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Pacific Conservation Biology

Linking social and biophysical systems to inform long-term, strategic management of coral reefs

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Table S1: Potential thresholds for threats known to affect coral reefs survival under future conditions that represent a limit beyond which the ecosystem resilience is lost. One of the main impacts of most of these threats is the decrease of coral cover, with the threshold of ≤ 10% characterising an alarming low coverage (Bruno et al., 2009).

Impact	**Threshold**	**Location**
Ocean warming		
Heat stress resulting in coral bleaching and mortality. Impacts are compounded by increased frequency, duration, and intensity of heat exposure events.	Effects arise following exposure to sea surface temperatures greater than 1°C above the pre-warming average (Ainsworth et al., 2016), or to ‘degree heating weeks’ greater than 6°C-weeks (Hughes et al., 2018).	Ainsworth et al. (2016) and Hughes et al. (2018) presented results for the Great Barrier Reef, Australia
Ocean acidification		
Changes in carbonate ions concentration, and aragonite saturation state (Ω_{ar}) that impact coral calcification/growth rates. Impacts are compounded by ongoing decrease in the pH of oceanic waters.	*Changes in pH*: Many ecological properties may be irreversible if pH reaches 7.8 (~ 480 ppm) (Fabricius et al., 2011). For example, the antioxidative defence system is capable of coping with acidic conditions for short periods (~ 16 days), however, longer exposure to acidic seawater induces oxidative stress, leading the oxidative damage to lipids and proteins (Luz et al., 2018). Also, based on results for the hydrocoral *Millepora alcicornis,* Ca-ATPase and carbonic anhydrase, which are enzymes related to the calcification process, are not capable to compensate for the effects of severe ocean acidification (pH 7.2) (Marangoni et al., 2017).	Fabricius et al. (2011) analysed coral reefs in Papua New Guinea. Luz et al. (2018) and Marangoni et al. (2017) analysed hydrocoral fragments of *M. alcicornis* collected in Bahia (Brazil) in a mesocosm system. Fine and Tchernov (2007) analysed coral fragments of the Mediterranean species

	In an experiment, colonies of the species *Oculina paragonica* and *Madracis pharencis* were subjected to pH values from 7.3 to 7.6 and 8.0 to 8.3 for one year. After one month, colonies achieved net dissolution with the skeleton-free fragments surviving until the end of the experiment. After the experiments, the fragments returned to ambient pH conditions, leading to calcification recovery (Fine and Tchernov, 2007). *Changes in the carbonate ions concentration:* 200µmol/Kg, when coral reefs reach net accretion=0. Such conditions are expected to happen when CO_2 emission reaches 450 ppm CO_2 (likely on 2050). At 560 ppm CO_2 erosion rates will exceed growth, resulting in net reef dissolution (Hoegh-Guldberg et al., 2007; Silverman et al., 2009). Calcification rates is affected similarly across species (Marubini et al., 2003). *Changes in the Aragonite saturation state (Ω_{ar}):* 2.92, when coral reef sediments will become net dissolving. This can result in loss of material to build shallow reef habitats (Eyre et al., 2018). Ideal Ω_{ar} conditions are around 3.1 to 4.1 (Eyre et al., 2018).	*Oculina paragonica* and *Madracis pharencis.* Hoegh-Guldberg et al. (2007) and Silverman et al. (2009) present estimates at global scale. Marubini et al. (2003) used four species (*Acropora verweyi, Galaxea fascicularis, Pavona cactus and Turbinaria reniformis*) from the culture reserves in the Oceanographic Museum of Monaco. Eyre et al. (2018) measured CaCO3 sediment dissolution at five (Bermuda, Hawaii, Heron Island, Tetiaroa and Cook Islands) reef locations in the Pacific and Atlantic Oceans.
Sea level rise		
Changes in sea level. Impacts are compounded by ongoing thermal expansion caused by ocean warming and increased	Reef depths > 6.6 m decreases the likelihood of corals undergoing a regime shift (Graham et al., 2015).	Graham et al. (2015) analysed data from Indo-Pacific corals.

melting of land-based ice (e.g. glaciers and ice sheets).		
Other threats		
In combination with climate threats on coral reefs, changes in juvenile coral densities, structure complexity, herbivores biomass, fishable biomass, primary production, macroalgae and coral cover, can also impact coral reefs.	*Juvenile coral densities:* > 6.2 per m^2 reduces the probability of a regime shift (Graham et al., 2015). *Structural complexity:* It can be measured by the widespread moderately complex relief metric. A threshold of 3.1 can decrease the risk of a regime shift trajectory (Graham et al., 2015). Most of thermal tolerant coral species are characterised by low structural complexity, which in turn, provide reduced habitat space for small-bodied coral reef fishes on which piscivorous mesopredators feed. In this case, mesopredators have lower lipid content in their muscle tissue, due to prey species availability or reduced biomass. In turn, this can affect growth, fecundity, and survival, leading to an unexpected population decline. Decrease in structural complexity can also trigger longer periods hunting and capturing preys (Hempson et al., 2018). *Herbivores biomass*: 177 kg ha^{-1} reduce the risk of a regime shift (Graham et al., 2015). *Fishable biomass*: Above 500 kg ha^{-1}, to maintain reefs in a desirable state: low macroalgae cover, high coral cover and high fish diversity (Norström et al., 2016). *Primary production:* 0.45 µg L^{-1} is a safe threshold for chlorophyll concentration (Norström et al., 2016).	Graham et al. (2015) analysed data from Indo-Pacific corals. Hempson et al. (2018) analysed data from Lizard Island (Great Barrier Reef, Australia). Norström et al. (2016) is a review on key drivers of change in coral reefs.

	Nutrient loads: It can be measured by C:N ratios in macroalgae fronds. A threshold of 38 reduces the likelihood of regime shifts (Graham et al., 2015).	
Macroalgae abundance		
Algae-dominant corals are related to fish biomass loss and increase microbial metabolism.	Herbivores are not capable of fully consuming/controlling *Turbinaria* thalli larger than 2 cm length. Associational refuge for vulnerable macroalgal life stages creates a feedback mechanism that facilitates persistent macroalgal assemblages (Davis, 2018). A severe phase shift has been associated with a threshold of ≤ 10% coral cover and macroalgae cover of > 60% in the Caribbean (Bruno et al., 2009).	Davis (2018) analysed data from French Polynesia. Bruno et al. (2009) analysed data from 1851 reefs to determine the coral to macroalgae phase shift.
Sedimentation		
Coral species show a gradient of tolerance to stress from sediment, with thresholds representing the concentrations of sediment which is likely to produce lethal or sub lethal effects.	When achieving a certain maximum concentration, corals can show a reduction of growth and reduced zooxanthella photosynthesis. If these conditions persist for a long period, sediment concentrations above critical thresholds can lead to mortality. Critical thresholds identified in the literature by Erftemeijer et al. (2012): - Coral reefs in the Great Barrier Reef (GBR, Australia): 3.3 mgL^{-1} of total suspended sediment - Coral reefs in the Fanning lagoon (Florida, USA): 10 mgL^{-1} of total suspended sediment - Coral reefs in the Caribbean: 10 mgL^{-1} of total suspended sediment - Coral reefs in Papua New Guinea: 15 mgL^{-1} of total suspended sediment - Coral reefs in Florida (USA): 20 mgL^{-1} of total suspended sediment	Erftemeijer et al. (2012) reviewed the environmental impacts of sediment disturbances in corals.

	- Coral reefs in the Dominican Republic: 20 mgL^{-1} of total suspended sediment - Marginal reef environments in Banten Bay (Java, Indonesia): 40 mgL^{-1} of total suspended sediment - Marginal reef environments in Paluma Shoals (Queensland, Australia): 40 mgL^{-1} of total suspended sediment - Nearshore fringing reefs (Magnetic Island, GBR): 75-120 mgL^{-1} of total suspended sediment - Nearshore fringing reefs (Cape Tribulation, GBR): 100- 260 mgL^{-1} of total suspended sediment

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