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Climate change impacts on the coral reefs of the UK Overseas Territory of the Pitcairn Islands: resilience and adaptation considerations

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Abstract

The coral reefs of the Pitcairn Islands are in one of the most remote areas of the Pacific Ocean, and yet they are exposed to the impacts of anthropogenic climate change. The Pitcairn Islands Marine Protected Area was designated in 2016 and is one of the largest in the world, but the marine environment around these highly isolated islands remains poorly documented. Evidence collated here indicates that while the Pitcairn Islands' reefs have thus far been relatively sheltered from the effect of warming sea temperatures, there is substantial risk of future coral decalcification due to ocean acidification. The projected acceleration in the rate of sea level rise, and the reefs' exposure to risks from distant ocean swells and cold-water intrusions, add further uncertainty as to whether these islands and their reefs will continue to adapt and persist into the future. Coordinated action within the context of the Pitcairn Islands Marine Protected Area can help enhance the resilience of the reefs in the Pitcairn Islands. Options include management of other human pressures, control of invasive species and active reef interventions. More research, however, is needed in order to better assess what are the most appropriate and feasible options to protect these reefs.

Introduction

Impacts from climate change and other human activities are causing a rapid global decline of coral reefs (Wilkinson, 2008; Burke *et al.*, 2011; IPCC, 2014*a*, 2022). Most of the world's tropical reefs have experienced severe bleaching events in the past 30 years, with widespread bleaching occurring in 1998, 2010 and through 2014–2017 (Heron *et al.*, 2016; Sully *et al.*, 2019). Warm-water corals are projected to decline further in the coming decades as they become increasingly exposed to thermal anomalies (Van Hooidonk *et al.*, 2016; Hughes *et al.*, 2017, 2018). Ocean acidification, storminess and the compounding impact of other anthropogenic pressures further raises the risk to corals into the future (Pandolfi *et al.*, 2011; Dutra *et al.*, 2021; IPCC, 2022). Stony corals have a disproportionately important role in the marine environment; changes in species composition can dramatically impair the ecological functioning of the reef with negative, knock-on consequences to associated biological communities (Glynn, 1993; Moberg & Folke, 1999; Baker *et al.*, 2008; Fisher *et al.*, 2015). In addition to their ecological importance, coral reefs provide a range of vital services to societies and economies, including food provision, coastal protection and tourism (Moberg & Folke, 1999; IPCC, 2014*a*), which are particularly important in the case of small oceanic islands.

The remote Pitcairn Islands group in the equatorial South Pacific includes the islands of Pitcairn, Oeno, Henderson and Ducie, with an aggregated land area of only 49 km^2 (Irving & Dawson, 2012). These islands are part of an outcrop along the Foundation Seamount chain in the central South Pacific (Figure 1). Pitcairn Island is volcanic and the only inhabited island, with 52 permanent residents as of January 2020 (Pitcairn Miscellany, 2020). The coastline of Pitcairn Island is rocky and steep and exposed to large ocean swells (Avagliano *et al.*, 2016). Henderson Island is formed from a raised coral reef, and Oeno and Ducie are low coral atolls (Spencer, 1995; Robinson *et al.*, 2017). The Pitcairn Islands Marine Protected Area (MPA) was designated in 2016 (The Government of the Pitcairn Islands, 2017) and is one of the largest in the world, covering 841,910 km^2 (UNEP-WCMC & IUCN, 2021). The

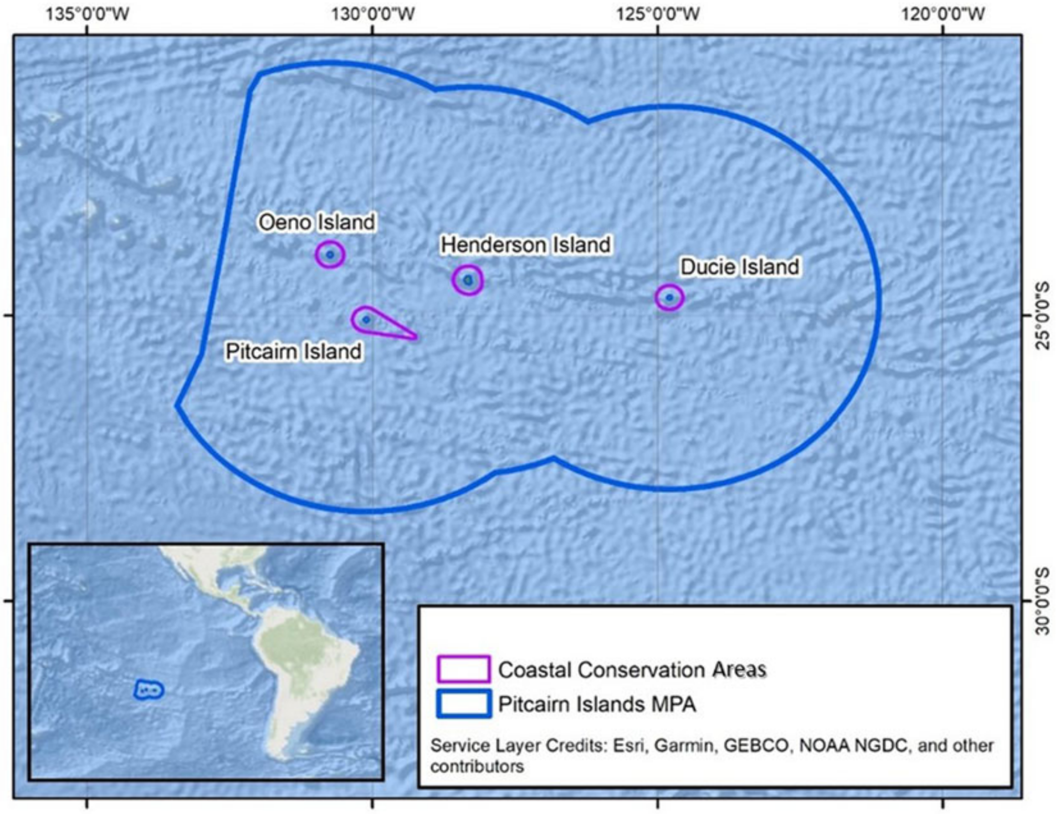

Fig. 1. Map of the Pitcairn Islands designated Marine Protected Area, which occupies the entire Exclusive Economic Zone. The no-take MPA extends over 841,910 km^2, with subsistence fishing allowed within coastal conservation areas.

Pitcairn Islands MPA encompasses the entire Pitcairn Exclusive Economic Zone (Figure 1) and is a highly protected, no-take area (The Government of the Pitcairn Islands, 2017). Marine Conservation Regulations are in preparation, and in 2017 a Fisheries Management Plan was introduced, to manage the only artisanal fisheries that are allowed within coastal conservation areas, mainly around Pitcairn Island (The Government of the Pitcairn Islands, 2017; Irving *et al*., 2019; Dawson & Irving, 2020).

The reefs of the Pitcairn Islands are located on the limits of coral growth at the eastern edge of the Indo-Pacific biogeographic realm, and are distinct from other reef systems due to their isolation. Some endemic species have been identified primarily at Ducie Island, the most remote island in the group, consisting of fish species endemic to the south-eastern tropical Pacific region as well as a few other species only found in these islands (Friedlander *et al*., 2014). Coral reefs are present around all four of the Pitcairn Islands, with Ducie having the highest coral cover, 56%, and Pitcairn the lowest, 5% (Friedlander *et al*., 2014). At Pitcairn Island, macroalgae are abundant (far more so than at the other three islands) and corals are predominantly absent above 10 m depth, possibly due to the combined impact of wave action and sand scouring, but are abundant below 10–30 m and deeper, due to the exceptional water clarity (Irving & Dawson, 2013; Duffy, 2014; Friedlander *et al*., 2014).

In this study we review the risk of climate change impacts to the coral reefs of the Pitcairn Islands, together with other local human pressures, in order to support the Pitcairn Islands MPA and inform potential management and resilience actions.

Materials and methods

A literature review of climate change and coral reefs of the UK Overseas Territories of the Pitcairn Islands, as well as the British Indian Ocean Territory (BIOT), was undertaken. This review, available as a separate technical report document (see Lincoln *et al*., 2021), covered key drivers of climate change and observed and expected impacts on the coral reefs and other important marine life. A policy summary was also produced, to inform decision making and conservation activities in these territories (see BlueBelt Report Card, 2021). The marine environment around the Pitcairn Islands remains vastly under-studied with few published scientific studies available. The scarcity of relevant literature prevented the use of a systematic review method. Instead, the authors used the information from key published studies of the Pitcairn Islands, and mined further literature from those and from other relevant regional and global studies. Where possible, climate projections were based on either of the main Representative Concentration Pathways (RCP) climate model projections: low (mitigation) emissions scenario (RCP2.6), medium (stabilization) scenarios (RCP4.5/RCP6) and high (baseline) emission scenarios (RCP8.5; Van Vuuren *et al*., 2011). RCP2.6 and RCP8.5 are extreme scenarios, and it is expected that actual future conditions will fall somewhere in between.

This article condenses the main findings of the original review report by Lincoln *et al.* (2021), offers a further insight into climate change risks to the coral reefs of the Pitcairn Islands, and discusses options that could help enhance the resilience of these reefs.

Results

Global Coral Reef Monitoring Network observations at Pitcairn Island between 2009–2014, found coral cover ranging from 10–20% (Moritz *et al*., 2018). An expedition to the islands in 2012 found Ducie to have a higher live coral cover (56%) compared with Oeno (28%) and Henderson (24%) Islands, while Pitcairn Island showed the lowest percentage (5%) of live coral cover

(Friedlander *et al*., 2014; Irving *et al*., 2019). Reefs appeared to be mostly composed of *Porites* spp., known to be thermally resistant, as well as more sensitive *Pocillopora* and *Millepora* (Irving & Dawson, 2013; Friedlander *et al*., 2014; Irving *et al*., 2019).

The following sections examine in detail evidence of climate change impacts and the potential future risks to these coral reefs.

Sea temperature

SST conditions

Sea surface temperature (SST) is defined as the subsurface bulk temperature in the top few metres of the ocean measured by ships, buoys and drifters (IPCC, 2013). In the tropical Pacific Ocean, SST has increased by 0.3°C between 1950 and 2009, while in the coral reef province of the western Pacific, SST has risen by over 0.4°C in the warmest months over the same period (IPCC, 2014*a*). Each year, trade winds and currents push warm equatorial water eastwards, creating a 'warm pool', also known as the equatorial Pacific warm water volume (Capotondi *et al*., 2020). This warm pool extends further east towards the Pitcairn Islands during El Niño years, and its extent has increased since the 1980s (Weller *et al*., 2016; Sutton, 2018). As the equatorial Pacific warm pool expands, a larger area of the tropical Pacific will experience higher than average annual temperatures over the rest of the 21st century (Sutton, 2018; Capotondi *et al*., 2020). The warm pool is controlled by the El Niño/Southern Oscillation (ENSO), but the high complexity of the ENSO phenomenon, its cyclic variability and increasing amplitude, hinder the ability of climate models to represent the diversity of El Niño events (Capotondi *et al*., 2020). At present, it is not possible to consistently predict changes in ENSO events over the coming century (IPCC, 2013; Cai *et al*., 2020; Capotondi *et al*., 2020; Fang & Yu, 2020).

The Pitcairn Islands are situated along the south-eastern edge of the tropical Pacific, where heat is absorbed near the equator and then cools towards the poles (Sutton, 2018). Three intense marine heatwaves were detected in 1995, 2006 and 2017 respectively, with temperature peaks that were more noticeable at Oeno, Pitcairn and Henderson Islands (Figure 2). However, the natural variability of SST of the Pacific Ocean, which is driven by the Pacific Decadal Oscillation and ENSO system and also influenced by the Pacific warm pool, makes it difficult to attribute SST increases to climate change (IPCC, 2014*a*). Nevertheless, recent reports indicate that ocean conditions in the wider South Pacific region are changing faster and more acutely than initially predicted due to climate change (IPCC, 2019*a*; Grose *et al*., 2020 – specifically for the region of Australia; IPCC, 2021). Bearing in mind these uncertainties, under medium emissions scenarios RCP4.5 or RCP6 (Van Vuuren *et al*., 2011), SST around the Pitcairn Islands is projected to rise by ~0.5°C by the middle of this century and by 0.9°C by the end of this century (NOAA Climate Change Portal, 2020). Under a high emissions scenario RCP8.5 (Van Vuuren *et al*., 2011) and by the end of this century, average SST is expected to warm by 2–2.5°C (Sellar *et al*., 2019).

Degree Heating Weeks (DHW) or Degree Heating Months (DHM) represent the number of weeks or months the corals are exposed to warming above a given threshold multiplied by temperature above the threshold. Based on SST satellite data, peaks of thermal stress expressed as DHWs occurred in 1995, 2006 and 2017 (see Figure 2 and Table 1), with Oeno reaching Bleaching Alert 1 (DHW 4–8) in all those three years (NOAA Coral Reef Watch, 2018). Pitcairn Island was the only island to experience DHWs higher than 8 (Bleaching Alert 2) during 2006, while Ducie Island did not experience thermal stress enough to trigger a bleaching alert (DHW less than 4; see Figure 2 and Table 1; NOAA Coral Reef Watch, 2018).

While there is no clear evidence of coral bleaching from seawater warming in the Pitcairn Islands, there are observations of coral damage caused by unusual oceanic cold intrusions in the Ducie atoll, with up to 40% coral damage by cold-water stress found between 10–15 m depth, as explained further in the extreme weather events section (Irving & Dawson, 2013; Dawson & Zhang, 2020). However, without baseline data it is not possible to accurately assess these factors or changes over time. Significant acute thermal stress (DHW 8.9) was experienced at Pitcairn Island in 2006, and Oeno Island (DHW 6) in 2006 and 2017, but otherwise the risk of acute thermal stress in the archipelago appears to remain low (Table 1). Undetected episodes of coral bleaching and mortality over the past 35 years in the Pitcairn Islands, however, remain a possibility.

Future SST projections

The Pitcairn Islands are located near the southern limit for optimal reef growth, with Ducie being the most southerly atoll island in the world. As a result of cooler conditions and slow projected warming, future SST conditions are likely to remain relatively suitable for coral growth, at least until the middle of this century (Couce *et al*., 2013; Jones *et al*., 2019). In the Pitcairn Islands and under a high emissions scenario, the onset of severe annual bleaching events is not expected until 2059, which is later than the average global onset threshold of 2043 (Van Hooidonk *et al*., 2016; Sellar *et al*., 2019). In addition, most reefs in the Pitcairn Islands are below 10 m depth (Irving & Dawson, 2013; Duffy, 2014; Friedlander *et al*., 2014), with the exception of the shallow reef flats at Oeno and Henderson and those in the Ducie lagoon, and it is expected that those deeper fore-reefs will be relatively sheltered from thermal stress (Nakamura & Van Woesik, 2001; Muir *et al*., 2017; Cowburn *et al*., 2019). Deeper areas of the outer-edge reefs on the Great Barrier Reef have been found to provide refuge from bleaching for *Acropora*, *Pocillopora* and *Porites* spp. (Baird *et al*., 2018). In the eastern Pacific, a depth refugia has also been demonstrated for *Millepora* spp. (Smith *et al*., 2014). However, the efficacy of these deeper reefs as refugia from warming will be relative, and will depend on the severity of the warming events and on the thermal sensitivity of the corals, as other evidence from the wider Pacific and from the Caribbean shows (Smith *et al*., 2016; Venegas *et al*., 2019). The extreme clarity of the water in the Pitcairn Islands also allows for deeper irradiance, which could to some extent counteract the cooling effect at depth. At Pitcairn Island, corals grow on reefs that reach down to 75 m depth and are dominated by thermally resistant *Porites* spp. and *Pocillopora* sp. and the hydrocoral, *Millepora* spp., which are more likely to withstand warming conditions (Irving & Dawson, 2013; Friedlander *et al*., 2014). However, in similar communities in the Central and East Pacific, those same coral species were found to die in large numbers during bleaching events (Glynn, 1984; Pratchett *et al*., 2013). This suggests that the corals of the Pitcairn Islands would still be relatively susceptible to thermal stress (Figure 2; Table 1), particularly in the shallower reefs around Ducie Island dominated by more sensitive corals such as *Acropora* and *Montipora* spp. (Loya *et al*., 2001).

Ocean acidification

Surface pH and aragonite saturation conditions

The increasing uptake of CO_2 by the world's oceans is manifested as changes to ocean carbon chemistry particularly pH and saturation state of calcium carbonate minerals such as aragonite and calcite, conditions which are critical to the growth and survival of corals and other calcifying organisms.

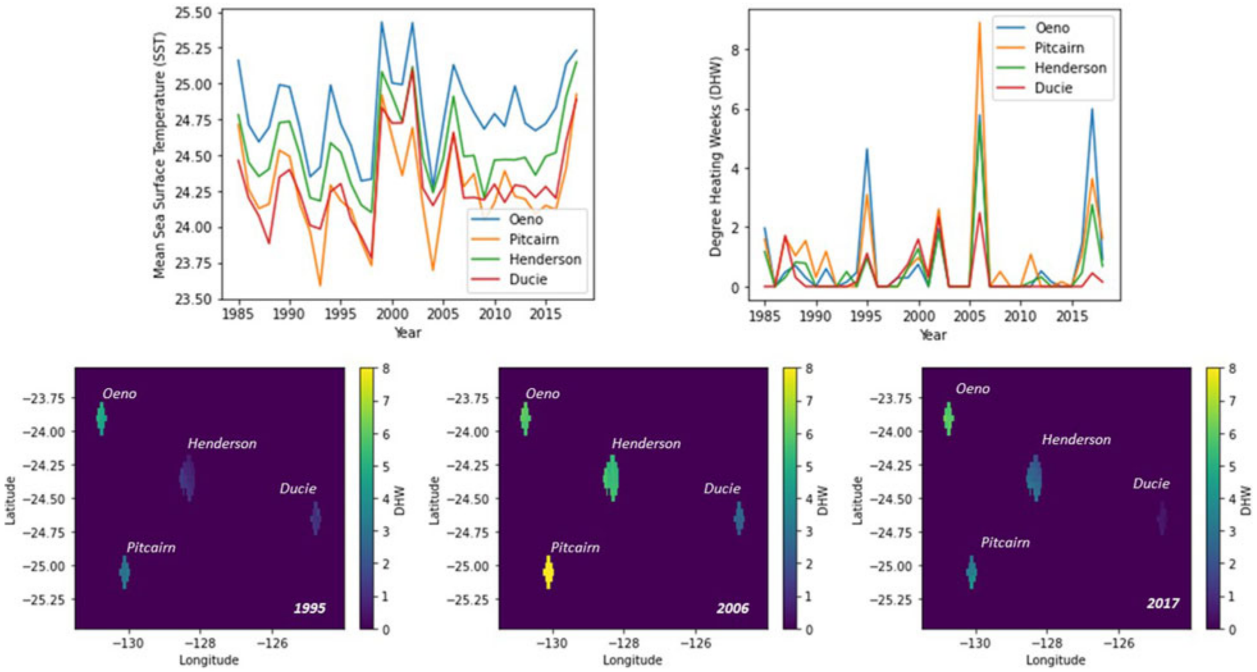

Fig. 2 Plots of thermal stress in the Pitcairn Islands showing: Time series of annual total Degree Heating Weeks (DHWs) from the four main islands (top right); time series of mean annual sea surface temperature (SST) (top left); and maps of DHWs during strong thermal stress years 1995, 2006, and 2017, showing the position of the islands. The dark blue areas denote no data. Data obtained from NOAA Coral Reef Watch (2018).

The largest changes in pH are projected for the surface layer except in the subtropics, where they are expected to occur where carbonate buffering capacity is lower between 200 and 300 m (IPCC, 2013). There is no long-term surface water pH data for the equatorial Pacific, making it difficult to ascertain trends (Lenton *et al.*, 2018; GOA-ON, 2020). A range of surface pH 7.91–8.12 has been previously estimated for the equatorial Pacific between 1997–2011 (Sutton *et al.*, 2014), values that are lower, and appear to be declining faster, than other open-ocean regions (Johnson *et al.*, 2015; Lauvset *et al.*, 2015; Wagener *et al.*, 2018). The pH of the wider tropical Pacific is projected to decrease by 0.15 pH units by 2050 under a high emissions scenario (Johnson *et al.*, 2015). Around the Pitcairn Islands, mean surface water pH is currently estimated near 8.12 and by the end of this century could decrease between 0.08 and 0.27 units, according to low and high emissions scenarios respectively (Figure 3; NOAA Climate Change Portal, 2020).

Table 1. Past thermal stress in each of the Pitcairn Islands showing mean SST at the start and end of a time series spanning 1985–2018 and the difference in mean SST, along with Degree Heating Weeks (DHWs) in potential bleaching years, the cumulative DHW, and the number or Alert Level 1 and 2 thermal stress events. Data obtained from NOAA Coral Reef Watch (2018).

Parameters of thermal stress	Oeno	Pitcairn	Henderson	Ducie
Mean SST (1985–89)	24.79°C	24.32°C	24.5°C	24.16°C
Mean SST (2013–18)	24.82°C	24.19°C	24.55°C	24.31°C
Difference in mean SST	0.03°C	−0.13°C	0.05°C	0.15°C
DHW 1995	4.6	3.1	1	1.1
DHW 2006	5.8	8.9	5.5	2.5
DHW 2017	6	3.6	2.8	0.5
Cumulative DHW	16.4	15.6	9.3	4.1
Alert 1 (DHW 4–8) frequency	3	2	1	0
Alert 2 (DHW >8) frequency	0	1	0	0

The saturation states of calcium carbonate minerals naturally decrease with depth as total dissolved CO_2 increases from a combination of respiration and cold temperatures, and there are indications that surface ocean aragonite saturation state in the Pacific has already declined from 4.5 to 3.8 (Feely *et al.*, 2009). Aragonite saturation below 3 is considered extremely marginal for coral growth, and no major reefs currently exist at such conditions (Langdon & Atkinson, 2005; Lenton *et al.*, 2018); while unprotected shells and skeletons will begin to dissolve when surrounding seawater saturation level declines below 1 (Feely *et al.*, 2009; Birchenough *et al.*, 2017). Levels of aragonite saturation in the South Pacific are already thought to be close to the point where it can weaken coral skeletons and slow down coral growth (Dutra *et al.*, 2018). However, direct field observations linking acidification and ocean chemistry changes to physiological impacts on corals are still rare (Doney *et al.*, 2020; Doo *et al.*, 2020). It is possible that the responses of corals to more acidic waters are still within the ranges of natural variability, and such responses would also be influenced by local conditions of water quality and circulation patterns (Field *et al.*, 2014). There are hardly any *in situ* studies of ocean acidification effects on corals in Pacific islands (Dutra *et al.*, 2018), while studies of ocean acidification impacts in other regions have found alterations in the physiology of the corals and the wider ecology of the reef, from changes in the pH of the calcifying fluid of the corals (Kubota *et al.*, 2017), to loss of skeletal density (Mollica *et al.*, 2018), to shifts in the species composition of colonies as well as increased algal cover and bioerosion (Fabricius *et al.*, 2011; Enochs *et al.*, 2015, 2016), to loss of ecological complexity and function of the reef (Mumby, 2009; Anthony *et al.*, 2011).

Future pH and aragonite saturation projections

ENSO dominates ocean climate in the Pacific, including ocean acidification and ocean carbon chemistry: during non-El Niño

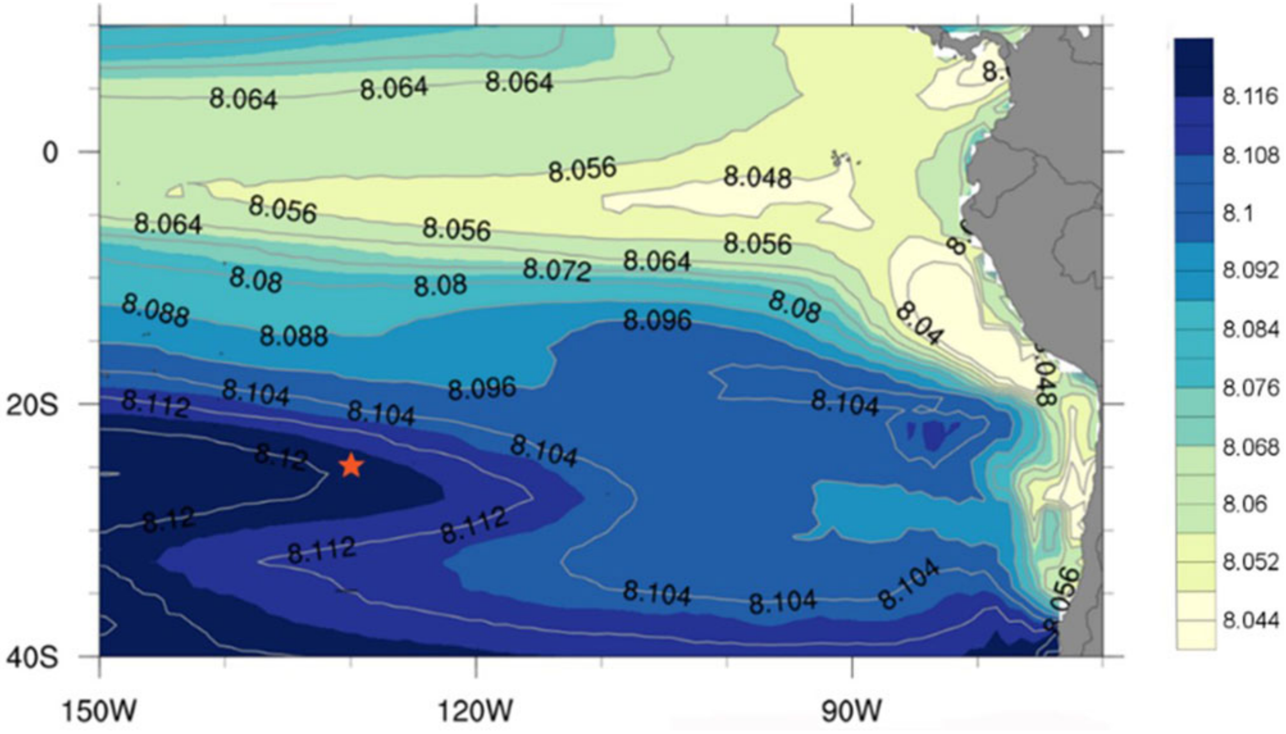

Fig. 3. Outputs from the CMIP5 ensemble showing mean surface water pH in the eastern Indian Ocean for the period 1956–2005. Image provided by the NOAA/OAR/ESRL Physical Sciences Laboratory, Boulder, CO, USA, from their website at http://psl.noaa.gov/ (NOAA Climate Change Web Portal, 2020). The approximate location of the Pitcairn Islands is indicated by the orange star symbol.

periods, ocean acidification has been observed to progress more rapidly due to the influx of upwelling deep, CO_2-rich water (McPhaden *et al.*, 2006; Sutton *et al.*, 2014; Fiedler & Lavín, 2017). Projections of aragonite saturation state to the end of this century under high emissions scenarios for the central South Pacific surrounding the Pitcairn Islands suggest that it is likely to decrease to 2.5 (Sellar *et al.*, 2019, see Figure 4), a sub-optimal level for coral calcification. But the confidence in these projections is only limited, due to the variability of the ENSO and the associated upwelling forcing, and the influence that these processes have on future ocean pH levels in the Pacific Ocean (Christensen *et al.*, 2013 and references therein). In addition, saturation of calcium carbonate minerals and pH can also vary at local scales depending on the habitat mosaic present (Cyronak *et al.*, 2018; Pacella *et al.*, 2018; Bergstrom *et al.*, 2019; Liu *et al.*, 2020) and it can be affected by biological processes like photosynthesis and respiration (Hurd *et al.*, 2018; Fabricius *et al.*, 2020).

The South Pacific Circulation Gyre is expected to slow down future changes in carbonate saturation and pH in the Pitcairn Islands region compared with the wider oceanic basin (Hoegh-Guldberg & Bruno, 2010; Friedlander *et al.*, 2014). However, across the tropical Pacific by mid-century under a high emissions scenario, average aragonite saturation is likely to

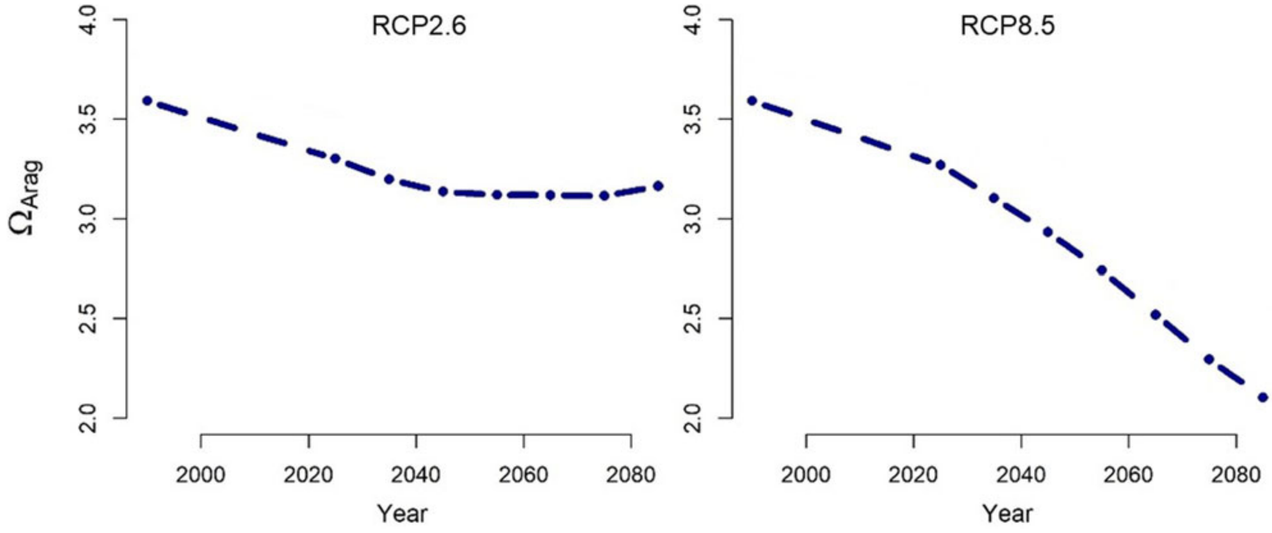

Fig. 4. Average sea surface aragonite saturation state (Ωar) for the Pitcairn Islands, showing the predicted decline in saturation under RCP2.6 (left) and RCP8.5 (right). Data from the UKESM1 forecast model, from Sellar *et al.* (2019).

decline to near 3, meaning a shift to sub-optimal conditions (Johnson *et al.*, 2015). This will cause a decline in coral calcification rate of about 10% (Chan & Connolly, 2013), which is projected to worsen as saturation continues to decline towards the end of the century.

Sea level rise and extreme weather events

Observed sea level rise and storminess trends

Sea level has risen across the Pacific Ocean by varying amounts due to large-scale climate processes, and extreme sea levels have also been detected driven by a combination of long-term sea level rise from climate change and short-term factors such as extreme tides, storm surges and the associated wind-wave setup (Australian Bureau of Meteorology and CSIRO, 2014). There are regional differences in sea level rise across the tropical Pacific (PSMSL, 2020), with the highest rates, ~12 mm year^{-1}, detected in the western South Pacific between 1993–2009 (Meyssignac *et al.*, 2012; Nurse *et al.*, 2014). These high sea level rise rates are thought to reflect modulations by natural phenomena such as ENSO, with lower/higher-than-average variability of sea levels during El Niño/La Niña events of the order of ±20 to 30 cm in the western tropical Pacific (Cazenave & Remy, 2011; Becker *et al.*, 2012). There are no tide gauge records from the Pitcairn Islands (Woodworth & Hibbert, 2015) but indirect estimations suggest that sea level has already risen almost 4 times the global average. It is thought that the low-lying atolls of Ducie and Oeno have persisted, and even increased in surface area and elevation by way of seasonal erosion and accretion processes following extreme events and changes in sediment supply (McLean & Kench, 2015). This has also been confirmed for other small atoll islands in the South Pacific, where high sea level rise rates have, as yet, not caused loss of dry land area overall (Kench *et al.*, 2015).

Storms can inflict substantial damage to shallow coral reefs. In the Pacific Ocean, the intensity of tropical cyclones appears to have increased since 1990 (Diamond *et al.*, 2013), although it is not clear whether there is a basin-wide trend in the number of very intense tropical cyclones across the Pacific basin (Australian Bureau of Meteorology and CSIRO, 2014; Holland & Bruyère, 2014; CSIRO *et al.*, 2015; Hoarau *et al.*, 2018; Lafale *et al.*, 2018; Dutheil *et al.*, 2020), and the attribution of this trend to climate change also remains in question (Collins *et al.*, 2019; Chand *et al.*, 2020). The trajectory and frequency of tropical cyclones in the South Pacific is typically driven by the natural variation of ENSO (Lafale *et al.*, 2018), and severe storms are more likely linked to extreme El Niño events with an extensive eastward propagation (Santoso *et al.*, 2013; Stephens & Ramsay, 2014). Deep ocean swells generated by extratropical cyclones in mid and high latitudes are also known to occasionally reach Pacific islands (IPCC, 2014*b*). For example, oceanic swells originated in the North Pacific, especially during years with a strong El Niño, have caused damage to reefs in Hawaii (Rooney *et al.*, 2004; Fletcher *et al.*, 2008). At Henderson Island, sections of fore-reef have been eroded exposing the bedrock underneath and coral rubble has been found below 30 m depth, all of which is likely to have been caused by storm wave action (Irving & Dawson, 2013). At Ducie Island, there are observations of coral damage caused by unusual oceanic cold intrusions in the atoll. Rehder & Randall (1975) documented up to 40% coral damage by cold-water stress found between 10–15 m depth recorded during an expedition in 1970. During diver surveys between 2016–2018, coral bleaching was documented between 10–15 m depth and linked to cold-water anomalies following the 2015–2016 El Niño event, confirmed by SST satellite data (Rehder & Randall, 1975; Irving & Dawson, 2013; Dawson & Zhang, 2020). Also in Ducie Island in 1975, parts of the land were found deforested by high waves (Rehder & Randall, 1975). There is also evidence of transient conditions of coastal turbidity and sediment runoff at Pitcairn Island in 2012 following a major rainfall event, the heaviest since records began, although it is thought that the prevailing strong currents around the island would have dispersed the suspended sediments, mitigating the effects of turbidity and siltation (Irving & Dawson, 2013; Friedlander *et al.*, 2014; Irving *et al.*, 2019). Given the small size of Pitcairn Island and its population and the domestic scale of current land use practices, the low cover of live coral could be attributed to exposure to wave action, rather than as an effect of runoff and sedimentation.

Future sea level rise and storm projections

Sea levels are highly variable in the Pacific, but it is very likely that under high emissions scenarios and by the end of this century, the South Pacific in particular will experience the largest sea level rise globally, ranging 54–217 cm (Nurse *et al.*, 2014; Lafale *et al.*, 2018; Vousdoukas *et al.*, 2018). This presents a significant risk for small coral islands, especially when combined with a potential intensification of tropical cyclones and degraded fringe reefs (The World Bank, 2016; Lafale *et al.*, 2018). A rise of more than 1 m by the end of the century is considered to be equivalent to a one in 100-year extreme sea level event currently (Vousdoukas *et al.*, 2018; Kench *et al.*, 2018*a*; Masselink *et al.*, 2020; Tajima *et al.*, 2020). For the Pitcairn Islands however, sea level projections are still highly uncertain (Zhang *et al.*, 2014) due to lack of resolution and long-term data, but there is an expectation that the rate of sea level rise is likely to accelerate and threaten the smaller low-lying islands (Kench *et al.*, 2015), particularly as compounded with coral decalcification.

Mean significant wave heights appear to have increased in regions of the Pacific and Southern Oceans, but there is as yet low confidence in these projections and the lack of data means it is challenging to discern between long-term climate trends and natural variability (Wang & Swail, 2006; Young *et al.*, 2011; Seneviratne *et al.*, 2012; Church *et al.*, 2013). At present however, most tropical cyclones in the South Pacific basin are formed in the region of the Vanuatu archipelago (Diamond *et al.*, 2013), strengthening as they move southwards, and so the Pitcairn Islands tend to miss the most severe events (Lafale *et al.*, 2018). Instead, the impact of long-distance ocean swells from remote low-pressure systems such as the Southern Ocean could be more significant for the Pitcairn Island corals.

Other human pressures in the Pitcairn Islands

In spite of their isolation and the small size of the resident human community, non-climatic anthropogenic pressures – some trans-boundary – may be impacting the marine environment of the Pitcairn Islands, and particularly the corals.

Fishing

Prior to 2016, most non-commercial fishing took place around Pitcairn Island, with occasional (every 4 to 5 years) trips to 40-Mile Reef to the east-south-east of the island (Irving and Dawson, 2012). There is no mandatory recording of catches at present and only intermittent fisheries monitoring, but reconstructed data indicate that landings by this small-scale fishery have been higher than the data reported by the Food and Agriculture Organization of the United Nations on behalf of the Pitcairn Islands, although they declined to 4 tonnes year^{-1} overall by 2014 (Sea Around Us, 2016; Coghlan *et al.*, 2017). Licenced commercial fishing declined sharply after 2005 as fleets withdrew to international waters outside the EEZ (Irving & Dawson, 2012). All forms of fishing have been banned within the Pitcairn Islands' MPA since its designation in 2016, apart from artisanal fishing by the local community which is allowed within the coastal conservation areas. There have been some concerns of overfishing targeting groupers, sharks and lobsters (Irving & Dawson, 2012; Coghlan *et al*., 2017) which could have negative consequences for the reef since some of these species, sharks particularly, play an important role in its resilience (Roff *et al*., 2016). A Fisheries Management Plan was introduced in 2017 for the management of the local fishery, particularly around Pitcairn Island (Irving *et al*., 2019; Dawson & Irving, 2020). The management plan brought in minimum catch sizes for a number of species of fish and shellfish and also banned the fishing of sharks.

Marine litter

Ocean-borne litter is an example of transboundary pressure in the Pitcairn Islands. Henderson Island is reported to have one of the highest levels of marine plastic litter on the planet despite it being uninhabited (Lavers & Bond, 2017; Forrest & Hindell, 2018; Irving *et al*., 2019; Ryan, 2020; Ryan & Schofield, 2020). This island is on the edge of the South Pacific Gyre, which collects litter from distant Pacific shores and deposits it on the island's shores (UK Gov Marine Developments, 2019). On the beaches of Henderson below the accumulated plastic, temperature within the sand was found to be +2.5°C above the daily maximum and dropped down by −1.5°C below the daily minimum, compared with areas with no plastic debris (Lavers *et al*., 2021). Quantities of plastic items were also found tangled on the surrounding reefs (S. Archer-Rand, personal communication).

Anchoring

Anchoring from visiting cruise ships and yachts and from supply vessels is another concern (Irving *et al*., 2019). Anchors and anchor warps can destroy large swathes of seabed as they settle and when retrieved (Giglio *et al*., 2017). Hard corals are especially susceptible to the impacts of anchoring, but the scale of damage and recovery timeframes remains unknown.

Non-native species

The presence of invasive non-native species, even on land, as well as coral diseases, remain important threats to coral reefs. Invasive rats on Henderson Island have caused dramatic declines of the biomass of resident seabirds, including endemic or endangered species (BirdLife International, 2020) and this could cause an indirect negative effect on the surrounding reefs as found in other oceanic coral islands, where declines in nesting seabird populations caused losses in reef productivity due to the loss of guano nutrient inputs (Graham *et al*., 2017, 2018; Benkwitt *et al*., 2019, 2021). The eradication of invasive rats should be important for the sustainable management of the natural environment of these islands (Graham *et al*., 2017; Benkwitt *et al*., 2019; BirdLife International, 2020; Perez-Correa *et al*., 2020). Corallivorous crown-of-thorns starfish have been reported in the Pitcairn Islands (Birkeland, 1989; Irving, 1995), as well as coral diseases.

Discussion

Corals can recover following bleaching and other climate change impacts such as storm damage, and healthy and well-balanced reefs hold the key to this resilience. Herbivorous reef-fish will for example encourage recruitment of new corals by grazing on the algae and preventing their encroachment on the reef (Mumby *et al*., 2016; Steneck *et al*., 2019). Good water quality is also particularly important to help recovery following bleaching and to reduce susceptibility to disease outbreaks and invasive species (Carlson *et al*., 2019; MacNeil *et al*., 2019). Large MPAs are effective options for reef resilience, as they minimize local stresses and support a wide range of species and functional groups, particularly when they include replicates of representative habitats, ensuring reef connectivity, and encompass different thermal regimes (Carpenter *et al*., 2008; McLeod *et al*., 2019). In the Pitcairn Islands MPA in particular, the deeper, cooler fore-reefs could act as areas of refugia from the effects of warming to corals and other species (Kleypas *et al*., 2010; Friedlander *et al*., 2014).

This study suggests that, in the Pitcairn Islands, thermal stress is likely to remain low compared with other tropical reefs globally, particularly in the deeper fore-reefs, although those deeper coral communities appear dominated by sensitive species which may heighten their vulnerability to thermal stress should it occur. The geographic isolation of these reefs is another challenge in terms of supply of healthy larvae, meaning these reefs would rely on self-seeding to boost recolonization and recovery (Robinson *et al*., 2017; Romero-Torres *et al*., 2018). On the other hand, the low level of other local detrimental pressures in these islands such as nutrient inputs or pollution, can help corals better withstand thermal stress (Wiedenmann *et al*., 2013). The additional protection granted by the MPA is expected to promote recovery following bleaching (Sheppard *et al*., 2008; Gilmour *et al*., 2013), although there is evidence that severe bleaching and mortality can still occur in highly protected reefs, as demonstrated by the Aldabra Atoll in the Western Indian Ocean (Cerutti *et al*., 2020), BIOT (Head *et al*., 2019), Jarvis Island in the central Equatorial Pacific (Vargas-Ángel *et al*., 2019) and the Great Barrier Reef (Hughes *et al*., 2017).

There are two main approaches for enhancing climate resilience of ecosystems: management of local pressures and implementation of adaptation and resilience-building actions. Efforts are increasing globally to understand coral recovery and promote adaptation using coordinated ecosystem-based management approaches (Obura & Grimsditch, 2009; NOAA Coral Reef Conservation Programme, 2014; Belokurov *et al*., 2016; Harvey *et al*., 2018; Roche *et al*., 2018; McLeod *et al*., 2019). The goal of these adaptation strategies is to 'maintain the ecosystem in a healthy, productive, and resilient condition so that it can continue to provide the services that society wants and needs' (NOAA Coral Reef Conservation Programme, 2014).

Here, we discuss potential options for enhancing the climate resilience of coral reefs in the Pitcairn Islands, based on examples from other reefs. Intervention and management actions should be underpinned by scientific evidence wherever possible, and include monitoring plans, review periods and adaptive management approaches (Belokurov *et al*., 2016). Decisions and actions should also be undertaken in consultation with and with the full involvement of the local community, as custodians and direct beneficiaries of these reefs, so they can contribute their valuable knowledge. An example of a step-by-step process that could be followed to develop an Action Plan for building and enhancing climate change adaptation and resilience of the coral reefs of the Pitcairn Islands is represented in Figure 5.

Next, we discuss a number of considerations to develop a plan of climate adaptation and resilience for the Pitcairn Islands' reefs, that could potentially be incorporated into the framework of the Pitcairn Islands MPA.

Enhancing resilience through management of local pressures

Reducing pressures from human activities and regulating the uses of the marine environment may not entirely prevent coral bleaching, or coral mortality, but boost the resilience of reefs and their chances of recovery (Nyström *et al*., 2008; IPCC, 2014*a*; UNEP, 2017). Approaches of this kind can help delay the onset of

Fig. 5. Conceptual diagram for the development of a climate change adaptation and resilience action plan for the coral reefs of the Pitcairn Islands, adapted from Obura & Grimsditch (2009) and Belokurov *et al.* (2016).

mass loss of corals, allowing time for emissions mitigation measures to take effect in limiting global warming (IPCC, 2014*a*, 2019*b*). There are strict regulations as part of the designation of the Pitcairn Islands MPA, a highly protected marine area and one of the largest in the world at 841,910 km^2 (UNEP-WCMC & IUCN, 2021). They include a 5-year Management Plan to limit local pressures as well as long-term monitoring of the coral reefs to assess reef health. This vast MPA hosts a network of shallow and deep reefs across a range of different thermal regimes, likely to offer taxonomic overlap and a well-connected reef system with areas of refugia and therefore appears to meet reef resilience management requirements (McLeod *et al.*, 2019). Given their isolated location and low population, the Pitcairn Islands are exposed to fewer pressures compared with other similar coral atoll islands, but nevertheless the following pressures have been identified in the Pitcairn MPA Management Plan: Illegal, Unreported and Unregulated (IUU) fishing by foreign fishing vessels; pollution including oil spills and marine plastics; anchor damage; erosion and run-off from land; and invasive non-native species.

Fishing

The implementation of large, highly protected marine areas such as the Pitcairn Islands MPA can be an effective climate resilience option for the corals and other marine communities (Hughes *et al.*, 2003; McClanahan *et al.*, 2008; Coghlan *et al.*, 2017; Hays *et al.*, 2020). The Pitcairn Islands MPA limits local fishing activities to coastal conservation areas (Pitcairn Government, 2017). A Fisheries Management Plan regulates the inshore artisanal fishery including gear restrictions and minimum landing sizes (Irving *et al.*, 2019; Dawson & Irving, 2020), and a separate Compliance and Enforcement Strategy covers the surveillance and prosecution of IUU fishing offences. An immediate ecological benefit to the reef results from allowing healthy stocks of herbivorous reef-fish and invertebrates to remain and graze on the algae that otherwise could occupy the reef, freeing up substrate for coral recruitment (Mumby *et al.*, 2007; Steneck *et al.*, 2019). There is evidence in the Caribbean region, where measures such as this enabled recovery of damaged reefs following hurricane impacts and bleaching (Steneck *et al.*, 2019).

Predatory fish are also important to keep smaller, corallivorous fish, and other trophic groups in check and therefore preserve a healthy functional reef. Previous fish assessments indicate that whilst fish communities in the Pitcairn Islands are relatively healthy, numbers of sharks and groupers have been locally impoverished due to targeted catches (Friedlander *et al.*, 2014; Coghlan *et al.*, 2017; Dawson & Irving, 2020; Duffy *et al.*, 2021).

Pollution and litter

Improving water quality can also promote climate resilience in corals. Ridge-to-reef coastal management approaches help control and reduce land sources of pollution and disturbance (Carlson *et al.*, 2019). Moreover, coral monitoring in the Great Barrier Reef show that improving water quality helps coral recovery following bleaching and it also reduces susceptibility to crown-of-thorns starfish outbreaks and diseases (MacNeil *et al.*, 2019). On Pitcairn Island, macroalgae are more abundant here compared with the other three islands, possibly as a combination of runoff (Irving *et al.*, 2017) and wave action. Changes in land use and soil erosion issues on Pitcairn Island have led to excess runoff inputs into coastal waters during heavy rain events resulting in short-term sedimentation turbidity (Friedlander *et al.*, 2014). However, coastal waters around all four islands are unusually clear overall suggesting oligotrophic conditions with low concentrations of dissolved inorganic nutrients. Preserving land vegetation and encouraging sustainable agricultural practices would help prevent soil erosion and maintain good water quality.

A more noticeable issue in terms of marine pollution in the case of the Pitcairn Islands is plastic litter, with Henderson Island declared to have some of the highest levels of ocean-borne plastic litter on the planet (Forrest & Hindell, 2018; Irving *et al.*, 2019; Ryan, 2020; Ryan & Schofield, 2020). Marine plastics are known to endanger many marine animals and although a specific direct link to the corals themselves (other than by physical damage from large-size items such as entangled fishing nets) is not overly clear, it has been suggested that the proliferation of plastic litter increases the risk of coral diseases (Lamb *et al.*, 2018).

Invasive species and coral diseases

Other important threats to corals are diseases and the presence of invasive and non-native species, even on land. A dramatic example is the introduction of rats to small islands, not just in the Pitcairn Islands but also in the British Indian Ocean Territory. As the rats caused a crash in the population of breeding seabirds, this resulted in a detrimental knock-on effect to coastal reefs following the loss of nutrients inputs from the birds' guano (Graham *et al.*, 2017, 2018; Benkwitt *et al.*, 2019). Eradication of rats should therefore be a conservation priority for the islands as it could have positive effects on the nearshore corals if seabird populations are able to re-establish their numbers to previous levels (BirdLife International, 2020), and the inputs of guano nutrients to the reef areas are restored (Graham *et al.*, 2017; Benkwitt *et al.*, 2019; BirdLife International, 2020; Perez-Correa *et al.*, 2020). Finally, although very challenging given the vast size and remoteness of the Pitcairn Islands MPA, early warning, monitoring or screening surveys (for example, by applying novel techniques such as detection of environmental DNA) could help detect outbreaks of crown-of-thorns and coral diseases, both of which can have equally devastating consequences for reefs (Birkeland, 1989; Irving, 1995; Galloway *et al.*, 2009).

Anchor damage

Anchoring can damage corals and other benthic communities (Irving *et al.*, 2019). Some measures have been taken towards limiting anchoring of cruise ships, yachts and supply vessels to certain areas, but the seabed around these locations should be monitored regularly, so that further measures can be put in place if necessary (Lewis *et al*., 2017; Sheppard & Sheppard, 2019). For example, permanent moorings can help reduce the impacts of anchoring.

Promoting coral recovery through adaptation and restoration

Reducing future global greenhouse gas emissions is, at present, the only feasible pathway to controlling future global warming and therefore effectively limiting climate change impacts on coral reefs (Bruno *et al*., 2019). Tangible and targeted management measures and regular monitoring can help in determining what, if any, active steps are required to further promote coral resilience and adaptation. These measures are likely to involve an array of interventions, from improving protection through MPA management, to reducing local pressures, and to restoring degraded and damaged reefs (Abelson, 2020).

Recent coral planting and seeding initiatives have had some local success in remediating coral reefs elsewhere (Doropoulos *et al*., 2019; IPCC, 2019*b*). Planting or seeding of corals can draw on thermally resistant species or strains (Dance, 2019), and so while this might change the diversity or species composition of the corals in an area, it can enhance the overall resilience of the reef. Coral recruitment can also be enhanced by collecting gametes from the sea during spawning, and following fertilization returning settled larvae to the sea a few days later (Dance, 2019). Research is underway in Australia to breed heat-tolerant coral species and strains (Cornwall, 2019). Coral husbandry also allows testing if corals can adapt to warming temperatures, and genetic manipulation of the bacteria or zooxanthellae in the corals, or even the corals themselves, may allow the creation of new heat-tolerant mixtures (Crabbe, 2019). However, coral restoration is usually only targeted at reefs that reach a critical stage of damage, to aid recovery, which is not the case in the Pitcairn Islands at this moment. Furthermore, coral restoration interventions are expensive and labour-intensive, and would be logistically challenging on remote reefs as these. Reducing bleaching during heatwaves by using artificial shading at times of high sea temperatures has also been proposed (Belokurov *et al*., 2016); again, this may not be a practical choice of intervention in the Pitcairn Islands' reefs.

All these potential interventions can be very labour intensive and costly, and often involve complex decisions (Abelson, 2020; Anthony *et al*., 2020) and are not without uncertainties and controversy as to their efficacy. Their implementation across large and remote areas such as the Pitcairn Islands MPA presents big challenges.

Further options for coral action on the Pitcairn Islands

Monitoring the reefs and other vulnerable benthic habitats around Pitcairn, Henderson, Oeno and Ducie Islands would help identify any impacts. It would be important to adopt a strategic approach to any monitoring, optimized for example by gathering additional data to support the Fisheries Management Plan, and by coordinating efforts and maximizing coverage of the MPA, and this is already contemplated as part of a Monitoring and Research Plan associated to the Pitcairn Islands MPA Management Plan.

Knowledge gaps and future research needs

Habitat mapping and reef vulnerability assessments

There remain large data gaps on the coral communities of the Pitcairn Islands (Friedlander *et al*., 2014) making it difficult to determine a pre-bleaching baseline, and therefore habitat mapping of coral reefs and other benthic communities across the MPA appears to be an important and necessary step. Regular coral monitoring of key ecological indicators could also be implemented, including, but not limited to: coral cover; species composition; disease screenings; occurrence of non-native invasive species such as crown-of-thorns; coral spawning and recruitment studies; water quality; changes to macroalgal cover; and fish groups counts. A smart and targeted approach to data acquisition would ensure that the information is ecologically relevant and provide the necessary evidence to support adaptive management measures.

A coral vulnerability assessment (Belokurov *et al*., 2016; UNEP, 2017) would be useful to characterize exposure and sensitivity to climate change or other pressures across the MPA and inform decisions on interventions. Coral monitoring can also be used to identify more resistant species or colonies (Belokurov *et al*., 2016), so they can be prioritized for protection and research.

Finally, further investigations on the deeper reefs looking at factors such as temperature profiles, light attenuation, coral community composition, and connectivity to shallow reefs, would help determine their potential as climate refugia.

Coral conservation interventions

While some of the emerging intervention techniques such as planting, seeding and genetic engineering of coral and zooxanthellae strains may appear promising in other global reef regions, some of those methods are still debatable and require further research and at this point would be too labour-intensive and expensive to be practical or even necessary in the case of the Pitcairn Islands. It has been proposed that some of the healthier reefs in the Pitcairn Islands have the potential to become coral seed banks for use in coral conservation and restoration projects in other degraded reefs in the wider Pacific. Given the remoteness of the Pitcairn Islands, this would present important logistical challenges; however as trials in the Great Barrier Reef show it remains a possibility. In any case it would require further research, not the least because unlike corals from the Red Sea and the Persian or Arabian Gulf, which are exposed to higher levels of environmental stress, the Pitcairn Islands corals are likely to be thermally naïve and therefore sensitive.

Ocean acidification

It is important to improve our understanding of ocean carbon chemistry and coral adaptation in the Pitcairn Islands, given the high and immediate risk posed by ocean acidification. These efforts could be integrated as part of the Global Ocean Acidification Observing Network (GOA-ON) monitoring network expansion, ideally by encouraging capacity in location. Given that this is a data-poor region, and taking into consideration the potential severity of calcium carbonate minerals saturation suggested by future projections, ocean acidification research in the Pitcairn Islands deserves urgent attention. The use of autonomous sensor technology could be a feasible, cost-effective option worth considering.

Research of ocean acidification on corals focuses on single-species responses. Increasingly, experiments now combine multiple climatic and non-climatic stressors on single species, which are revealing how other stressors interact with ocean acidification. It is not yet clear to what extent corals and other marine organisms can acclimatize and adapt to ocean acidification, however. *In situ* studies are required to build an understanding of effects in single species, and extrapolate these responses to impacts on whole reef systems and functions, including food webs and competition.

Sea level

It is important to better understand the processes by which coral islands adjust to sea level rise (Barnett & O'Neill, 2012; Kench *et al.*, 2015). Rising sea level is expected to cause coastal erosion, remobilize sediments and destabilize islands, but there is debate about the likely physical changes to atolls in the future (Kench *et al.*, 2015, 2018*b*; Storlazzi *et al.*, 2018; Ford *et al.*, 2020). Further research into atoll coastal processes in response to sea level rise and reef erosion in the Pitcairn Islands, particularly at Ducie, Henderson and Oeno, would be important.

Implementation of fisheries management and collection of catch records

There is a need for an effective management of the local artisanal fishery (Bell *et al.*, 2011; Coghlan *et al.*, 2017; Dawson & Irving, 2020). Data and information gathered as part of the fisheries management and catch recording should be integrated and coordinated with marine monitoring activities across the wider MPA, including corals. There are plans to address this as part of the MPA Management Plan and associated Monitoring and Research Plan.

Summary and conclusions

The Pitcairn Islands are some of the most remote and best preserved oceanic island environments (Readman *et al.*, 2013; Moritz *et al.*, 2018) where the low level of other human pressures could allow them to persist longer into the future (UNEP, 2017). To date, no significant changes in average SST have been detected, although marine heatwaves have been observed (in 1995, 2006 and 2017). There is, so far, no evidence of coral bleaching from seawater warming in the Pitcairn Islands, but the reefs' species composition suggests that they would likely be sensitive to thermal stress should that occur. Also, the geographic isolation of these reefs is an added challenge in terms of larval recruitment. Although recruitment of juvenile corals has yet to be assessed, the isolation of these islands, being further than 100 km away from each other and even further removed from any other reefs, indicates limited connectivity and high reliance on self-seeding (Swearer *et al.*, 1999; Wood *et al.*, 2014). Furthermore, even if these reefs persist their composition and structural complexity is likely to change (Sheppard *et al.*, 2020). Ocean acidification appears to be a significant and more immediate risk to these reefs, likely to lead to coral de-calcification by the end of the century under a high emissions scenario.

Future climate change is also likely to bring about a host of combined pressures, feedbacks and indirect impacts on coral reefs, some of which are unknown. The knowledge and appreciation of such cumulative impacts are growing rapidly (Ateweberhan *et al.*, 2013; Cinner *et al.*, 2016; Bruno *et al.*, 2019). Even among the direct impacts, there are major differences in the understanding and confidence surrounding impact pathways, that are partly attributable to differences in the timing of impacts: for example while impacts from warming SST and storms are already being observed, those from sea level rise and ocean acidification will take time to emerge (Cinner *et al.*, 2016). As research in these fields continues, it is expected that new impact pathways will be found (Cinner *et al.*, 2016). For example, ocean acidification is likely to increase susceptibility of corals to storm damage because a lower seawater pH will weaken coral skeleton density and strength (Hoegh-Guldberg *et al.*, 2007; Madin *et al.*, 2008). De-calcification may also be exacerbated by warming ocean temperature, as is the case for coralline algae (Martin & Gattuso, 2009). To date, research on how synergies between key climate drivers affect coral reef systems is very limited (Ban *et al.*, 2014) and therefore assessments of climate change impacts usually focus on individual drivers, rather than on cumulative effects (Cinner *et al.*, 2016). Latest IPCC projections for warm-water coral reefs globally indicate that increased water depth due to combined coral loss, reef erosion and loss of structural complexity will exacerbate the risk of flooding to reef-fringed shorelines and islands and will cause declines of reef fish populations (IPCC, 2022).

Owing to their isolation and low levels of human impacts, further studies of the Pitcairn Islands' reefs can help disentangle these synergies and provide answers to many of these scientific questions, for the benefit of this as well as other reef areas around the world.

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