarily affects Caribbean massive corals, including *Orbicella annularis* and *Orbicella faveolata*. It has been documented predominantly in the Caribbean and in the Indo-Pacific on other species (Gil-Agudelo *et al.*, 2004).

Ecological consequences:

This disease contributes to slow but progressive tissue loss (~1 cm/day) (Cervino *et al.*, 2001; 2008), weakening colony health and reducing reproductive output, which cumulatively impacts coral population resilience (Weil *et al.*, 2006).

Dark spot syndrome (DSS) *1996*

Credits: Valeria Pizarro

Etiology and symptoms:

DSS is characterized by distinct, irregularly shaped dark lesions on coral tissue. The exact etiology remains uncertain, though microbial dysbiosis and cyanobacteria involvement have been proposed (Nugues *et al.*, 2004).

Main affected species and locations:

It predominantly affects *Siderastrea siderea*, *Orbicella annularis*, and *Pseudodiploria strigosa*. DSS is prevalent in the Caribbean, with notable outbreaks in the Florida Keys (Bruckner & Bruckner, 1997).

Ecological consequences:

DSS contributes to partial tissue mortality and increased susceptibility to secondary infections, ultimately affecting coral community composition (Borger & Steiner, 2005).

Skeletal eroding band (SEB) *1999*

Etiology and symptoms:

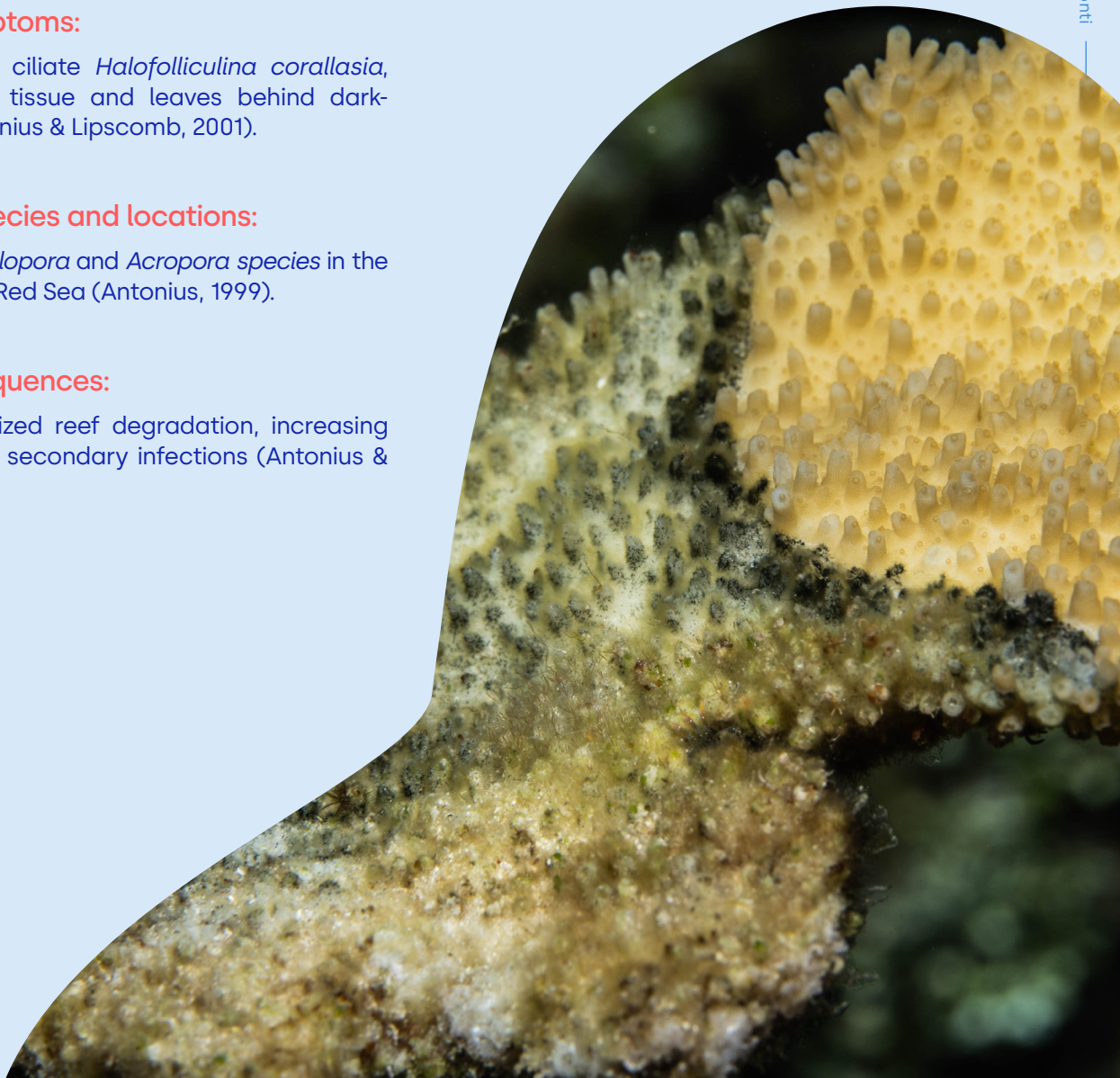
SEB is linked to the ciliate *Halofolliculina corallasia*, which erodes coral tissue and leaves behind dark-colored lesions (Antonius & Lipscomb, 2001).

Main affected species and locations:

Primarily affects *Pocillopora* and *Acropora species* in the Indo-Pacific and the Red Sea (Antonius, 1999).

Ecological consequences:

Contributes to localized reef degradation, increasing coral vulnerability to secondary infections (Antonius & Lipscomb, 2001).



Credits: Matteo Monti

Stony coral tissue loss disease (SCTLD) *2014*

Credits: Lorenzo Alvarez-Filip

Etiology and symptoms:

SCTLD is characterized by rapid tissue loss and high mortality rates, affecting more than 20 species of scleractinian corals. The causative agent is suspected to be a bacterial or viral pathogen, possibly transmitted via waterborne vectors (Precht *et al.*, 2016, Work *et al.*, 2021).

Main affected species and locations:

First documented off the coast of Florida in 2014, SCTLD has since spread across the Caribbean, affecting approximately 23 coral species including *Dendrogyra cylindrus*, *Orbicella annularis*, and *Pseudodiploria strigosa* (Estrada-Saldivar *et al.*, 2020).

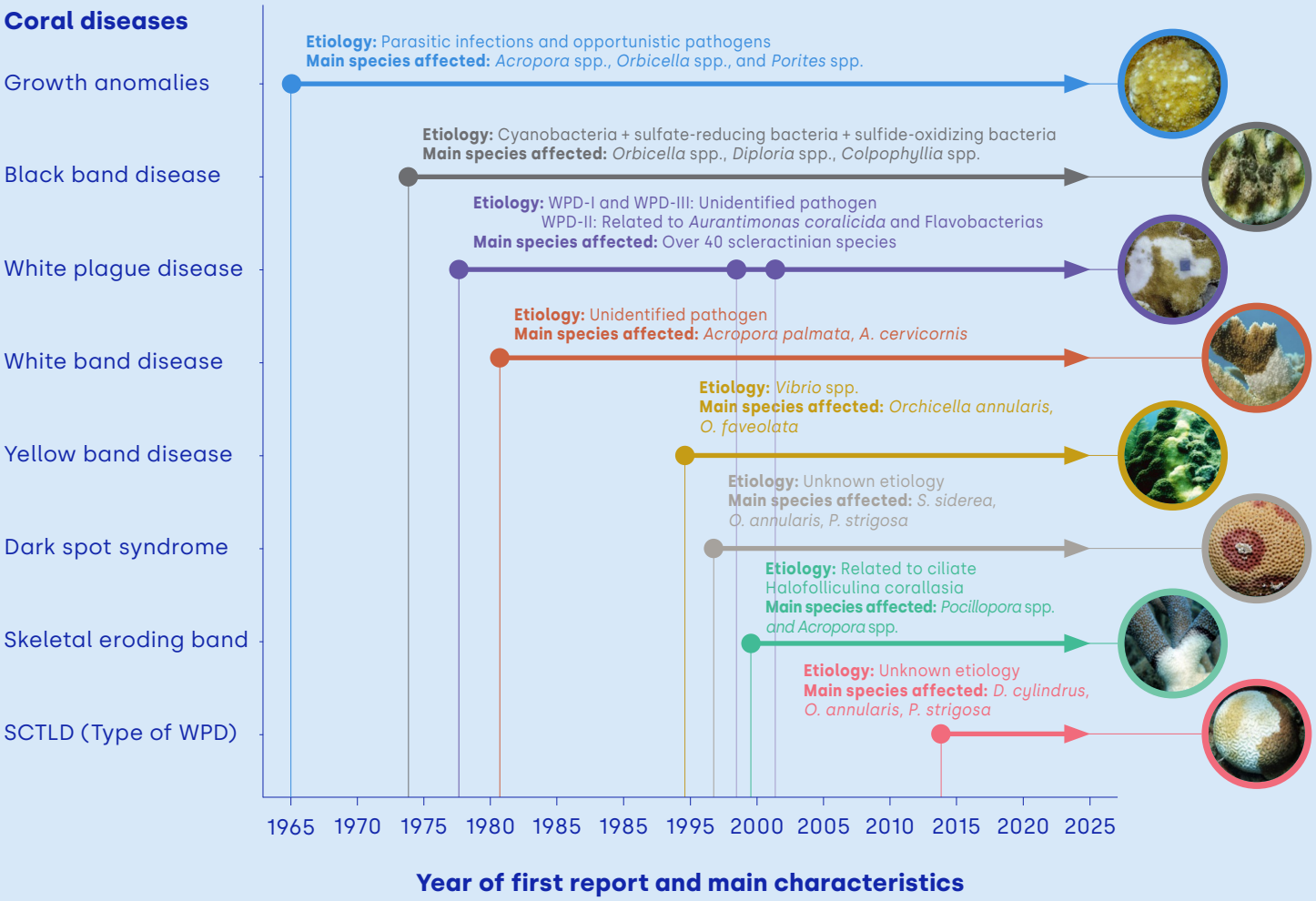
Ecological consequences:

SCTLD leads to rapid colony mortality, with tissue loss rates of up to 10 cm^2 per day. It significantly impacts reef accretion potential and ecosystem functionality, threatening the persistence of affected species and other reef organisms (Walton *et al.*, 2018).

The emergence and spread of coral diseases from 1973 to 2014 underscore the **escalating threat to global coral reef health.**

These diseases have led to significant declines in coral cover, structural complexity, and biodiversity, with particularly severe impacts in the Caribbean and Eastern Tropical Pacific. Understanding the etiologies, transmission mechanisms, and environmental drivers of these diseases is essential for developing effective mitigation strategies. Continued research is needed to elucidate the complex interactions between coral hosts, pathogens, and environmental stressors in an era of accelerating climate change.

Timeline of main coral diseases



Source: Sutherland *et al.* 2004, Morais *et al.* 2022, Vega-Thurber *et al.* 2024

Relative progression of main coral diseases

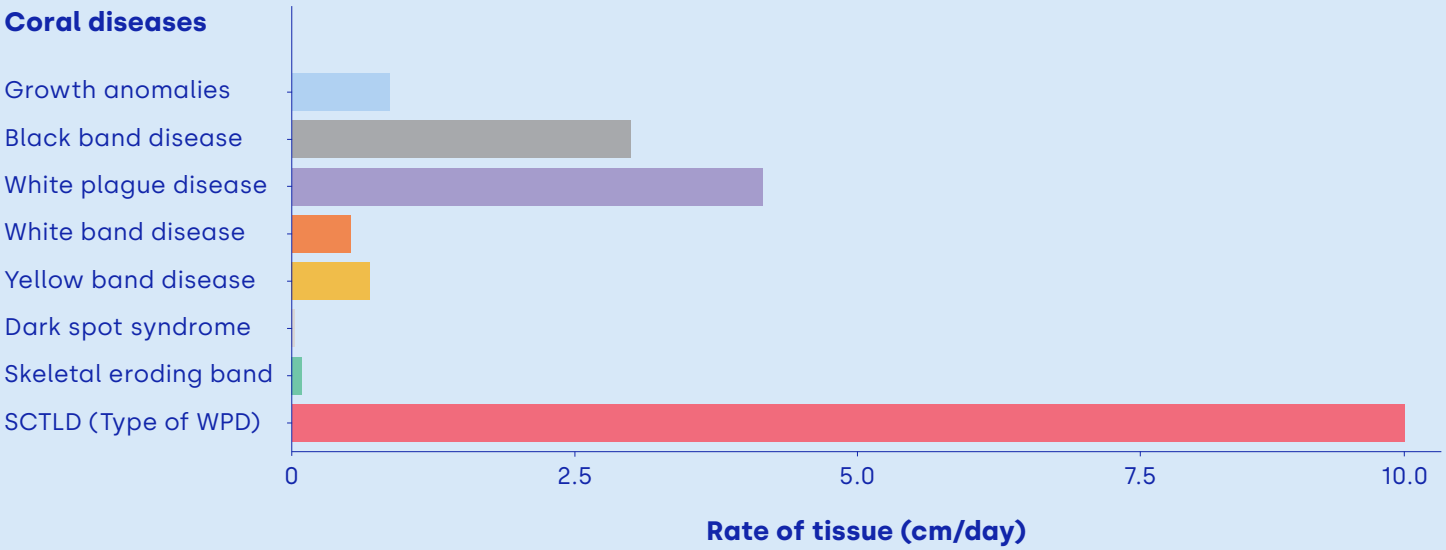
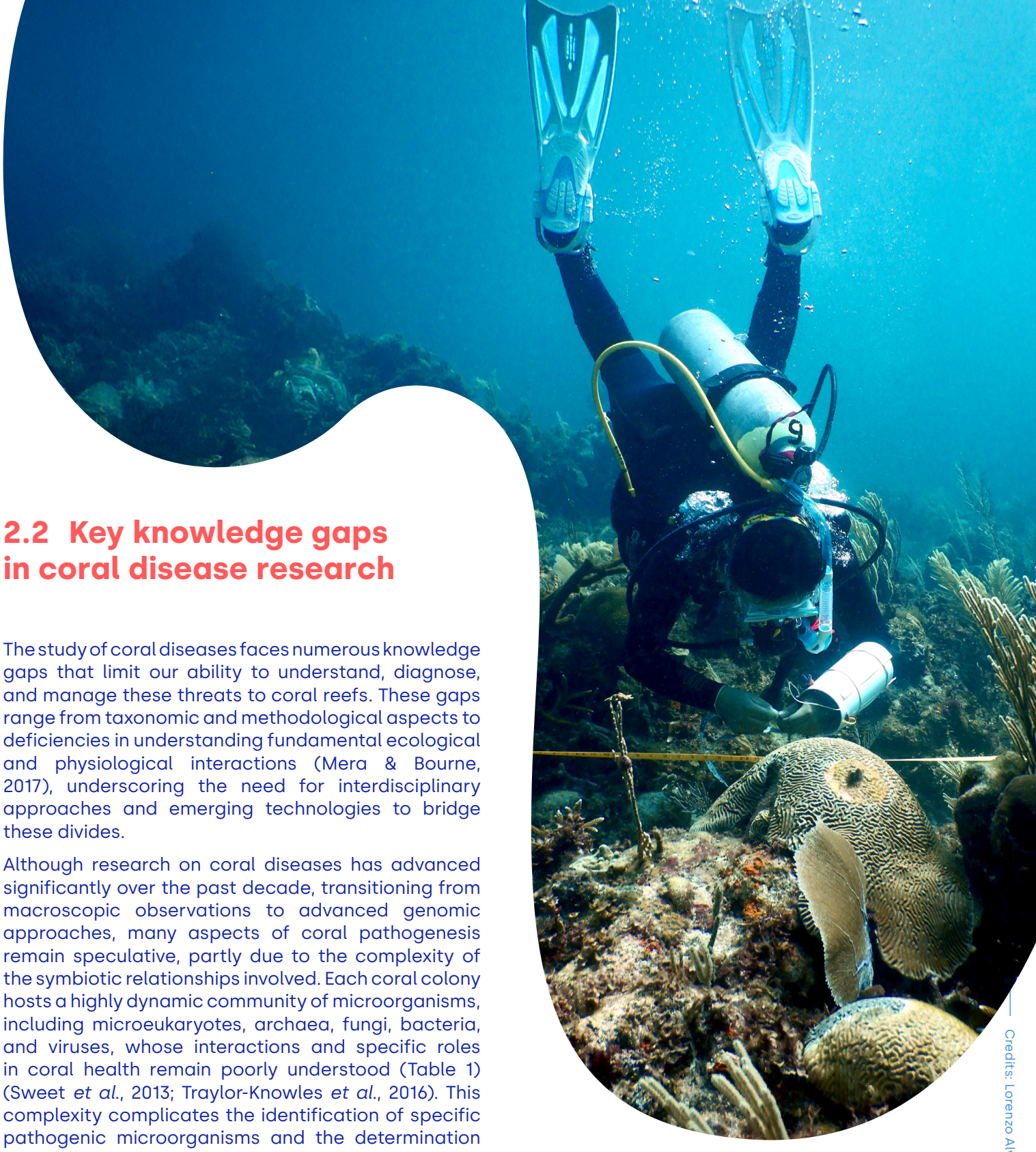


Figure 2. Timeline and progression rates of major coral diseases (1965–2025).
The upper panel presents the chronology of the first reports of the most ecologically significant coral diseases, detailing their etiology, affected species, and progression. The lower panel shows the tissue loss rates for these diseases, except for growth anomalies (GA), which are represented only by their progression. Diseases such as Stony Coral Tissue Loss Disease (SCTLD), black band disease (BBD), and white plague (WP) exhibit the highest tissue loss rates, while others progress more slowly. Understanding disease progression is crucial for reef conservation efforts in the face of climate change and anthropogenic stressors.



Credits: Lorenzo Alvarez-Filip

2.2 Key knowledge gaps in coral disease research

The study of coral diseases faces numerous knowledge gaps that limit our ability to understand, diagnose, and manage these threats to coral reefs. These gaps range from taxonomic and methodological aspects to deficiencies in understanding fundamental ecological and physiological interactions (Mera & Bourne, 2017), underscoring the need for interdisciplinary approaches and emerging technologies to bridge these divides.

Although research on coral diseases has advanced significantly over the past decade, transitioning from macroscopic observations to advanced genomic approaches, many aspects of coral pathogenesis remain speculative, partly due to the complexity of the symbiotic relationships involved. Each coral colony hosts a highly dynamic community of microorganisms, including microeukaryotes, archaea, fungi, bacteria, and viruses, whose interactions and specific roles in coral health remain poorly understood (Table 1) (Sweet *et al.*, 2013; Traylor-Knowles *et al.*, 2016). This complexity complicates the identification of specific pathogenic microorganisms and the determination of underlying disease mechanisms (Harvell *et al.*, 2002; Sutherland *et al.*, 2004). Advances in genomics and molecular techniques, such as high-throughput sequencing, have provided more detailed insights into coral-microorganism interactions, but this information is often confounded by the high temporal and spatial variability of microbial consortia (Reshef *et al.*, 2006). This highlights the need to integrate molecular tools and advanced techniques to develop specific biomarkers and more accurate diagnostic tests.

Table 1. Overview of the most common coral diseases around the world.
This table provides a comprehensive summary of major coral diseases, their identified primary pathogens, the principal coral species affected, and their known geographic distributions. The information is supported by key references to facilitate further understanding and research into coral disease dynamics.

Diseases	Principal pathogens	Principal spp. affected	Geographic distribution	References
Growth anomalies (GAs) **1965**	Parasitic infections Opportunistic pathogens Related with processes that alter the homeostasis such as pollution and temperature anomalies	*Acropora* spp. *Montipora* spp. *Porites* spp.	Global	Squires, 1965 Aeby *et al.*, 2011 Work *et al.*, 2015 Ricci *et al.*, 2022
Black band disease (BBD) **1973**	*Roseofilum reptotaenium* *Trichodesmium erythraeum* *Phormidium* spp. *Desulfovibrio* spp. *Vibrio coralliilyticus* *Beggiatoa* spp	*Orbicella* spp. *Colpophyllia* spp. *Acropora* spp. *Montipora* spp. *Diploria* spp. *Porites* spp. *Siderastrea* spp.	Global	Antonius, 1973 Carlton & Richardson, 1995 Sato *et al.*, 2016 Buerguer *et al.*, 2016 Aeby *et al.*, 2015
White-band disease (WBD) **1977**	*Aquarickettsia rohweri* *Philaster lucinda*	*Acropora cervicornis* *Acropora palmata* *Acropora prolifera* (hybrid of above species)	Tropical western Atlantic Ocean Caribbean Sea Gulf of Mexico	Gladfelter, 1982 Casas *et al.*, 2004 Miller *et al.*, 2014 Klinges *et al.*, 2019 Sweet, *et al.*, 2014

Table 1. (Continued).

Diseases	Principal pathogens	Principal spp. affected	Geographic distribution	References
White plague disease (WPD) **WPD Type I** **1977** **WPD Type II** **1998** **WPD Type III** **2001**	*Vibrio harveyi (charchariae)* *Aurantimonas coralicida* *Philaster lucinda*	*Colpophyllia natans* *Pseudodiploria strigosa* *Orbicella annularis* *Acropora cervicornis*	Global	Dustan, 1977 Antonius, 1985 Richardson *et al.*, 1998 Denner *et al.*, 2003 Gil-Agudelo *et al.*, 2006 Miller *et al.*, 2009
Aspergillosis of gorgonians **1984**	*Aspergillus sydowii*	*Gorgonia flabellum* *Gorgonia ventalina*	Caribbean	Guzman & Cortez, 1984 Kim & Harvell, 2004
***Vibrio shiloi* induced bleaching** **1996**	*Vibrio shiloi*	*Oculina* spp.	Indo-Pacific	Kushmaro *et al.*., 1998 Israely *et al.*, 2001
Yellow band disease (YBD) **1994**	*Vibrio consortium*	*Orbicella* spp. *Diploastrea heliopora* *Fungia* spp. *Herpolitha* spp.	Indo-Pacific and Caribbean	Cervino *et al.*, 2004, 2008 Sweet *et al.*, 2013 Gil-Agudelo *et al.*, 2004
White syndrome (WS) **1996**	*Vibrio harveyi* *Vibrio coralliilyticus* *Philaster Lucinda* *Rhodobacteraceae*	*Acroporidae* *Pocilloporidae*	Global	Antonius, 1981 Willis *et al.*, 2004 Bourne *et al.*., 2015 Pollock *et al.*, 2017

Table 1. (Continued).

Diseases	Principal pathogens	Principal spp. affected	Geographic distribution	References
Montipora (WS) **2010**	*Vibrio owensii* *Vibrio coralliilyticus*	*Montipora capitata*	Hawaii	Aeby *et al.*, 2010, 2016 Ross *et al.*, 2012 Shore-Maggio *et al.*, 2018 Ushijima *et al.*., 2012, 2014
Acropora (WS) **2005**	*Vibrio coralliilyticus*	Acropora cytherea	Indo-Pacific	Aeby *et al.*, 2005, 2011 Ushijima *et al.*, 2016
Dark spots syndrome (DSS) **1996**	*Unknown*	*Siderastrea siderea* *Orbicella annularis* *Pseudodiploria strigosa*	Global	Goreau *et al.*, 1998 Gochfeld *et al.*, 2006 Weil, 2004
Skeletal eroding band (SEB) **1999**	*Folliculinid ciliate* *Halofolliculina covallasia*	*Pocillopora spp.* *Acropora spp.*	Global	Antonius, 1999 Antonius & Lipscomb, 2001 Page & Willis, 2008
Brown band disease (BrBD) **2000**	*Philaster guamense* *Philaster lucinda* *Arcobacter* spp.	Acroporidae Pocilloporidae Faviidae	Indo-Pacific and Caribbean	Nicolet *et al.*, 2013 Bourne *et al.*, 2008 Montano *et al.*, 2016 Lobban *et al.*, 2011 Bharath *et al.*, 2020
***Porites* trematodiasis** **2000**	*Podocotyloides stenometra*	*Porites* spp.	Hawaii	Aeby *et al.*, 2002, 2007

Table 1. (Continued).

Diseases	Principal pathogens	Principal spp. affected	Geographic distribution	References
Vibriosis bleaching **2002**	*Vibrio coralliilyticus* *Vibrio* spp.	*Pocillopora damicornis* *Oculina patagonica*	Indo-Pacific Red Sea	Ben-Haim & Rosenberg, 2002 Ben-Haim *et al.*, 2003 Munn, 2015
Stony coral tissue loss disease (SCTLD) **2014**	*Unknown*	*Meandrina meandrites* *Orbicella* spp. *Pseudodiploria* spp. *Dendrogyra cylindrus* *Montastraea* spp. *Porites* spp. *Siderastrea* spp.	Caribbean	Precht *et al.*, 2016 Walton *et al.*, 2018 Aeby *et al.*, 2019 Alvarez-Filip *et al.*, 2019 Ushijima *et al.*, 2020 Estrada-Saldivar *et al.*, 2020

Another major challenge is the lack of standardized and widely accepted nomenclature for coral diseases. Additionally, the absence of monitoring protocols to identify and assess disease dynamics and trajectories presents a significant obstacle. For instance, despite advancements in coral disease research, inconsistencies persist in describing macroscopic signs and in the terminology used to identify diseases and outcomes (Work & Aeby, 2006; Muller & van Woesik, 2012; Mera & Bourne, 2017). These inconsistencies hinder data comparison across regions and studies, complicating the identification of global patterns in coral diseases and impeding rapid response efforts to address and manage emerging outbreaks (Sutherland *et al.*, 2004).

Furthermore, changing climatic factors and anthropogenic pressures have been linked to the increase in coral disease outbreaks and their virulence, but direct causality is often difficult to establish (Harvell *et al.*, 2009; Willis *et al.*, 2004). For example, elevated SST are associated with the proliferation of diseases such as BBD and white syndromes, but it is not fully understood whether this is due to increased pathogen virulence, heightened coral vulnerability from thermal stress, or an interaction between the two (Muller & van Woesik, 2012). Additionally, other environmental factors, such as light intensity, influence the progression of certain diseases, highlighting the need to investigate multifactorial interactions between temperature, light, and other environmental stressors (Harvell *et al.*, 2009; Sato *et al.*, 2011). Similarly, the cumulative impacts of pollutants associated with human activities have not been thoroughly studied in the context of disease dynamics (Burge *et al.*, 2014). Recent work with other infectious diseases of foundational marine taxa shows continental scale impacts fueled by heatwaves and warm temperature anomalies (Harvell *et al.*, 2019; Aoki *et al.*, 2022).

This lack of understanding of the interactions between environmental factors and pathogens, along with the absence of standardized protocols for monitoring and managing diseases under different environmental conditions, underscores the urgency of conducting interdisciplinary research to address these issues. Only through a holistic approach can effective strategies be developed to mitigate the impact of diseases on coral ecosystems in a changing climate (Figure 3 and Table 2).

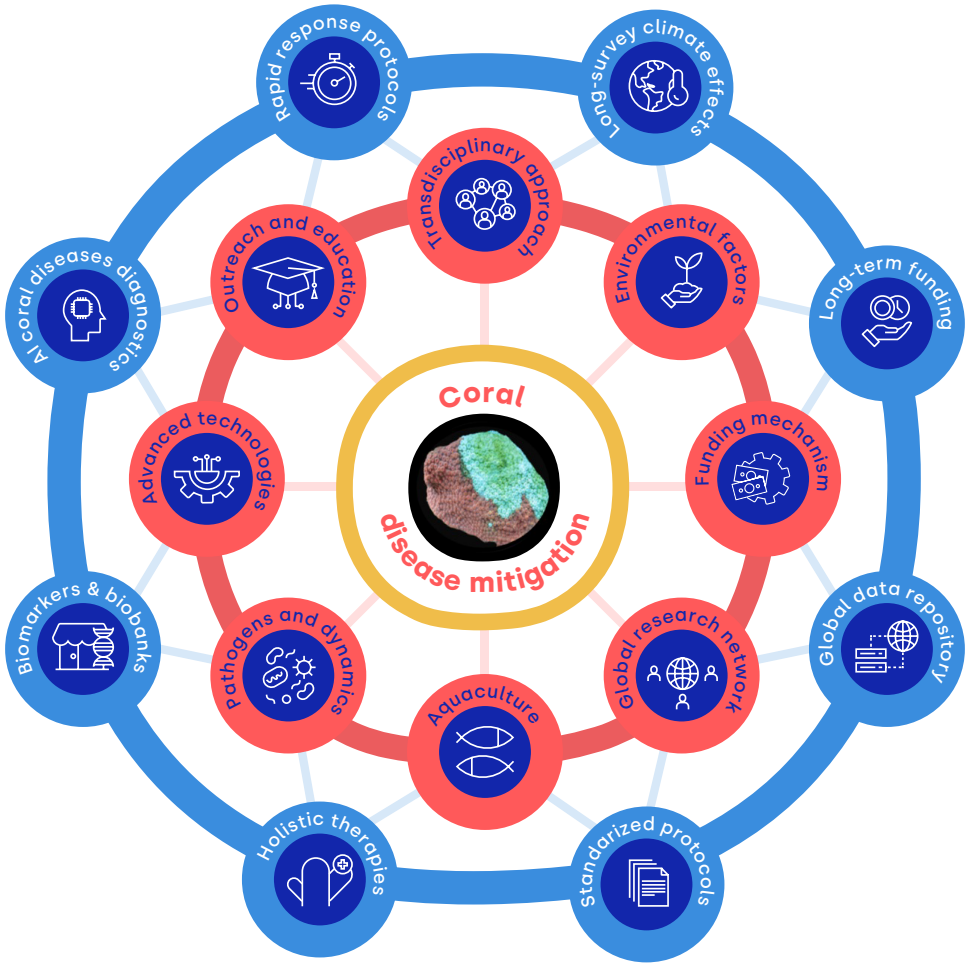


Figure 3. The conceptual diagram represents a holistic framework for addressing coral diseases.
Key interconnected themes orbit around the central node (coral disease mitigation), and their proximity reflects their relative importance or centrality to the issue of coral disease management. This visual synthesis highlights the multifaceted approach required to effectively understand, manage, and mitigate coral diseases, emphasizing the interconnectedness of scientific, environmental, and social dimensions.

Table 2. Comprehensive framework for advancing coral disease research and response. This table provides a structured, transdisciplinary approach to addressing coral disease research and response priorities. By identifying key knowledge gaps, prioritizing solutions, and recognizing the diverse stakeholders involved, this framework emphasizes the critical importance of collaboration, innovation, and resource mobilization to mitigate coral disease impacts globally.

Main theme	Key components	Knowledge gaps/ Opportunities for improvement	Importance/impact	Required disciplines	Stakeholders
1. Transdisciplinary approaches	– Need for standardized health indicators. – Strategies for global collaboration and data exchange. – Differentiation between lesions caused by trauma or predation and those caused by diseases.	– Absence of universal diagnostic standards. – Gaps in genetic and molecular basis of coral resistance. – Lack of rapid-response protocol implementation (i.e., Woodley *et al.*, 2008; Raymundo *et al.*, 2008).	Critical: Improves diagnostics and enables rapid-response frameworks for outbreaks. Standardizes data collection and enhances coordination.	Molecular biology, ecology, and genomics.	Universities, regional laboratories, and government research institutions.
2. Environmental factors	– Systematic studies on water quality. – Development of water management protocols. – Effects of climate change on pathogen virulence and transmission.	– Direct link between water quality and disease outbreaks remains unclear. – Long-term effects of climate change on disease dynamics remain underexplored.	High: Enhances understanding of environmental drivers of disease outbreaks.	Biochemistry, ecology, and physiology.	Universities, and governmental research agencies.

Table 2. (Continued).

Main theme	Key components	Knowledge gaps/ Opportunities for improvement	Importance/impact	Required disciplines	Stakeholders
3. Pathogens and disease dynamics	– Identification of specific pathogens and biomarkers. – Investigation into coral resistance mechanisms. – Integration of the "One Health" approach.	– Mechanisms driving pathogen virulence and transmission remain poorly understood. – Limited availability of accessible, rapid diagnostic tools.	Critical: Significantly accelerates understanding of disease dynamics. Can lead to development of low-cost, field-ready diagnostic kits.	Microbiology, pathology, and biotechnology.	Universities, regional laboratories, and government research institutions.
4. Holistic therapies and approaches	– Development of microbial therapies. – Integrated multi-trophic aquaculture strategies. – Research into host-symbiont dynamics.	– Efficiency, scalability, and environmental safety of microbial therapies are unknown. – Insufficient quarantine protocols. – Role of key organisms in disease mitigation remains unclear.	Moderate: Provides mitigation strategies for disease prevalence.	Applied microbiology, and aquaculture.	Universities, and governmental research institutions.
5. Advanced technologies	– Limited applications of AI in coral disease analysis. – Predictive models using AI. – Molecular biology repositories.	– Practical implementation of AI models for large-scale analysis is lacking.	Moderate: Enhances scalability and diagnostic accuracy.	Bioinformatics, and Mathematical modeling.	Universities, private sector, regional laboratories.

Table 2. (Continued).

Main theme	Key components	Knowledge gaps/ Opportunities for improvement	Importance/impact	Required disciplines	Stakeholders
6. Citizen science	– Training citizen scientists for coral disease monitoring. – Development of community-based monitoring programs.	– Effective methods to involve communities in monitoring remain underdeveloped.	Critical: Enables timely management and detection of disease outbreaks.	Environmental education, ecology, and communication.	NGOs, environmental agencies, and local communities.
7. Global research network	– Creation of a centralized, international data integration platform. – Digital repository for coral disease data. – GIS-based disease mapping for spatial analysis.	– Insufficient collaboration and data exchange across regions. – Lack of long-term datasets and standardized protocols. – Limited data-sharing agreements.	Critical: Strengthens international networks and enhances collaboration. Create centralized data repositories. Reduces research gaps, particularly in developing nations.	Data science, and Informatics.	Universities, NGOs, regional laboratories, and government research institutions.
8. Funding mechanisms	– Development of long-term funding strategies. – Flexible and adaptive funding frameworks.	– Funding models remain insufficient in low- and middle-income countries (LMICs).	Critical: Addresses resource gaps in participation, research, and data acquisition. Introduction of innovative financial tools such as tourism/carbon taxes.	Environmental economics, and policy.	Conservation organizations, private sector, policymakers.

Credits: Francisco Medellín

2.3 Guidelines for advancing coral disease research

The growing threat of coral diseases discussed above demands discussed above demands urgent action. Coral diseases are now widespread, increasingly severe, and affecting multiple coral taxa simultaneously. These outbreaks are often triggered or exacerbated by environmental stressors such as rising sea surface temperatures, nutrient enrichment, sedimentation, and pollution – creating a positive feedback loop that, in turn, maximizes these impacts. As coral reef degradation accelerates under climate change, mitigating disease impacts is no longer optional, but an essential pillar of reef conservation and restoration strategies.

Coral diseases are complex and multifactorial, involving dynamic interactions between hosts, pathogens, and the surrounding environment (see Box 2). Yet, compared to other stressors such as bleaching or overfishing, disease remains poorly understood, under-monitored, and under-addressed. Historically, most efforts have focused on identifying pathogens or documenting outbreaks, with limited success in developing scalable treatments or predictive tools. The use of antibiotics, while effective in some cases, such as amoxicillin pastes for SCTLD (Neely *et al.* 2020), is unsustainable and promotes considerable ecological risks, likely promoting antimicrobial resistance and untargeted changes in the microbiome of corals and other reef organisms. There is an urgent need to shift toward integrative, proactive, and ecosystem-friendly solution.

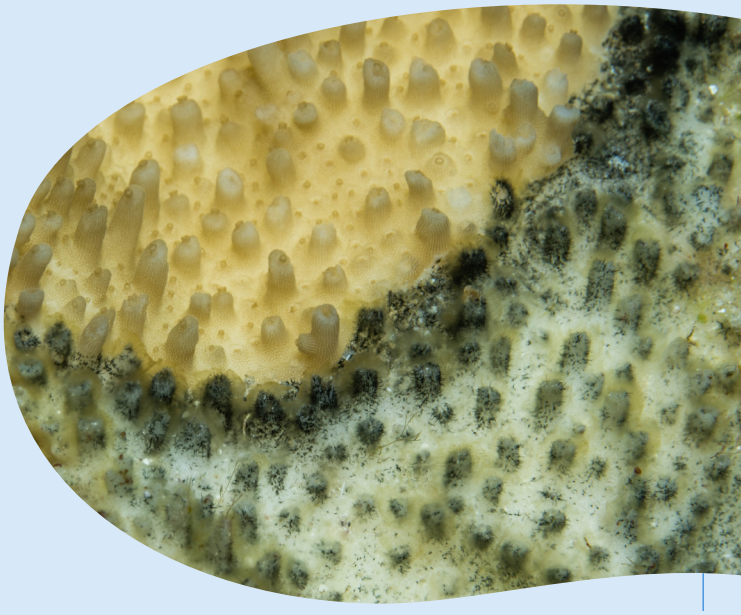
In particular, microbiome-based therapies, such as coral probiotics, postbiotics, phage therapies, and microbiome transplants are emerging as promising, nature-based tools to reduce disease susceptibility and promote coral recovery (Peixoto *et al.*, 2017; Rosado *et al.*, 2019; Doering *et al.*, 2021; Ushijima *et al.*, 2023; Garcias-Bonet *et al.*, 2024). These approaches aim to modulate the coral holobiont's microbiome to restore beneficial members and prevent opportunistic pathogen proliferation. Such microbiome stewardship is correlated with enhanced coral resilience and disease mitigation. While still experimental, microbial therapies represent a paradigm shift from a sole focus on symptom treatment to a holistic host health enhancement and pathogen control, offering a potentially safer and more adaptive alternative to chemical treatments.

This framework is not only important for the conservation of coral reefs worldwide but also an integral part of active coral reef restoration, one of the three essential pillars to protect coral reefs (Knowlton *et al.*, 2021). The integration of these strategies with assisted evolution (van Oppen *et al.*, 2015), selective breeding (Voolstra *et al.*, 2021), and ultimately, the integration of all these approaches into active assisted restauration (Peixoto *et al.*, 2025) provides an unprecedented opportunity to reshape the coral disease response. As coral nurseries expand globally and restoration becomes a key climate adaptation tool, incorporating disease mitigation, via microbial screening, symbiont optimization, and thermal preconditioning into restoration pipelines will be essential for long-term success.

Box 2: Coral defense mechanisms against diseases: The role of mucus, tissue, and the skeleton.

Corals have developed various defense mechanisms to counter pathogenic threats, relying on a combination of physical barriers, immune responses, and microbial symbioses (Work & Aeby, 2006).

These mechanisms operate across three primary structural components: the mucus layer, the living tissue, and the skeletal framework. Each of these components has a distinct yet interconnected role in preventing pathogen colonization and mitigating infections.



Credits: Matteo Monti

The surface mucus layer functions as the first line of defense.

The surface mucus layer (SML) serves as the initial barrier, acting as both a physical and biochemical shield. It is secreted by epidermal mucocytes and contains antimicrobial compounds that inhibit bacterial colonization (Brown & Bythell, 2005). The SML hosts a highly diverse microbiome, which is crucial in preventing pathogen invasion by competitive exclusion and the production of antimicrobial metabolites (Ritchie, 2006; Nissimov *et al.*, 2009).

Furthermore, the periodic shedding of mucus, especially under environmental stress, removes potential pathogens attached to the coral surface, similar to the mucosal immunity seen in vertebrates (Geffen & Rosenberg, 2005). Stress-induced mucus release also includes bioactive compounds with bacteriostatic effects, further lowering the risk of infection (Patton *et al.*, 1977).

The role of coral tissue in immune defense.

Beneath the SML, the coral's living tissue supports immune defense through the activity of specialized immune cells and biochemical pathways. Circulating granular amoebocytes, which are essential for wound repair and histocompatibility, have been observed mounting inflammatory responses against microbial infections (Mydlarz *et al.*, 2008). These cells increase in number in response to fungal invasion, potentially containing the spread of pathogens (Douglas *et al.*, 2007). The coral immune system also generates reactive oxygen species (ROS) that display potent antimicrobial properties. Oxygen supersaturation, driven by photosynthetic symbionts, leads to the formation of ROS, which selectively target microbial invaders that lack oxidative stress resistance mechanisms (Banin *et al.*, 2003). Additionally, enzymes such as chitinases and melanin-producing pathways contribute to antifungal defense, particularly against *Aspergillus sydowii*, a common coral pathogen (Mydlarz *et al.*, 2006).

The coral skeleton as an immune structure.

The coral skeleton, traditionally viewed as a structural element, also plays a role in pathogen defense (Levi *et al.*, 2022). Composed primarily of aragonite, the skeleton provides both a physical shield and a biochemical barrier. The calicodermis layer, which mediates skeletal deposition, can produce antimicrobial peptides that regulate microbial populations within the skeleton (Reshef *et al.*, 2006). Endolithic microbial communities residing within the skeleton may enhance coral immunity by outcompeting potential pathogens or producing antimicrobial compounds (Sweet *et al.*, 2013). Melanin, well-known for its role in immune defense, has been detected in the skeletal matrix and may improve resistance to microbial penetration (Ainsworth *et al.*, 2007).

Additionally, proteins with toxin and metallopeptidases have been identified in the skeleton, suggesting a role in immune modulation and pathogen defense (Mullen *et al.*, 2004).

Together, these layers — mucus, tissue, and skeleton — form an integrated defense network that enables corals to withstand microbial challenges.

The interplay between microbial symbionts, immune effectors, and structural barriers highlights the complexity of coral disease resistance, emphasizing the importance of holistic approaches in coral health research and conservation.

Credits: Alex Mustard / Ocean Image Bank

To achieve this, the scientific community must adopt a transdisciplinary and forward-looking research agenda that bridges basic and applied science, experimental and field research, and local and global collaboration. The roadmap below outlines key priorities to advance this effort.

1. Foster multidisciplinary collaboration

The study of coral diseases requires cooperation among physiologists, microbiologists, ecologists, veterinary pathologists, and climate scientists (Work & Aeby, 2006). Collaborations must also extend to local communities, reef managers, and citizen scientists, who play a critical role in data collection and the implementation of management strategies (Harvell *et al.*, 2009). Establishing international networks and global platforms will enable effective knowledge, methods, and data exchange (Ruiz-Moreno *et al.*, 2012).

2. Advance diagnostic and monitoring technologies

The use of advanced technologies, such as genomic, transcriptomic, and metabolomic tools, in conjunction with histopathological examinations of tissue condition (Traylor-Knowles *et al.*, 2022; Hawthorn *et al.*, 2023), is essential for identifying the metabolic and biochemical processes underlying coral diseases (Reshef *et al.*, 2006; Bosch & Miller, 2016). These techniques should be complemented with functional studies of the coral microbiome to identify potential targets for interventions (Sweet *et al.*, 2013). Finally, the integration of AI-based diagnostic tools could be used for the rapid detection of outbreaks of various diseases and help generate early warning programs. More specifically, we propose the following priorities: (i) the development AI-based lesion recognition, underwater imaging, and eDNA metabarcoding tools to identify early signs of disease; (ii) the screening for mobile, field-ready diagnostic kits for rapid pathogen detection, and (iii), the combination of data with oceanograpihc models to generate real-time outbreak prediction tools.

3. Design experimental platforms for mechanistic understanding

Experimental models like *Exaiptasia pallida* and coral cell culture provide controlled systems to study disease progression and evaluate mitigation strategies (Roger *et al.*, 2021; Puntin *et al.*, 2022). We propose that the use model systems and controlled aquarium trials is another priority of the field, as it can quickly advance our knowledge on causative agents and mechanisms underlying host-pathogen dynamics and the development of coral diseases. We also argue that the validation of results obtained using model organisms must be further

Credits: Christina A. Kellogg

Credits: Christina A. Kellogg

validated in corals and that the surveys performed *ex situ* should be also be validated as pilot *in situ*, through pilot experiments and following risk assessment steps (Peixoto *et al.*, 2022).

4. Standardize protocols for coral disease detection, reporting, and response

Developing standardized methods for data collection and coral health monitoring is urgent and crucial for a coordinated effort to mitigate coral disease and control their spread. This includes predefined indicators to assess coral conditions before, during, and after interventions (Bourne *et al.*, 2015). Integrated global monitoring systems will facilitate early outbreak detection and intervention impact assessments (Harvell *et al.*, 1999). Moreover, creating an accessible digital repository, particularly for regions with limited resources, will enable better understanding of global and regional patterns of coral diseases (AIMS Long-term Reef Monitoring Program, 2017). Objectively, we propose that standardized guidelines for disease diagnosis (e.g., visual signs, histopathology, microbial profiling) and proposed and established, as well as the creation of open-access coral disease databases that include geospatial, environmental, and microbial metadata. We also need to define clear, science-based intervention thresholds and decision trees for disease treatment in restoration context.

5. Experimental approaches and field validation

Aquarium-based experiments must be carefully designed to replicate natural environmental interactions and complemented with field studies to validate experimental results (Work & Meteyer, 2014). These combined approaches will overcome the limitations of each method and generate more robust insights into the interaction between environmental factors and pathogens, helping us understand the progression of different diseases under varying environmental conditions (see Box 3) (Ainsworth & Hoegh-Guldberg, 2009).

6. Rapid response and outbreak management

Establishing dedicated infrastructure for continuous monitoring and specialized personnel training is crucial for rapid responses to emerging outbreaks (Sweet *et al.*, 2012). This includes improving coordination among institutions, streamlining permitting processes, and ensuring timely funding availability (Florida Coral Disease Response and Epidemiology Team, 2018). Initiatives like the Disease Advisory Committee have proven effective in coordinating efforts but require enhanced speed and scalability. Adopting these approaches will significantly reduce disease spread and mortality rates when implemented effectively.

7. Integrate coral disease management into restoration programs

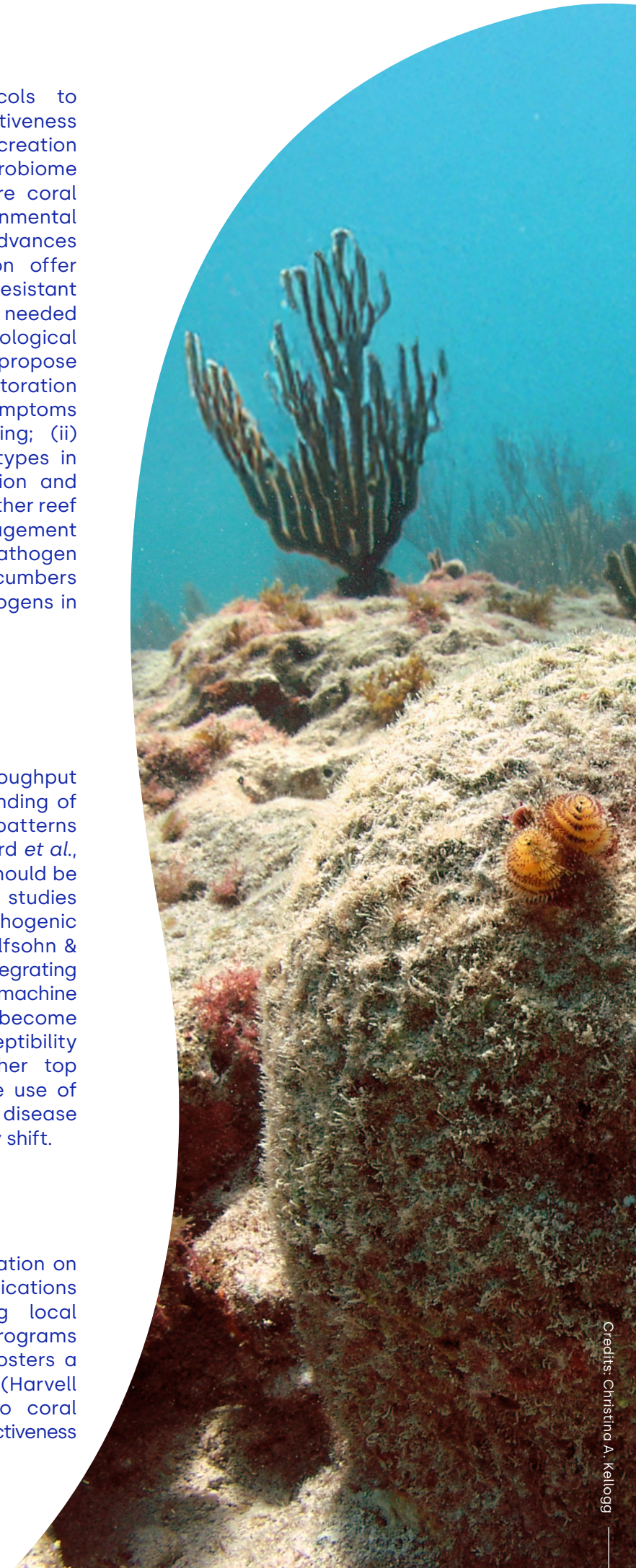
Restoration efforts must integrate protocols to minimize disease spread and evaluate the effectiveness of interventions (Peixoto *et al.*, 2024). The creation of coral genetic banks and associated microbiome reserves will serve as crucial tools to ensure coral resilience and survival under changing environmental conditions (Sheridan *et al.*, 2013). Additionally, advances in selective breeding and assisted evolution offer promising strategies for developing disease-resistant coral strains. However, further research is needed to determine their long-term viability and ecological impact in natural reef systems. Specifically, we propose the following steps to be incorporated into restoration efforts: (i) screen nursery stock for disease symptoms and microbiome dysbiosis before outplanting; (ii) incorporate heat- and disease-resilient genotypes in propagation efforts through assisted evolution and selective breeding; (iii), investigate the role of other reef organisms and ecological microbiome management improve microbial water quality and reduce pathogen loads (e.g., through the management of sea cucumbers that can highly minimize the presence of pathogens in the ecosystem).

8. Build predictive models of disease emergence and spread

Epidemiological modeling and high-throughput sequencing tools can transform the understanding of coral disease dynamics, uncovering hidden patterns and enabling more precise predictions (Maynard *et al.*, 2011; Caldwell *et al.*, 2016). These innovations should be integrated with advanced histopathological studies that link tissue changes with specific pathogenic processes (Ainsworth *et al.*, 2007; Gignoux-Wolfsohn & Vollmer, 2015). We suggest, for example, that integrating ecological, microbial, and climate variables into machine learning-based epidemiological models would become a powerful surveillance tool. Mapping host susceptibility across species and habitats is also another top priority to identify high-risk zones. Finally, the use of network analysis can also help understanding disease transmission pathways and microbial community shift.

9. Education and outreach

Promoting education and effective communication on the importance of coral diseases and their implications for marine ecosystems is vital. Engaging local communities in monitoring and restoration programs not only enhances data collection but also fosters a sense of responsibility and collective action (Harvell *et al.*, 1999). Integrating this approach into coral disease management strategies enhances effectiveness



Credits: Christina A. Kellogg

Credits: Christina A. Kellogg

while ensuring interventions are culturally appropriate. Some actionable priorities would be: (i) launch public awareness campaigns about coral diseases and citizen science disease reporting programs, perhaps using apps that could allow for the upload of images and reports about lesions and/or outbreaks; (ii), collaborate with reef managers, NGOs, and Indigenous communities to co-develop culturally appropriate disease response strategies; (iii), integrate disease risk assessment into marine spatial planning, protected area design, and blue carbon policy frameworks.

10. Develop and validate new treatments

The ultimate goal is to mitigate and contain the spread of disease. We therefore need to advance the emerging microbial therapies already being developed, using concepts from advanced medicine (precise/customized approaches and microbiome stewardship and host health improvement rather than solely focus on infection control). For that, experiments comparing microbial therapies with conventional treatments (such as antibiotics) in terms of efficacy, safety, scalability, and ecosystem impact. Another relevant aspect is the development of delivery systems (e.g., probiotic pastes and pills, automated deployment) suitable for both nurseries and wild reefs. The screening and selection of efficient Build beneficial microbial strains with known BMC properties (e.g., antibacterial, antiviral, ROS scavenging, nitrogen cycling) is also a priority. Furthermore, innovation, for example based on cutting-edge technologies from other fields, such as stem cell therapy for tissue rescue (Talice *et al.*, 2024), gene drive technology to bias inheritance of specific genes thereby increasing prevalence beyond the standard 50% Mendelian (Wang *et al.*, 2021), surface functionalized nanocarriers with tailored payloads (e.g., immune boosters, antimicrobial moleculars, free radical scavenging molecules) for delivery to specific cell types or specific organelles (Mout *et al.*, 2012), smart materials (i.e., coating, biopolymers or hydrogels) loaded with antimicrobial peptides with directional release to minimize off target effects (Contardi *et al.*, 2024), will further create alternative treatments to be tested.

The scientific community must adopt a holistic approach that combines basic and applied research, technological innovation, and global collaboration. These actions will enable the effective addressing of existing knowledge gaps, the development of more robust mitigation strategies, and the long-term protection of coral reefs against increasing environmental challenges.

Box 3: Environmental stressors and the breakdown of coral disease resistance

The increasing frequency and severity of coral disease outbreaks are tightly linked to a complex interplay of environmental stressors (Figure 4), including rising sea temperatures, declining water quality, and ocean acidification (Harvell *et al.*, 2002; Burge *et al.*, 2014). These abiotic factors do not act in isolation but rather synergistically weaken coral health because they are also pathogens, disrupt microbiome stability, and enhance microbial pathogen virulence, creating a feedback loop that accelerates reef degradation.

Thermal stress

Thermal stress is one of the most immediate threats to coral health, disrupting the delicate balance between corals and their symbiotic microbiota. Elevated temperatures not only induce coral bleaching but also promote dysbiosis, allowing opportunistic pathogens to proliferate while impairing the coral's immune responses (Sutherland *et al.*, 2004; Muller & van Woesik, 2012). For instance, outbreaks of white syndromes (WS) have been directly linked to anomalous heat events, such as the 30-fold increase in WS incidence following the 2002 mass bleaching event on the Great Barrier Reef (Willis *et al.*, 2004).

Water quality

Simultaneously, declining water quality — driven by coastal runoff, nutrient enrichment, and pollution — exacerbates disease susceptibility by further destabilizing microbial communities and increasing pathogen load (Ruiz-Moreno *et al.*, 2012). Excessive nutrients fuel the proliferation of microbial opportunists, some of which produce virulence factors that compromise coral tissue integrity. Contaminants such as heavy metals and hydrocarbons also disrupt immune function, reducing the coral's ability to fend off infections (Reshef *et al.*, 2006).

Ocean acidification

Ocean acidification compounds these threats by undermining coral skeletal integrity and impairing calcification processes (Bosch & Miller, 2016). As seawater pH declines, aragonite saturation levels drop, weakening coral skeletons and making them more susceptible to bioerosion and pathogenic colonization (Sweet *et al.*, 2013). Furthermore, acidification alters the composition of the skeletal microbiome, potentially shifting it toward a more pathogenic state, thus intensifying disease risk.

These stressors create a cascading effect where each factor amplifies the impact of the others.

Temperature-induced bleaching weakens coral defenses, allowing pollution-enhanced pathogens to colonize already vulnerable tissues, while acidification further deteriorates structural integrity, compounding overall susceptibility to disease. As climate change accelerates, these interactions will likely intensify, reinforcing the urgency of mitigating anthropogenic pressures to prevent the collapse of reef ecosystems.

Credits: Lorenzo Alvarez-Filip

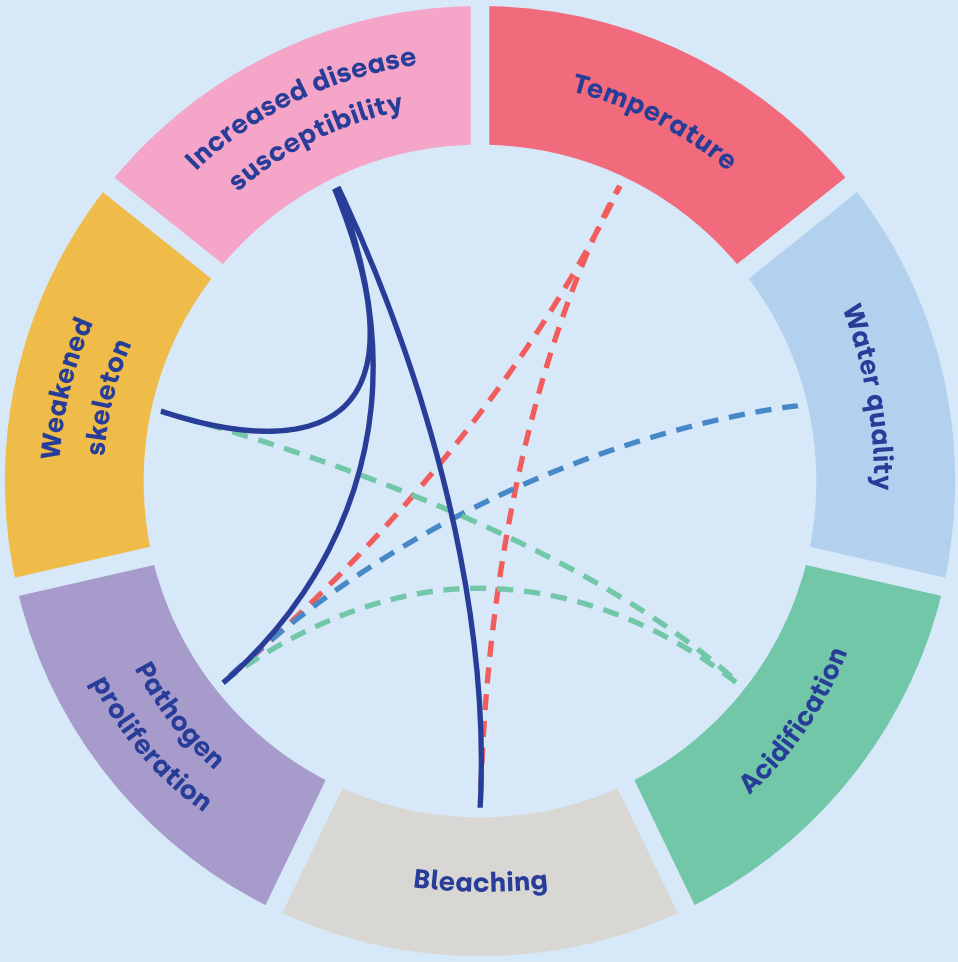


Figure 4. Environmental stressors and their interactions in coral disease susceptibility.
The diagram illustrates the complex interplay between environmental stressors (e.g., increased sea surface temperatures, declining water quality, and acidification) and coral health responses, including bleaching, weakened skeletons, pathogen proliferation, and increased disease susceptibility. Arrows represent relationships among factors, with dashed lines indicating indirect effects and solid lines representing direct links. These stressors act synergistically to destabilize coral-microbial associations, impair immune function, and enhance microbial pathogen virulence, ultimately accelerating reef degradation. Understanding these interactions is crucial for predicting disease outbreaks and developing effective coral reef conservation strategies.

Credits: Greta Aeby

3. Conclusions

The complexity of coral diseases requires a paradigm shift in both research and conservation strategies to bridge existing knowledge gaps and develop effective intervention frameworks. Despite considerable advances in understanding the various pathologies affecting corals, gaps persist in our comprehension of the multifactorial nature of disease emergence, their interactions with the holobiont (holobiont-pathogen-environment), and the long-term evolutionary pathways of coral resilience to diseases. These uncertainties limit the predictive capacity of current studies and impede the development of effective mitigation strategies.

To address these gaps, it is crucial to gain a comprehensive understanding of the dynamics of coral diseases across multiple spatial and temporal scales. Future studies must extend beyond localized assessments and establish long-term multiregional monitoring programs that capture the variability in disease prevalence and the environmental stressors triggering different diseases. Integrative approaches at broad geographic scales should be prioritized, combining molecular diagnostics of coral diseases, long-term ecological monitoring, and predictive modeling.

The role of the coral holobiont in disease resistance remains an underexplored frontier. Therefore, particular attention should be paid to developing analyses that investigate the functional interactions between corals, their microbiomes, and environmental stress factors. This includes targeted investigations into microbial manipulation strategies, such as probiotics, phage therapy and microbial transplants, to enhance coral immunity and mitigate pathogen infections. These approaches must undergo rigorous ecological risk assessments, balanced against the risk of inaction and/or the use of alterntive options (e.g., antibiotics), to ensure their long-term safety and efficacy in coral reef ecosystems across different latitudes.

The implementation of these methodologies should adhere to standardized protocols through global research networks, ensuring data comparability and reproducibility. This will enable researchers to identify epidemiological trends and evaluate the effectiveness of the strategies employed.

Finally, an interinstitutional framework is necessary to implement disease mitigation at ecologically relevant scales. Establishing this institutional network will facilitate the creation or enhancement of global data exchange platforms and promote collaboration to accelerate the translation of research findings into viable conservation policies.

In conclusion, tackling coral diseases requires a transition from reactive crisis management to proactive intervention strategies grounded in scientific evidence. This necessitates sustained funding commitments, the integration of traditional ecological knowledge with cutting-edge technological advancements, and the development of adaptive management frameworks that account for the rapid pace of climate change. By systematically addressing the persistent knowledge gaps in coral disease research, the scientific community can progress toward scalable and resilient solutions that protect coral reef ecosystems for future generations.

Credits: Francisco Medellin

Credits: Francisco Medellin

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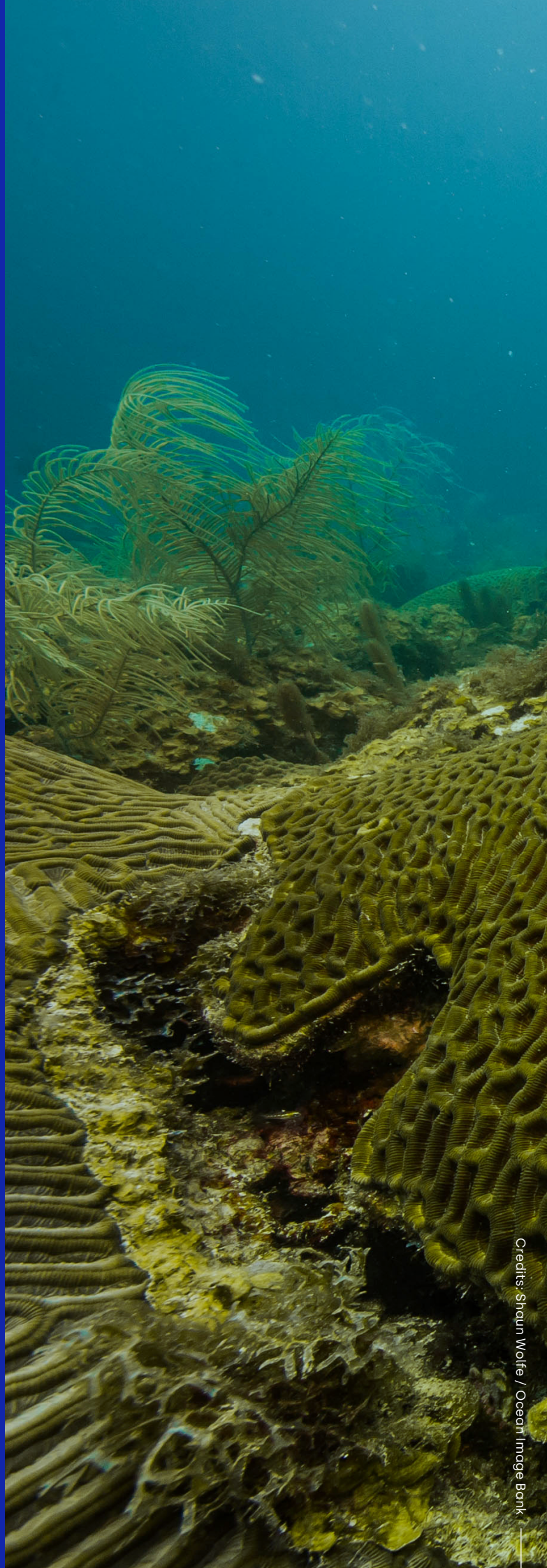

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