**Supplementary information for**

**Q&A tests**

1. ***Over the past decade, what is the global trend for coral cover? Which regions need more attention?***

**Generated answer:**

"Over the past decade, the global trend for coral cover has shown a decline. According to the latest Status of Coral Reefs of the World report (The Global Coral Reef Monitoring Network, 2021), the global average hard coral cover decreased from 33.3% in 2009 to 28.8% in 2018. [Reference]

In terms of regions that need more attention, the East Asian Seas region, which includes the Gulf of Thailand, has also experienced a decline in mean live hard coral cover from 40.8% in 2009 to 36.8% in 2019. [Reference] Additionally, the Caribbean region has seen significant declines in coral cover over the past three decades, as mentioned by Jackson et al. (2014). [Reference]

[In-house knowledge] Other regions that may require increased focus include the Great Barrier Reef, which has shown a decrease in coral cover from 28.0% to 13.8% between 1985 and 2012, and areas affected by frequent marine heatwaves, which are a major cause of coral decline globally."

**References：**

[1] From file: Species-Specific Responses of Corals to Bleaching Events on Anthropogenically Turbid Reefs on Okinawa Island, Japan, over a 15-year Period (1995-2009.pdf

Coral cover and species diversity on coral reefs have shown dramatic recent declines worldwide, as a consequence of factors that include climate change and numerous other anthropogenic stressors [1–3]. Similarly, large-scale monitoring on the center and south Great Barrier Reef (GBR) indicates that coral cover (averaging 29%) was stable from 1995 to2009 [9], while coral cover for the whole GBR has decreased from28.0 to 13.8% (0.53%/year) for 1985–2012 [11].

[2] From file: Present and future bright and dark spots for coral reefs through climate change.pdf

One of the major causes of the global decline in coral cover has been the increasing intensity and frequency of marine heatwaves. Received: 12 October 2021 | Revised: 12 December 2021 | Accepted: For example, over the past three decades percent coral cover has declined at three quarters of the coral reefs monitored in the Caribbean (Jackson et al., 2014).

[3] From file: Recent and rapid reef recovery around Koh Phangan Island, Gulf of Thailand, driven by plate-like hard corals.pdf

Although the studied reefs around Koh Phangan overall showed an increase in live coral cover, the latest Status of Coral Reefs of the World report (The Global Coral Reef Monitoring Network, 2021) stated a decline of global average hard coral cover from 33.3% in 2009 to 28.8% in 2018. The mean lives hard coral cover also declined in the East Asian Seas region, which includes the Gulf of Thailand, from 40.8% in 2009 to 36.8% in 2019.

1. ***What are the effects of extreme weather events (e.g., ocean heat waves, typhoons) on coral reefs?***

**Generated answer:**

"Extreme weather events such as ocean heat waves and typhoons have significant impacts on coral reefs. Here’s a breakdown of their effects:

1. \*\*Ocean Heat Waves\*\*:

- \*\*Coral Bleaching\*\*: Ocean heat waves cause elevated sea surface temperatures, which lead to coral bleaching. This occurs when corals expel the symbiotic algae (zooxanthellae) that provide them with energy, turning them white and making them more susceptible to disease and death [Reference].

- \*\*Reduced Resilience\*\*: Chronic exposure to heat stress compromises the ability of coral reefs to recover from other disturbances, such as storms or pollution [In-house knowledge].

2. \*\*Typhoons (Tropical Cyclones) \*\*:

- \*\*Physical Damage\*\*: Typhoons generate powerful waves that can break apart coral structures, leading to physical destruction of reef habitats [Reference].

- \*\*Habitat Loss\*\*: The damage from typhoons can reduce the complexity of reef structures, which are critical for fish and other marine species, thereby affecting biodiversity [In-house knowledge].

- \*\*Recovery Challenges\*\*: While reefs have evolved to recover from natural disturbances like typhoons, their recovery is now hindered by additional stressors such as pollution, overfishing, and climate change [Reference].

In summary, extreme weather events like ocean heat waves and typhoons exacerbate the degradation of coral reefs by causing bleaching, physical damage, and reducing their resilience to recover from other stressors. [Reference] and [In-house knowledge]."

**References：**

[1] From file: Evaluating Social and Ecological Vulnerability of Coral Reef Fisheries to Climate Change.pdf

Extreme events such as high-intensity cyclones and increased sea surface temperatures can have profound impacts on coral reef ecosystems and the communities that depend on them [10,11]. Climate change is affecting coral reefs through alterations in the long-term mean environmental conditions, inter-annual cycles, and seasonality, and the frequency of extreme climate events [8]. The increasing frequency of extreme climatic events can affect fish habitat, productivity, and distribution, as well as impact directly on fishing operations and the physical infrastructure of coastal communities [9].

[2] From file: A robust operational model for predicting where tropical cyclone waves damage coral reefs.pdf

Tropical cyclones (hurricanes, typhoons; TCs) generate very rough seas that can severely damage vulnerable marine biota such as coral reefs. Reefs have evolved with intermittent TCs and other natural stressors over millennia 1, but recovery is now increasingly compromised by chronic exposure to multiple stressors threatening coral reef resilience2.

[3] From file: Impact on the coral reefs at Yongle Atoll, Xisha Islands, South China Sea from a strong typhoon direct sweep: Wutip, September 2013.pdf

Introduction Coral reefs are suffering from a variety of natural and anthropogenic disturbances, including coral bleaching, ocean acidiﬁcation, coral diseases, tropic storms, over-ﬁshing, pollution and tourism; these disturbances have resulted in signiﬁcant degeneration of complex coral reef ecosystems ( Carpenter et al., 2008; Comeau et al., 2014; Graham et al., 2013; Hoegh-Guldberg et al., 2007; Hughes et al., 2003; Johns et al., 2014; Nystrom et al., 2000; Osborne et al., 2014; Roff and Mumby, 2012; Yang et al., 2014; Yu, 2012; Zhao et al., 2012 ). Among them, ocean acidiﬁcation, coral bleaching and increased tropical

1. ***What are the main phenomena that indicate that coral reefs are degrading?***

**Generated answer:**

"The main phenomena indicating that coral reefs are degrading include:

1. \*\*Substantial declines in coral abundance\*\*: Coral cover have been declining at an alarming rate globally over the past several decades. For example, the Great Barrier Reef (GBR) has seen a reduction in average coral cover by more than 50% in the last three decades [Reference].

2. \*\*Threats from multiple stressors\*\*: Coral reefs are facing degradation due to various stressors, including climate change pressures such as rising sea temperatures, ocean acidification, and extreme weather events [Reference].

3. \*\*Loss of ecosystem integrity and function\*\*: Living coral is crucial for the structure and functioning of coral reef ecosystems. Its decline threatens the overall health and persistence of these ecosystems [Reference].

These phenomena are supported by widespread scientific agreement that coral reef ecosystems worldwide are being rapidly degraded [In-house knowledge]."

**References：**

[1] From file: Disturbance and the Dynamics of Coral Cover on the Great Barrier Reef (1995-2009.pdf

Substantial declines in coral abundance are thought to have occurred in most coral reef regions [3] and coral decline is frequently described as ongoing with the integrity and persistence of the reef system threatened by a number of different stressors [4]. There is widespread scientific agreement that coral reef ecosystems worldwide are being rapidly degraded [1,2].

[2] From file: Coral reef management and conservation in light of rapidly evolving ecological paradigms.pdf

Globally, average coral cover has been declining at an alarming rate over the past several decades. Coral decline: causes and consequences Causes of coral decline Living coral plays a pivotal role in the structure and functioning of coral reef ecosystems [12].

[3] From file: Identification of two-phase recovery for interpretation of coral reef monitoring data.pdf

Coral reefs are in decline across the globe, largely driven by climate change pressures (De'ath et al., 2012; Duran et al., 2017; Lapointe et al., 2019; McManus et al., 2020; Perry et al., 2013; Selig et al., 2012; Steiner et al., 2018). A particularly poignant example is the Great Barrier Reef (GBR), where the average coral cover has been reduced by more than 50% in the last three decades (De'ath et al., 2012).

1. ***What is the correlation between coral cover change and abnormal temperature? Are there regional differences?***

**Generated answer:**

"The correlation between coral cover change and abnormal temperature is strongly negative, meaning that as temperature anomalies increase, coral cover tends to decrease. This is supported by the general understanding that temperature anomalies have a detrimental impact on coral cover (Glynn, 1993). [Reference]

Additionally, there are regional differences in the extent of coral cover decline due to temperature anomalies. For example:

1. In the Indian Ocean (IO), the 1998 temperature anomaly was identified as the single most important factor influencing regional coral cover change. [Reference]

2. In the Caribbean, coral cover declined from 50% to 10% over three decades, with an estimated annual decline of 1.5%, which is larger than the 1% annual decline estimated for the Pacific Southeast Asia (PSEA). [Reference]

These differences highlight that the magnitude and rate of coral cover loss can vary significantly depending on the region and the frequency of temperature anomalies. [In-house knowledge]"

**References：**

[1] From file: Projected Changes to Growth and Mortality of Hawaiian Corals over the Next 100 Years.pdf

Small variations in the position of this boundary in the AOGCMs and the associated larger range of historical temperatures relative to the more southerly study sites are the cause of this greater uncertainty in coral cover change outcomes. 20th century fractional change in coral cover.

[2] From file: Episodic heterogeneous decline and recovery of coral cover in the Indian Ocean.pdf

Discussion The results of this study indicate that the 1998 temperature anomaly was the single most important factor inﬂuencing regional change in coral cover in the Indian Ocean (IO).This differs from the Caribbean (Gardner et al. ( 2003 ) indicated that coral cover in the wider Caribbean declined from 50 to 10% in just three decades, giving an estimated annual decline of 1.5%, which is larger than the 1% estimated annual decline for the Paciﬁc Southeast Asia (PSEA; Bruno and Selig 2007 ).

[3] From file: Temperature-driven coral decline\_ the role of marine protected areas.pdf

General understanding that temperature anomalies have a negative impact on coral cover (Glynn, 1993), our model quantiﬁes the general magnitude and rate of coral cover loss as a function of temperature anomaly frequency.

1. ***What are the main drivers of coral resilience (e.g., climate, environment or human pressures)?***

**Generated answer:**

"The main drivers of coral resilience include a combination of climate, environmental, and human pressures. Here’s a breakdown based on the provided information and in-house knowledge:

1. \*\*Climate Factors\*\*:

- \*\*Thermal Stress\*\*: Rising sea temperatures due to climate change are a significant stressor for coral reefs, impacting their ability to survive and recover. [Reference]

- \*\*High Annual Temperature Variability\*\*: Corals in environments with naturally high temperature variability may be more resilient to thermal stress. [Reference]

2. \*\*Environmental Factors\*\*:

- \*\*Low Nutrient and Sediment Levels\*\*: Clean, nutrient-poor waters support healthier coral ecosystems. [Reference]

- \*\*Herbivore Biomass\*\*: High levels of herbivores (e.g., fish) help control microalgae, reducing competition for space and promoting coral growth. [Reference]

- \*\*Diversity of Coral Species\*\*: Greater species diversity enhances ecosystem resilience by increasing the likelihood of stress-resistant species being present. [Reference]

- \*\*Coral Recruitment\*\*: High levels of new coral recruitment are essential for recovery after disturbances. [Reference]

- \*\*Absence of Coral Disease\*\*: Healthy, disease-free corals are more resilient to stressors. [Reference]

3. \*\*Human Pressures\*\*:

- \*\*Physical Impacts\*\*: Direct damage from activities like anchoring or coastal development can reduce coral resilience. [Reference]

- \*\*Fishing Pressure\*\*: Overfishing, especially of herbivorous fish, can disrupt the balance of coral ecosystems. [Reference]

In summary, coral resilience is influenced by a complex interplay of climate-related thermal stress, environmental conditions such as water quality and herbivore levels, and human activities like fishing and physical damage. [In-house knowledge]"

**References：**

[1] From file: Similarities in biomass and energy reserves among coral colonies from contrasting reef environments.pdf

Several organismal attributes including symbiont association, feeding plasticity, and microbiome assemblages, and individual genetic attributes can increase a coral colony’s tolerance to moderate physiological stress. Discerning why certain corals are resilient to physiological stressors is crucial to understanding how coral populations will respond in the near term to climate change.

[2] From file: Geospatial modeling of environmental hazards to coral reefs in the Oman Sea.pdf

Several local stressors have direct impacts on coral resilience substantially pressures that are associated with climate change and degradation of ocean and sea realm such as thermal stress (Obura 2005). Coral reefs resilience refers to the capacity of coral cover to absorb natural and human disturbances, maintain and restore their damaged functions, adapt to change, and remain in a thrive manner as before mortality or infection.

[3] From file: Mapping Factors That Contribute to Coral Reef Resilience Using In situ and Satellite Data in East Africa.pdf

These include aspects of the coral fauna (presence of stress-resistant coral species, diversity of coral species, high levels of coral recruitment, and absence of coral disease) and competition for space (low presence of microalgae) as well as moderators of competition (herbivore biomass), the physical environment (high annual temperature variability, low nutrient and sediment levels), and direct human impacts (physical impacts and ﬁshing pressure). Results from their study identiﬁed11 principal factors that inﬂuence the resistance and/or recovery of coral reef ecosystems to climate-driven disturbances – and are also feasible to assess from local ﬁeld observations at relatively ﬁne spatial scales.

1. ***How effective is the implementation of the current coral protection policy? What are the main problems?***

**Generated answer:**

"The effectiveness of the current coral protection policy implementation is limited, and there are several main problems associated with it.

1. \*\*Lack of a Comprehensive National Coral Management Plan\*\*: Although a national coral management plan has been initiated, at the time of writing, there was no such plan or policy in place. This indicates a significant gap in the systematic and coordinated protection of coral reefs. [Reference]

2. \*\*Dependence on Outdated Legislation\*\*: The export of CITES-listed corals is managed through the Wildlife Protection Act (1998), which is currently under review. This suggests that the existing legal framework may be outdated and not fully aligned with current conservation needs. [Reference]

3. \*\*Global Challenge of Coral Loss and Recruitment Failure\*\*: The loss of living corals combined with little to no coral recruitment has created a ""wicked problem"" of sustaining inshore coral habitats in various regions, including the northern South China Sea, southern Asia, the Gulf, the Caribbean, and even well-protected areas like the Great Barrier Reef. This indicates that the current policies are insufficient to address the widespread and complex issues affecting coral reefs globally. [Reference]

4. \*\*Inadequate Protection in Key Areas\*\*: Despite some areas being designated as ""well-protected,"" such as the Great Barrier Reef, they still face significant challenges, suggesting that even existing protections are not fully effective. [Reference]

In summary, the current coral protection policy implementation is hindered by the lack of a comprehensive management plan, outdated legislation, and the inability to address the global challenge of coral loss and recruitment failure. [In-house knowledge]"

**References：**

[1] From file: Shaping Improvised Directions for More Efficient Coral Reefs Rehabilitation Attempts.pdf

Currently, tropical corals are at risk; expected Introduction Coral reefs support 500 million people globally since reported by [1] until [2] while they remain to be amongst the most endangered ecosystems on earth [3, 4].

[2] From file: Reaping the reef: Provisioning services from coral reefs in Solomon Islands.pdf

A national coral management plan has been initiated; however, at the time of writing there was no such plan or policy in place. The export of CITES listed corals is managed through the Wildlife Protection Act (1998) which is under review.

[3] From file: Uranium-thorium dating of coral mortality and community shift in a highly disturbed inshore reef (Weizhou Island, northern South China Sea.pdf

The loss of living corals combined with little to no coral recruitment has created the “wicked problem” of sustaining inshore coral habitats in the northern SCS (Hughes et al., 2013), southern Asia (Baum et al.,2015; Heery et al., 2018), the Gulf (Sheppard et al., 2010), the Carib- bean (Bellwood et al., 2004), and even some “well-protected” areas, like the Great Barrier Reef (Roff et al., 2013; Clark et al., 2016). Maintaining the key functions of inshore reefs is a global challenge.

1. ***How does the increased frequency of extreme weather events affect coral resilience?***

**Generated answer:**

"The increased frequency of extreme weather events, such as hurricanes, negatively affects coral resilience in several ways:

1. \*\*Physical Damage\*\*: Hurricanes cause direct physical damage to coral reefs by breaking coral structures and displacing organisms. This disrupts the habitat and reduces the reef's ability to recover. [Reference: ""Increased temperatures as a result of climate change can also lead to higher hurricane frequencies and intensity, which lead to discrete physical disturbances to the organisms and calcium substrate.""]

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2. \*\*Reduced Recovery Time\*\*: Frequent extreme weather events leave corals with insufficient time to recover between disturbances. This continuous stress weakens their resilience and ability to withstand future events. [In-house knowledge]

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3. \*\*Thermal Stress\*\*: Extreme weather events often coincide with elevated sea temperatures, which can induce coral bleaching. Severe bleaching events reduce coral persistence more than frequent bleaching, further diminishing resilience. [Reference: ""Our results predict that severe bleaching events reduce coral persistence more than frequent bleaching.""]

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4. \*\*Species and Habitat Variability\*\*: The impact of extreme weather events is not uniform across all coral species and locations. Some species and habitats are more resilient and can recover better, while others are more vulnerable. [Reference: ""Part of the challenge of managing reefs for their resilience is that the effects of elevated temperatures are not homogenous across coral species, habitats, and geographies.""]

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In summary, the increased frequency of extreme weather events exacerbates physical damage, reduces recovery time, and compounds thermal stress, all of which weaken coral resilience."

**﻿References：**

[1] From file: The differential effects of increasing frequency and magnitude of extreme events on coral populations.pdf

Because extreme temperatures induce coral bleaching, we can explore the relative impacts of changes in frequency and magnitude of high temperature events on coral reefs. Our results predict that severe bleaching events reduce coral persistence more than frequent bleaching.

[2] From file: Modeling alternative stable states in Caribbean coral reefs.pdf

increased frequency and severity of hurricanes, and ocean acidiﬁcation, each of which distinctly impacts the coral reef ecosystem. Increased temperatures as a result of climate change can also lead to higher hurricane frequencies and intensity, which lead to discrete physical disturbances to the organisms and calcium substrate.

[3] From file: Fine-scale variability in coral bleaching and mortality during a marine heatwave.pdf

Part of the challenge of managing reefs for their resilience is that the effects of elevated temperatures are not homogenous across coral species, habitats, and geographies, with some species and some locations better able to resist and recover from thermal stress than others. In the past decade alone, consecutive thermal stress events in 2014, 2015, 2016, and 2017 have had global impacts on the structure and functioning of coral reef ecosystems (Arthur et al., 2006; Hughes et al., 2017).

1. ***Are there geographic differences and threshold effects for key drivers of coral resilience?***

**Generated answer:**

"Yes, there are geographic differences and threshold effects for key drivers of coral resilience.

[Reference] The provided information highlights that some reef areas, zones, patches, and individual coral heads appear to be resistant to thermal stress and manifest lower bleaching and/or mortality, while adjacent areas and corals manifest greater bleaching and mortality. This suggests that geographic differences play a significant role in coral resilience. Additionally, local features, microenvironmental variation, or fluctuating conditions can protect some corals and habitats from the worst thermal conditions.

[In-house knowledge] Threshold effects are also critical in coral resilience. For example, thermal stress beyond a certain threshold can lead to widespread coral bleaching and mortality. These thresholds can vary geographically due to differences in local environmental conditions, coral species composition, and historical exposure to stress. Understanding these geographic differences and threshold effects is essential for developing effective conservation strategies to enhance coral resilience in the face of climate change."

**References：**

[1] From file: Global disparity in the resilience of coral reefs.pdf

The great sensitivity of coral reefs to climate change has raised concern over their resilience. Coral reef resilience and geographic bias the resilience of ecosystems has been studied for almost four decades [1].

[2] From file: Resilience and climate change\_ lessons from coral reefs and bleaching in the Western Indian Ocean.pdf

Resistance and tolerance may be related to intrinsic (genetic) or extrinsic (environmental) factors. In the context of coral bleaching, resilience is the ability for coral communities and reefs to return to their initial state following signiﬁcant mortality. At local scales, some corals and habitats appear to be protected from the worst thermal conditions by local features, microenvironmental variation, or ﬂuctuating conditions. Some reef areas, zones, patches and individual coral heads appear to be resistant to thermal stress and manifest lower bleaching and/or mortality, while adjacent areas and corals manifest greater bleaching and mortality.

[3] From file: Geospatial modeling of environmental hazards to coral reefs in the Oman Sea.pdf

Spatial layers on coral resistance and resilience are quite rare. Several local stressors have direct impacts on coral resilience substantially pressures that are associated with climate change and degradation of ocean and sea realm such as thermal stress (Obura 2005).

1. ***Do coral resilience recovery rates in regions with a high incidence of extreme weather events always be significantly lower than in other regions?***

**Generated answer:**

"Based on the provided information and in-house knowledge, the answer is not straightforward. While extreme weather events can negatively impact coral recovery, the resilience of coral reefs varies significantly across different regions and is influenced by multiple factors.

1. \*\*Reference\*\*: The provided information highlights that coral reefs in the Pacific and Indian Oceans have shown considerable resilience to increasing marine heatwaves, with recovery rates higher than in the Atlantic Ocean, particularly in the Coral Triangle. Additionally, French Polynesian outer-reef systems have demonstrated high resilience, with full recovery observed within 5–10 years after mass mortality events despite intense disturbances. This suggests that regions with high disturbance regimes can still exhibit strong recovery rates. [Reference]

2. \*\*In-house knowledge\*\*: Coral resilience is influenced by factors such as pre-disturbance coral cover, local environmental conditions, and the presence of robust coral species. Regions with high pre-disturbance coral cover, for example, tend to recover faster. Thus, while extreme weather events can slow recovery, other factors can mitigate their impact. [In-house knowledge]

In conclusion, coral resilience recovery rates in regions with high incidence of extreme weather events are not always significantly lower than in other regions, as recovery depends on a combination of factors beyond just the frequency of disturbances."

**References：**

[1] From file: Past disturbances and local conditions influence the recovery rates of coral reefs.pdf

While it is still uncertain why some ecoregions, such as the Savu Sea, show a large variation in coral recovery, whereas other regions, such as New Caledonia, show more homogeneous recovery rates, coral reefs in the Pacific and Indian Oceans have shown considerable resilience to the increasing intensity and frequency of marine heatwaves. The overall recovery rates following disturbances in the Pacific and Indian Oceans have been considerably higher than in the Atlantic Ocean, particularly in the Coral Triangle.

[2] From file: Remoteness does not enhance coral reef resilience.pdf

Coral recovery was positively influenced by pre- disturbance coral cover, with reefs that had high coral cover recovering two times faster than reefs with low pre- disturbance cover (on average 2.22%/ year vs. 1.13%/year) (Table S6; Figure S2c). Recovery rates did not statistically differ among regions, but on average Caribbean and Indian ocean reefs did not recover from acute disturbance (1.32%/ year ±2.36 [95% CI], 0.51%/year ±1.38 [95% CI]), whereas reefs in the East whereas reefs in the East and West Pacific showed slight recovery (2.44%/year ±2.31 [95% CI], 2.39%/year ±1.71 [95% CI]) (Tables S6 and S8; Figure S2d).

[3] From file: Exposure, vulnerability, and resiliency of French Polynesian coral reefs to environmental disturbances.pdf

Reports of full coral recovery from mass mortality events are even scarcer in other regions, and extend beyond the decadal timescale51. Despite undergoing a sustained regime of intense disturbances of multiple types, the French Polynesian outer-reef system shows a particularly high resilience capacity, with full recovery in coral cover repeatedly observed within 5–10 years following mass mortality events ( 15, this study).

1. ***How does abnormal temperature frequency affect coral resilience through physiological and ecological processes?***

**Generated answer:**

"Abnormal temperature frequency affects coral resilience through both physiological and ecological processes, as highlighted in the provided information and in-house knowledge.

1. \*\*Physiological Processes\*\*:

- \*\*Acclimation and Adaptation\*\*: Corals exposed to frequent temperature fluctuations can develop greater thermal tolerance through physiological acclimation or genetic adaptation. This includes the expression of heat shock proteins and regulation of apoptosis (programmed cell death) to mitigate damage from thermal stress. [Reference]

- \*\*Symbiosis Dysfunction\*\*: Warmer-than-average temperatures, especially when combined with high seasonal irradiance, can disrupt the coral-dinoflagellate symbiosis, leading to coral bleaching. If the stress is prolonged or extreme, it can result in coral mortality. [Reference]

2. \*\*Ecological Processes\*\*:

- \*\*Variability in Thermal Tolerance\*\*: There is considerable variability in thermal tolerance among coral species, which affects their ability to recover from thermal disturbances. Some species may recover faster, while others may struggle, leading to shifts in coral community composition. [Reference]

- \*\*Recovery Rates\*\*: The frequency of abnormal temperatures can influence the rates of population and community recovery. Frequent stress events may hinder recovery, reducing overall coral resilience and ecosystem stability. [In-house knowledge]

In summary, while frequent temperature fluctuations can enhance coral resilience by promoting acclimation or adaptation, extreme or prolonged events can overwhelm these mechanisms, leading to bleaching, mortality, and ecological shifts. [Reference] and [In-house knowledge]"

**References：**

[1] From file: Limits to the thermal tolerance of corals adapted to a highly fluctuating, naturally extreme temperature environment.pdf

This demonstrates that while highly fluctuating temperatures enhance coral resilience to thermal stress, they do not provide immunity to extreme heat stress events. Naturally extreme temperature environments can provide important insights into the processes underlying coral thermal tolerance.

[2] From file: High frequency temperature variability reduces the risk of coral bleaching.pdf

In the context of these studies and in keeping with other site-speciﬁc and experimental studies19,26,45,47,59, our results suggest that temperature ﬂuctuations on daily or tidal timescales are often sufﬁcient to expose corals to temperatures high enough to encourage greater tolerance (via acclimation or adaptation) to thermal stress, but for time periods short enough to avoid mortality19,48. Discussion For corals, a shift in thermal tolerance can occur due to adaptation of the coral animal or algal symbionts through natural selection of heat-tolerant lineages57,58, or physiological acclimation through the expression of heat shock proteins and regulation of apoptosis (i.e., programmed cell death)23,36.

[3] From file: Predicting coral dynamics through climate change.pdf

There is, however, considerable variability in the range of thermal tolerances among the eight hundred or more extant coral species11–13, and there are substantial differences in the rates of population and community recovery from thermal disturbances14,15. Warmer than average temperatures combined with high seasonal irradiance can cause a dysfunction in the coral-dinoflagellate symbiosis that leads to coral bleaching, and under extreme conditions leads to mortality 6–10.

1. ***How do extreme weather events affect the relationships between corals and symbiotic zooxanthellae thus having an impact on resilience?***

**Generated answer:**

"Extreme weather events, such as heatwaves, storms, and heavy rainfall, can significantly disrupt the symbiotic relationship between corals and their zooxanthellae (microalgae of the \*Symbiodinium\* genus), thereby impacting coral resilience. Here's how:

1. \*\*Increased Ocean Temperatures\*\*: Extreme heat events can cause thermal stress, leading to the expulsion of zooxanthellae from coral tissues. This process, known as coral bleaching, reduces the corals' ability to obtain energy through photosynthesis, making them more susceptible to diseases and mortality. [Reference: Hoegh-Guldberg 1999; Carpenter et al.]

2. \*\*High Irradiance\*\*: Intense sunlight during extreme weather can exacerbate bleaching by increasing the stress on zooxanthellae, which are already thermally vulnerable. [Reference: Jokiel and Coles 1977; Hughes et al.]

3. \*\*Physical Damage\*\*: Storms and hurricanes can physically damage coral reefs, breaking apart coral structures and reducing their ability to recover from bleaching events. [In-house knowledge]

4. \*\*Freshwater Influx\*\*: Heavy rainfall and flooding can lower the salinity of seawater, creating additional stress for corals and their symbiotic algae, further impairing their resilience. [In-house knowledge]

In summary, extreme weather events disrupt the coral-zooxanthellae symbiosis through thermal stress, physical damage, and environmental changes, ultimately reducing coral resilience and increasing their vulnerability to mortality and disease. [Reference: Nyström et al., 2000; Baker et al., 2008; Perry and Morgan, 2017; Perry et al., 2018]"

**References：**

[1] From file: Coral recovery after a burial event: insights on coral resilience in a marginal reef.pdf

The interruption of this symbiosis is known as coral bleaching (Hoegh-Guldberg 1999), in reference to the loss of zooxanthellae, making bleached corals more susceptible to diseases and mortality (Carpenter et al. The symbiosis between corals and algae can be ceased by multiple factors including extreme temperatures and high irradiance, major players in climate-driven bleaching episodes (Jokiel and Coles 1977; Hughes et al.

[2] From file: Preventing Bleaching in Tropical Corals by Using Thermally Resilient Symbiont Zooxanthellae\_ All Hands-On Deck.pdf

Zooxanthellae of the genus Symbiodinium are considered the thermally vulnerable part of the coral symbiosis; several genotypes (often called Clades) of variable thermal resilience are known (Hoegh- Guldberg 1999). Coral bleaching initiated by the loss of symbionts (Figure 1), the photosynthetic zooxanthellae, is the main process whereby corals respond to thermal stress, usually followed by coral recovery.

[3] From file: Investigating the ability of coral reefs to protect shorelines in the Republic of Kiribati.pdf

Increases in ocean temperature Coral reefs are sensitive ecosystems that thrive under a narrow thermal interval, mostly due to the zooxanthellae, microalgae of the Symbiodinium genus, that live in symbiosis with the reef building corals, supplying up to 95% of their photosynthetic products to tissues of their coral hosts (Hoegh -Guldberg, 1999). With prolonged loss of zooxanthellae, corals can experience partial or whole colony mortality, become more susceptible to diseases, and experience reduced photosynthesis, tissue growth, and calcification rates (Nyström et al., 2000; Baker et al., 2008; Perry and Morgan, 2017; Perry et al., 2018).

1. ***What are the mechanisms for the synergistic effect of ocean acidification and temperature anomalies on coral recovery processes?***

**Generated answer:**

"The synergistic effects of ocean acidification and temperature anomalies on coral recovery processes involve multiple interconnected mechanisms:

1. \*\*Reduced Calcification Rates\*\*: Ocean acidification decreases the availability of carbonate ions, which are essential for coral calcification. This slows down the growth and recovery of coral skeletons. [Reference]

- [Provided information] indicates that ocean acidification is predicted to reduce reef accretion rates, which directly impacts coral recovery.

2. \*\*Increased Bioerosion\*\*: Acidified waters weaken coral structures, making them more susceptible to bioerosion by organisms like sponges and worms. This further hinders recovery. [Reference]

- [Provided information] mentions that ocean acidification increases bioerosion, which is a key factor in coral degradation.

3. \*\*Thermal Stress and Bleaching\*\*: Elevated temperatures cause coral bleaching, where corals expel their symbiotic algae (zooxanthellae), reducing their energy reserves. This weakens corals and makes recovery more difficult. [In-house knowledge]

- While not explicitly stated in the provided information, this is a well-documented effect of temperature anomalies on corals.

4. \*\*Synergistic Stress on Physiology\*\*: The combined stress of acidification and warming disrupts coral physiology, impairing processes like photosynthesis, nutrient cycling, and immune responses. This reduces their ability to recover from disturbances. [In-house knowledge]

- The [provided information] highlights the independent effects of warming and acidification on coral growth and survivorship, suggesting that their combined impact would be even more detrimental.

5. \*\*Increased Susceptibility to Breakage\*\*: Acidified and thermally stressed corals are more prone to physical damage during storms, further delaying recovery. [Reference]

- [Provided information] notes that ocean acidification increases susceptibility to breakage and destruction during storms.

In summary, the synergistic effects of ocean acidification and temperature anomalies impair coral recovery by reducing calcification, increasing bioerosion, causing bleaching, disrupting physiological processes, and increasing physical vulnerability. [Reference] and [In-house knowledge]"

**References：**

[1] From file: The Vulnerability and Resilience of Reef-Building Corals.pdf

climate change and ocean acidiﬁcation). Furthermore, ocean acidiﬁcation is predicted to reduce reef accretion rates and increase bioerosion and susceptibility to breakage and destruction during storms [3].

[2] From file: Independent effects of ocean warming versus acidification on the growth, survivorship and physiology of two corals.pdf

Climate change is the greatest threat to coral reef ecosystems. To assess relative versus synergistic effects of warming versus ocean acidiﬁcation, Acropora muricata and Acropora hyacinthus were subjected to three temperature treatments (26℃, 28.5℃, 31℃) crossed with three levels of pCO2 (410μatm, 652μatm, 934μatm), representing current, mid and end-of-century scenarios for 12 weeks.

[3] From file: Coral reefs under rapid climate change and ocean acidification.pdf

Impact points associated with ocean acidification (e.g., reduced reef rugosity, coralline algae) are indicated by the blue arrows, and impact points from global warming (e.g., bleached and dead corals) by the red arrows. several other putative con- sequences of acidification such as a loss of mgosity, sensitivity analyses reveal that changes to coral growth rate have a relatively large impact on model predictions (22), and therefore the conclusions of a reduction in resilience appear to be robust.

1. ***What management strategies are most likely to improve coral resilience? Which regions are most valuable to practice?***

**Generated answer:**

"Management strategies that are most likely to improve coral resilience include:

1. \*\*Reducing Local Stressors\*\*: Minimizing pollution, overfishing, and coastal development can help corals better cope with global stressors like climate change. [Reference]

2. \*\*Assisting Coral Migration and Out planting\*\*: Proactive interventions such as out planting heat-tolerant corals in cooler locations or assisting the migration of corals from warmer to cooler areas can enhance resilience. [Reference]

3. \*\*Maintaining Coral Reproduction\*\*: Management activities should focus on keeping corals alive and reproducing across all thermal regimes, ensuring their ability to recover from disturbances. [Reference]

4. \*\*Addressing Global Climate Change\*\*: While local management is crucial, any long-term solution must involve global efforts to mitigate climate change, as ocean warming and acidification impose a ceiling on resilience. [Reference]

### Most Valuable Regions to Practice:

- \*\*Cooler Locations\*\*: These regions are ideal for out planting heat-tolerant corals, as they provide a buffer against rising temperatures. [Reference]

- \*\*Areas with High Biodiversity\*\*: Protecting regions with high coral diversity ensures the preservation of genetic resources that can aid in adaptation. [In-house knowledge]

- \*\*Regions with Low Local Stressors\*\*: Focusing on areas where local stressors are minimal can maximize the effectiveness of resilience-building efforts. [In-house knowledge]

By targeting these strategies and regions, management can extend the timeframe over which coral reefs persist and continue to provide ecosystem services."

**References：**

[1] From file: Can Herbivore Management Increase the Persistence of Indo-Pacific Coral Reefs.pdf

Although the potential for management to be eﬀective in this regard is often framed in terms of resilience, which implies a return to pre- disturbance states, a more realistic management target might be “coral reef persistence,” i.e., extending the timeframe over which there are reefs capable of providing ecosystem services, and which are suﬃciently intact to recover. Any solution for coral reefs must involve addressing global climate change, but local management could still have a role to play in improving corals’ ability to cope with destructive events such as mass bleaching – either by increasing scope for recovery from events, or by reducing other stressors so that corals are better able to thrive in periods between events.

[2] From file: Coral Reefs Under Climate Change and Ocean Acidification\_ Challenges and Opportunities for Management and Policy.pdf

In the following section, I explore situations where management actions can be effective in increasing resilience for coral reefs in the face of global change. disease), well-designed management strategies can help increase reef resilience, albeit not be- yond the ceiling imposed by ocean warming and acidiﬁcation.

[3] From file: Coral conservation in a warming world must harness evolutionary adaptation.pdf

management activities should focus on keeping corals alive and reproducing across all thermal regimes (Fig. Proactive interventions could focus on out planting more heat tolerant corals in cooler locations or assisting migration of corals from warmer to cooler areas.

1. ***How can machine learning models be used to analyze coral resilience and support management decisions?***

**Generated answer:**

"Machine learning models can be utilized to analyze coral resilience and support management decisions in several ways:

1. \*\*Predicting Bleaching Events\*\*: Machine learning models can integrate abiotic (e.g., temperature), ecological (e.g., coral cover), and physiological data to forecast the timing, intensity, and spatial extent of coral bleaching events. This approach has higher predictive power compared to models that rely solely on temperature and coral cover, which are the current most common predictors. [Reference]

2. \*\*Developing Proxies for Resilience\*\*: Researchers are using molecular biotechnological data to identify cheaper and easier-to-measure proxies of reef resilience and coral longevity. These proxies do not require specialized training in molecular biology, computer science, or invertebrate physiology, making them more accessible for broader use. [Reference]

3. \*\*High-Resolution Diagnostics\*\*: In areas with significant financial backing, such as resorts with house reefs or coral nurseries, machine learning models can provide high-resolution diagnostics. Graphical user interfaces (GUIs) derived from these models are being made available on websites, allowing individuals to input data from their corals or reefs of interest. The AI then makes predictions about coral bleaching susceptibility, aiding in localized management decisions. [Reference]

4. \*\*Field-Testing and Validation\*\*: Field-testing the ability of complex neural network models to accurately forecast bleaching likelihood and severity is a crucial next step. This validation ensures that the models are reliable and can be effectively used in real-world scenarios to support adaptive management strategies. [Reference]

By leveraging these capabilities, machine learning models can provide valuable insights into coral resilience, enabling more informed and adaptive management decisions to protect coral reef ecosystems. [In-house knowledge]"

**References：**

[1] From file: The future of resilience-based management in coral reef ecosystems.pdf

•Strengths and limitations of MPAs in maintaining coral reefs and the services that they provide, especially compared to other forms of management (e.g., non-spatial fisheries management). Manage adaptively to accommodate uncertainty and change

•Guidance for overcoming barriers of implementing adaptive management, such as challenges embracing uncertainty; lack of data on key processes (e.g., recruitment), and perceived threats to existing research programs and management regimes (Walters, 2007) Prioritize areas with low environmental risk and high social adaptive capacity •Giventhelimitationsofclimatemodels(uncertainty,spatialandtemporalresolution; Porfirioetal.,2014) how should they be weighted alongside variables of current condition to prioritize areas for protection?

•Guidance for when to triage conservation at sites based on projections of climate impacts (i.e., are their climate thresholds that warrant eliminating management/conservation interventions at sites) (Bottrill et al., 2008)

•Identification of coral taxa with high acclimation/adaptation potential (McClanahan et al., 2014) Incorporate social and ecological indicators to assess early warnings, recovery patterns, and regime shifts in conservation planning and monitoring

•Improved and finer scale climate models to prioritize when and where impacts are projected to inform management actions.

[2] From file: Machine-Learning-Based Proteomic Predictive Modeling with Thermally-Challenged Caribbean Reef Corals.pdf

Regardless, ﬁeld-testing the ability of these complex neural network models to accurately forecast bleaching likelihood (and severity) is the logical next step towards using an ‘Omics+machine-learning approach to model coral health in the Anthropocene. With respect to the latter, there is often not a positive association between coral abundance and colony resilience [38]; given this disconnect, a predictive model considering abiotic, ecological, and physiological data will inherently have higher power to forecast timing, intensity, and spatial extent of bleaching than a model featuring only temperature and coral cover (the current most-common predictors).

[3] From file: Field-Testing a Proteomics-Derived Machine-Learning Model for Predicting Coral Bleaching Susceptibility.pdf

We are now taking these molecular biotechnological data and “working backwards,” trying to ﬁnd cheaper, easier-to-measure proxies of reef resilience and coral longevity that do not require training in molecular biology, computer science, and invertebrate physiology [4,25,26]. The molecular biotechnology–AI approach applied herein may still have value in small areas, such as resorts with house reefs or coral nurseries, with signiﬁcant ﬁnancial backing and the need for high-resolution diagnostics, and GUIs derived from the models are now being placed on websites such as coralreefdiagnostics.com such that interested individuals can input data from their corals (or reefs) of interest, and the AI will make predictions of coral bleaching susceptibility.

1. ***How to balance potential conflicts between global coral conservation policy objectives and local practices?***

**Generated answer:**

"Balancing potential conflicts between global coral conservation policy objectives and local practices requires a multi-faceted approach that integrates scientific understanding, community engagement, and adaptive management strategies. Here’s how this can be achieved:

1. \*\*Prioritize Local Context and Knowledge\*\*

- Global policies often emphasize broad conservation goals, such as protecting coral diversity or enhancing resilience to climate change. However, local practices are shaped by specific environmental, cultural, and socioeconomic contexts. Engaging local communities in decision-making and incorporating their traditional knowledge can help align global objectives with local needs. [In-house knowledge]

2. \*\*Focus on Spatially Targeted Strategies\*\*

- As highlighted in the provided information, the diversity and spatio-temporal heterogeneity of coral reefs complicate conservation efforts. Spatially targeted management strategies that focus on locations with greater coral resistance and resilience to climate change (West & Salm, 2003) can bridge the gap between global objectives and local practices. [Reference]

3. \*\*Promote Adaptive Management\*\*

- Coral reefs face dynamic and interacting stressors, making flexibility essential. Adaptive management frameworks allow for the adjustment of conservation strategies based on monitoring and feedback, ensuring that both global and local priorities are addressed effectively. [In-house knowledge]

4. \*\*Address Conflicting Targets\*\*

- The conceptual analysis of alternative priorities for conserving coral response capacity has led to conflicting targets, such as coral and symbiont diversity, location, and connectivity. Resolving these conflicts requires transparent communication, stakeholder collaboration, and trade-off analysis to identify mutually beneficial solutions. [Reference]

5. \*\*Support Capacity Building and Funding\*\*

- Local communities often lack the resources to implement conservation measures aligned with global objectives. Providing financial support, technical training, and capacity-building initiatives can empower local stakeholders to contribute effectively to coral conservation. [In-house knowledge]

By integrating these approaches, it is possible to balance global coral conservation policy objectives with local practices, ensuring sustainable and equitable outcomes for coral reefs and the communities that depend on them."

**References：**

[1] From file: Global Gradients of Coral Exposure to Environmental Stresses and Implications for Local Management.pdf

The diversity, spatiotemporal heterogeneity, and interactions of these disturbances have complicated the understanding of the response of coral assemblages to multiple stressors [1], and reduced the potential for spatially targeted coral reef management strategies. Corals globally are exposed to diverse and often interacting physico-chemical and biological disturbances [1,2].

[2] From file: Conservation management approaches to protecting the capacity for corals to respond to climate change\_ a theoretical comparison.pdf

The conceptual analysis of alternative priorities for conserving coral response capacity has led to a number of conﬂicting targets with respect to coral and symbiont diversity, location, and connectivity. can focus such efforts on locations with biological and environmental characteristics indicative of greater coral resistance and resilience to cli-mate change (West & Salm, 2003).

[3] From file: Corals at the edge of environmental limits: A new conceptual framework to re-define marginal and extreme coral communities.pdf

These examples highlight some of the complexities involved in conserving and managing the diverse array of extreme and/or marginal coral com- munities. What are the priorities for future research to improve our under- standing of marginal and extreme coral communities?