

# Current Ecological Status of Remote Coral Reefs of Clipperton Island, Tropical Eastern Pacific

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## Research Article

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# Abstract

Clipperton, an uninhabited and remote coral atoll from the Eastern Pacific, is an important steppingstone area that harbors a high marine biodiversity. Despite its biogeographic importance, little information on the ecological status of its coral reefs is available from the last decade. Herein, we characterized the benthic coral community and health status among four different shallow reef-zones (North to South) of Clipperton during the *Tara Pacific* expedition in 2018. The benthic composition and coverage percentage, as well as occurrence of a pink-spotted coral phenotype (trematodiasis infection) was assessed. Total live coral cover on Clipperton reefs was 66% (55-85%), differing between sites, with massive *Porites* and branching *Pocillopora* corals dominating the benthic community with an average 48% (32-66%), and 15% (3-21%), respectively. While Clipperton reefs exhibited significant live coral cover overall, the trematode infection was commonly observed, with a higher occurrence in massive corals (*Porites* 27%, and *Pavona* 31%). This observation is possibly related to the combined effects of previously heatwaves, and local inputs of guano-derived nutrients discharged during storms and hurricanes. These results demonstrates that even highly remote reefs supporting high coral cover can be subjected to local and global threats, including but not limited to parasite prevalence, likely in relation to natural disturbances such as thermal stress and tropical cyclones.

## Introduction

Clipperton Island (10° 18' N, 109° 13' E) constitutes a small uninhabited coral atoll located at the Western Edge of the Eastern Tropical Pacific (ETP) region (Robertson and Allen 1996). It lies about 1,100 km SW of the closest part of the American mainland and about 950 km off the nearest offshore islands, the Revillagigedo Islands. Thereby, it constitutes one of the largest and most isolated coral reefs in the ETP (Robertson and Allen 1996), and also as an important biogeographic stepping stone for tropical biota, facilitating dispersal between the Eastern and Western Pacific regions (Robertson and Allen 1996; Romero-Torres et al. 2018; Boissin et al. 2019). On land, Clipperton hosts the largest breeding aggregation of masked booby and second largest aggregation of brown booby (*Sula dactylatra* and *S. leucogaster*). Under water, well-established fringing reefs with a relatively high diversity of reef-building scleractinian corals (18 species) have been documented (Glynn et al. 1996; Carricart-Ganivet and Reyes-Bonilla 1999). Yet, high live coral cover ranging from 10-100% between depths of 8–60m (Glynn et al. 1996) along some 3.4 km of the atoll has been reported, which stands in contrast to the marginal patchy coral ecosystems situated closer to Continental America (Stuhldreier et al. 2015a,b). Global reports indicate partial to total mortality of the dominant reef-building coral genera *Porites* and *Pocillopora* for the entire Pacific region (Hughes et al. 2017, 2018; Eakin et al. 2019), including the ETP (Reyes-Bonilla and Calderón-Aguilera 1993; Reyes-Bonilla et al. 2002).

In the majority of observations on Clipperton Island, coral mortality has been mainly attributed to the El Niño Southern Oscillation (ENSO), high storm activity and long-period swells (Robertson and Allen 1996; Wang and Fiedler 2006). So far, reports of the ecosystem status suggest the land-seascape of Clipperton Island is healthy (Jost and Andréfouët 2006). Yet, no further studies have examined potential threat

factors (e.g., diseases, bleaching and hurricane events) that may jeopardize the reef's health status. In this context, no data on the current benthic coral coverage and community status are available for Clipperton Island (Glynn et al. 1996; Jost and Andréfouët 2006; Wu et al. 2014).

In coral reef ecosystems, documentation of the structure and composition of key reef-building species communities provides critical baseline data to identify potential local stressors affecting the ecosystem (Hughes et al., 2018). While regular monitoring efforts may not be possible due to the remoteness of reef locations such as Clipperton Island, periodic monitoring of coral assemblages may help provide relevant insights to identify potential threats to coral reef functionality (Perry and Alvarez-Filip 2018). During a scientific sampling campaign as part of the *Tara Pacific* Expedition at Clipperton Island in August 2018, we assessed morpho-functional benthic community (i.e., reef-building species, non-reef building species, space-competitive algae and non-organic structures) abundance and composition, as well as the proportion of reef-building coral colonies that displayed signs of compromised health, specifically a pink-spotted phenotype that indicative of trematodiasis, an infection with parasitic trematodes. As *Porites* trematodiasis has recently been reported the most common disease in the Hawaiian Archipelago, occurring on over 60% of reefs in the region (Couch et al. 2014; Aeby 2016), we here provide a first assessment of pink spot incidence on the isolated and remote shallow reefs of Clipperton Island. The data presented on the status of reef benthic assemblage will be valuable for monitoring purposes and potential management recommendations to preserve the unique coral reef system of remote Clipperton Island.

## Materials And Methods

### Study area and data collection

The remote Clipperton Atoll in the tropical northeastern Pacific is situated 1,100 km from the nearest continental coast (Fig. 1) (Pitman et al. 2006; Robertson and Allen 1996). The island is of volcanic origin, and due to its 10 km<sup>2</sup> extension and enclosed eutrophic inner lagoon considered an almost-atoll (Jost and Andréfouët 2006). The coral reef is composed by a 3.7 km<sup>2</sup> well-developed fringing reef that is irregularly segmented by spurs and groves, reef terraces and seaward slopes dominated by massive *Porites* spp. and branching *Pocillopora* corals in shallower waters (1-15 m), and massive *Porites*, *Pavona* and *Leptoseris* corals in deeper waters (20-70 m) (Wellington et al. 1995; Glynn et al. 1996). The oceanographic environment is fairly stable in terms of the ambient sea water temperature (Glynn et al. 1996; Romero-Torres et al. 2020). Yet, episodic ENSO events have influenced the seascape of the Clipperton area, for instance intense swells and hurricanes occur during the tropical storm season from May to October (Wang and Fiedler 2006; Zhao and Raga 2015).

For benthic coral reef surveys, four different study sites were selected for each representative reef location around the atoll: North, South, East, and West of Clipperton Island's shallow reef zones (10-13 m water depth) (Fig. 1b). Benthic assessments were conducted on SCUBA using line intercept point (LIP) along three transects of 20 m length parallel to the shoreline. The LIP surveys used a weight suspended

technique recording benthic data each 50 cm interval along the transect line (120 data points) for each site. The following benthic categories of morpho-functional groups were recorded: Corals: *Pocillopora* spp., *Porites* spp., *Pavona* spp., *Leptoseris* spp.; algae: macroalgae, crustose coralline algae (CCA); rubble (encompassing small not recently dead corals), rock, sand, and turf algae. Total live coral cover was calculated from the percentage sum product of all *Pocillopora* (branching), *Porites* (massive), *Pavona* (massive), *Leptoseris* (encrusting) corals for each site. In addition, the proportion of corals displaying signs of trematode infection (*Podocotyloides stenometra*), evident as pink spots on live tissue (Fig. 1) (Aeby, 2003) was recorded along with coral cover. Incidence of the trematode infection was recorded, i.e., all colonies displaying pink spots, regardless of whether infection was mild (few spots) or heavy (high densities of pink spots, covering > 50% of the colony).

As explanatory environmental variable, annual seawater temperature (SWT) from monthly data of the last decade (2008-2018) were acquired from satellite images of 4 km<sup>2</sup> grid resolution (<https://oceancolor.gsfc.nasa.gov>), using type AquaModis® at level 3, and analyzed with Wam\_Statistit® ver. 6.33 software. To identified intensity of thermal-stress periods derived by El Niño South Oscillation (ENSO, warm “El Niño” and cold “La Niña” phases), the Ocean Niño Index 3.4 region was used (<https://ggweather.com/enso/oni.htm/>). We also recognized and categorized tropical cyclones that influenced Clipperton area, using data from the National Hurricane Center, NOAA (<https://www.nhc.noaa.gov/data/>) during past decade.

## Data analysis

Multiple permutational analyses of variance (ANOVAs) and their respective post-hoc tests based on Euclidean matrices were used to evaluate differences in benthic morpho-functional group coverage and reef benthic composition (Shannon diversity,  $H'$ ). Statistical significance of ANOVAs was tested with unrestricted permutations (10,000) of raw data. For live coral cover, we performed one-way permutational Analysis of Variance (PERMANOVA) to test differences between reef zones (North, West, South, and East). and a principal coordinate analysis (PCoA) to determine coral composition resemblances at genus level among reef zones based on PERMANOVA's yields. All PERMANOVAs were conducted in PRIMER v.6 with PERMANOVA+ extension.

## Results

Total live coral cover across the four sites surveyed averaged  $66 \pm 7.7\%$  (range ~54-85%), with statistically significant differences between reef zones (PERMANOVA;  $F= 3.6931$ ,  $P= 0.0002$ ) where evident for the North and the South reefs, with the highest live coral cover compared with the West and East reefs of the atoll (Fig. 2a and Table 1). No significant differences were found for diversity of benthic assemblages (Shannon diversity,  $H'$ ) between reef zones (PERMANOVA;  $F= 0.71818$ ,  $P= 0.6045$ ), revealing similar assemblage patterns for the entire Clipperton reef (Fig. 2 and Supplementary information). The benthic community was dominated by *Porites* spp. at all four reef sites (in total ~45% across all sites), followed by *Pocillopora* spp. (~ 15% across all sites). Rubble, algae, other life coral, rock,

and CCA each individually contributed 5–10% of total benthic cover. Recently dead corals contributed ~5% to total benthic cover, and were dominated by dead branching *Pocillopora* (Table 1). The PCO results showed that live coral cover on the North reef was dominated mainly by the massive corals *Porites* and *Pavona* (~80%), and at the rest of the sites, coral cover was dominated by *Porites* and *Pocillopora* (~60%) (Fig. 2).

Table 1  
Mean benthic cover proportion (% ± SD of total) of each morpho-functional group, including proportion of pink-spotted corals (potentially reflecting prevalence of trematode infections) for all Clipperton Island reef zones

Benthic group	Benthic cover (% of total)				
	North	South	East	West	All reefs
<i>Porites</i>	52.26 ± 22.87	23.19 ± 6.49	27.13 ± 15.81	25.63 ± 1.65	32.05 ± 17.30
<i>Porites</i> (PS)	14.78 ± 12.17	16.54 ± 5.27	13.11 ± 13.43	7.40 ± 6.50	12.96 ± 9.23
<i>Pavona</i>	5.81 ± 5.79	1.67 ± 2.89	4.17 ± 5.20	-	2.91 ± 4.24
<i>Pavona</i> (PS)	9.88 ± 8.56	-	1.67 ± 2.89	0.81 ± 1.41	3.09 ± 5.69
<i>Leptoseris</i>	-	-	-	1.67 ± 2.89	0.42 ± 1.44
<i>Leptoseris</i> (PS)	-	0.81 ± 1.41	-	-	0.20 ± 0.70
<i>Pocillopora</i>	2.48 ± 2.50	16.48 ± 4.90	20.69 ± 4.01	19.07 ± 5.95	14.68 ± 8.45
CCA	1.65 ± 1.43	4.13 ± 3.81	10.77 ± 5.83	19.07 ± 9.57	8.90 ± 8.69
Macroalgae	-	4.96 ± 0.07	18.29 ± 11.62	0.83 ± 1.44	6.02 ± 9.14
Dead coral	3.33 ± 5.77	-	2.50 ± 4.33	1.65 ± 1.43	1.87 ± 3.39
Rock	1.63 ± 2.82	13.23 ± 3.86	1.67 ± 1.44	4.94 ± 4.28	5.37 ± 5.69
Rubble	7.38 ± 6.41	14.86 ± 6.54	-	16.44 ± 9.75	9.67 ± 8.90
Sand	0.81 ± 1.41	2.46 ± 2.44	-	2.50 ± 2.50	1.44 ± 1.96
Turf	-	1.67 ± 1.44	-	-	0.42 ± 0.97

Prevalence of pink spots, i.e., infection with the parasitic trematode *P. stenometra* were apparent at all sites, with an average of 26 and 31% (range 21 – 38 and 0 – 66%) prevalence in *Porites* spp. and other massive corals (*Pavona* and *Leptoseris*), respectively (Fig. 2). No other discolorations suggesting other diseases were observed. While pink spots occasionally matched the presence of small vermetid snails growing in the coral, this was only observed for a minuscule proportion of pink spots observed (estimated < 5% of total observations; personal observation C.P.). *Porites* displaying pink spots were frequent along

transects at all four sites, while other infected coral genera were observed only at the north and south reefs of the atoll (Fig. 2a, Table 1). Infection was heavy in an estimated more than 50% of the surveyed massive coral colonies, including large specimens (>1m diameter). Despite the high proportion of trematode-infected coral, highest coral mortality was noted mainly for branching corals and minimal in massive corals with signs of recent macroalgae and coralline algae overgrowth.

Annual Sea water Temperature was  $28.40 \pm 0.80^{\circ}\text{C}$ , the 2015-2016 period had the highest values of SWT and corresponded with the strongest 2015-2016 El Niño warm event over the past 10-years (Supplementary material Table S1). Also, synergic events (ENSO + cyclones) occurred in the many year periods, a total of 10 hurricanes and 6 tropical storms influenced (in some cases two events per year) Clipperton Atoll area (Table 2).

Table 2

Historical data of tropical cyclones at Saffir-Simson scale, annual sea water temperature (SWT), and the intensity of ENSO periods (based on Oni index 3.4) from 2008 to 2018 at Clipperton Island

Tropical cyclones	Category (Saffir-Simson)	Temp (°C)	ENSO intensity	Year
Boris / Fausto	Tropical storm /Hurricane	$28.5 \pm 0.90$	La Niña weak	2008
Carlos	Tropical storm	$28.5 \pm 0.80$	El Niño moderate	2009
Celia	Hurricane 2	$28.0 \pm 0.80$	La Niña strong	2010
Jova /Eugene / Kenneth	Tropical storm /Hurricane 1/ Hurricane 1	$28.0 \pm 1.00$	La Niña moderate	2011
Emilia	Hurricane 1	$28.2 \pm 0.60$	Neutral	2012
Alvin	Tropical storm	$28.3 \pm 0.80$	Neutral	2013
Amanda /Marie /Vance	Hurricane 1 (all)	$28.5 \pm 0.80$	La Niño weak	2014
Blanca /Sandra	Hurricane 1/ Hurricane 2	$29.0 \pm 0.90$	La Niño very strong	2015
Blas	Tropical storm	$28.8 \pm 0.70$	La Niña weak	2016
Fernanda	Tropical storm	$28.5 \pm 0.80$	La Niña weak	2017
Fabio / Sergio	Tropical storm / Tropical storm	$28.2 \pm 0.80$	La Niño weak	2018

## Discussion

The benthic reef community composition of Clipperton Island is dominated by reef-building corals, and exhibits a higher live coral cover (in particular of the genera *Porites* and *Pocillopora*, exceeding >60%) compared with other localities along the ETP. This high coral cover suggests overall fair health of this unique coral reef (Wellington et al. 1996; Glynn and Ault 2000; Jost and Andréfouët 2006; Romero-Torres et al. 2020). Yet, in spite of the geographic isolation of Clipperton Island, Clipperton, an uninhabited and remote coral atoll from the Eastern Pacific, is an important steppingstone area that harbors a high marine biodiversity. Despite its biogeographic importance, little information on the status of its coral reefs is available from the last decade. Herein, we characterized the benthic coral community and health status among different shallow reef-zones (North to South) of Clipperton during the *Tara Pacific* expedition in 2018. The benthic composition (as percentage cover) as well as occurrence of trematodiasis infection was assessed. Total live coral cover on Clipperton reefs was 66% (55-85%), differing between sites, with massive *Porites* and branching *Pocillopora* corals dominating the benthic community with an average 48% (32-66%), and 15% (3-21%), respectively. While Clipperton reefs exhibited significant live coral cover overall, the trematode infection was commonly observed, with a higher occurrence in massive corals (*Porites* 27%, and *Pavona* 31%). This observation is possibly related to the combined effects of previously heatwaves, and local inputs of guano-derived nutrients discharged into the reefs during cyclones events. These results demonstrates that even highly remote reefs supporting high coral cover can be subjected to local threats, including but not limited to parasite prevalence, likely in relation to natural disturbances such as thermal stress and tropical cyclones.

Our data reveals that live coral cover of the benthic reef community of Clipperton Island exhibits a similar range of proportion (10-100%) compared to what was reported two decades earlier (Glynn et al., 1996), and characterized by the dominance of only four reef-building coral genera. In addition, coral cover appears to have remained relatively stable, or potentially has rapidly recovered from mass coral mortality events previously reported for the ETP region (Glynn 2000; Hughes et al. 2017, 2018; Eakin et al. 2019; Romero-Torres et al. 2020). The composition of benthic morpho-functional groups remains homogenous around the entire atoll, yet differences between reef zones, evidencing steady changes in coral composition from branching to massive corals mainly in the shallow reef community (Fig. 2) (Cabral-Tena et al. 2018; Romero-Torres et al. 2020). This observation may be explained due to different exposure to wave energy. The Southern and Eastern reef zones in particular are more protected and may act as shelter areas for branching coral species (i.e., *Pocillopora*), in contrast to North-Western zones, which are more fragmented in shallow depths where massive resistant species (i.e., *Porites* and *Pavona*) dominate (Figs. 1, 2b).

Clipperton Island coral assemblages are remarkable different to common ETP reefs due to its prevalence and high abundance of stress-tolerant massive corals over branching corals even on shallow reefs. This feature may be related to extensive loss of cover and poor recovery of Pocilloporidae after heat events (i.e., El Niño ENSO 1982-83, 1997-98 and 2015-16). These results may suggest that relatively coral diversity (dominated by massive forms) may be able to uphold reef formation and maintain the major geomorphologic features characteristic of an atoll. Yet, coral assemblages shifting from fast-complex-growth to low-simpler-growth could alter and constrain certain ecological traits, such as rugosity and

carbonate production, which will in turn inevitably affect ecosystem functionality (Glynn et al. 1996; Perry and Alvarez-Filip 2018; Cabral-Tena et al. 2020). Thus, implementation of active restoration of *Pocillopora* species is recommended as a conservation tool to mitigate the likely low functional redundancy of shallow Clipperton reef areas (Perry and Alvarez-Filip 2018).

A high prevalence of dead and partially dead *Porites* and *Pocillopora* at greater depth (18-20 m) previously reported by Glynn et al. (1996) was not apparent in this study, but coral mortality and extreme fragmentation of *Pocillopora* were evident (personal observation by the authors). This observation may be due to mechanical impacts of severe storms and hurricanes (Table 2) that frequently disturb the reef frames of branching corals in the shallower reef areas of Clipperton (Hutchings 1986; Zhao and Raga 2015). The intensive and increasingly frequent storm events (i.e., tropical cyclones and ENSO) is known to benefit other benthic reef groups (e.g., macroalgae, coralline algae and massive corals) less prone to fragmentation, and which compete for available open spaces to settle on the substrate (Sheppard et al. 2009).

For massive corals, partial mortality could be related to the prevalence of *P. stenometra* infection in *Porites* spp., as suggested by a high incidence of observations of pink spots and tissue lesions on corals off Clipperton Island (Fig. 2). Incidence of *P. stenometra* infection have previously been observed in *Porites* spp. throughout the Pacific, ranging from reefs off Hawaii to Guam, Papua New Guinea, Australia, and French Polynesia (Aeby 2003). Previous studies have reported that *P. stenometra* infection can have a negative effect on coral calcification rate, reducing growth rates up to 50%, and increasing bioerosion and space-competition, eventually resulting in coral mortality (Aeby 1992; Trillobet and Gobulic 2011). Of note, *Porites* corals only constitute intermediate hosts of infection with *P. stenometra*. The final hosts are fish feeding on coral polyps, such as butterfly fish (Aeby 1992, 2003), which are characterized by a low diversity and abundance on Clipperton Island reefs (Robertson and Allen 1996). Therefore, little top-down control of trematode infection may occur, which could in part explain the high incidence of pink spots on coral. Parasite infection-acquisition could further be related to the interchange of eutrophic water produced by the phosphate-rich sediments of meromictic enclosed lagoon waters and guano-derived nutrients, which are commonly discharged into the reefs during intense storms and hurricanes (Bourrouilh-LeJan et al. 1985; Jost and Andréfouët 2006). This effect coincides with the observation of higher proportions of pink-spotted, i.e., trematode-infected coral colonies in the Northern and Eastern reefs (Fig. 2), which are closer to the inner lagoon entrances (narrowest carbonate barrier) of the atoll.

This study demonstrates that remote shallow oceanic Clipperton Island reefs sustain high live coral cover but may be subject to local threats such as parasite (trematode) prevalence and natural disturbances, such as thermal stress and storm events. Considering the pronounced effects of such stressors that may slowly erode the fitness of the reef community (as reflected in reduced coral growth and accretion of the reef framework, and/or reduced coral cover and community complexity), we recommend the establishment of standardized monitoring of coral disease incidence. Further, synergic effects of thermal stress and local stressors of corals should be investigated further for a better understanding of long-term dynamics of remote reef systems, natural species resilience and their potential implications (causes and

consequences) in the maintenance of the Clipperton benthic coral reef community. Finally, we highlight the importance of establishing long-term coral reef monitoring based on the live coral cover, structure and composition of corals species and other biological and ecological indicators that may provide more extensive information that help develop conservation and management strategies to reduce reef stressors, and protect the endemism, dispersion hotspot, and the natural refuge of coral reef biodiversity that Clipperton provides to the ETP region.

## Declarations

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**Conflict of interest** The authors declare no conflict of interest.

**Ethical approval** No animal testing was performed during this study

**Sampling and field studies** All necessary permits for sampling and observational field studies have been obtained by the authors from the competent authorities and are mentioned in the acknowledgments, if applicable.

**Data availability** All data generated or analyzed during this study are included in this published article and its supplementary information files.

**Author contributions** CP, EEGC conceived the study, collected data and writing (original draft). EEGC conceived the study, supervising and funding acquisition CP collected data. JJATL analyzed data and writing (original draft). All authors review, edits and approved the final version of this manuscript.

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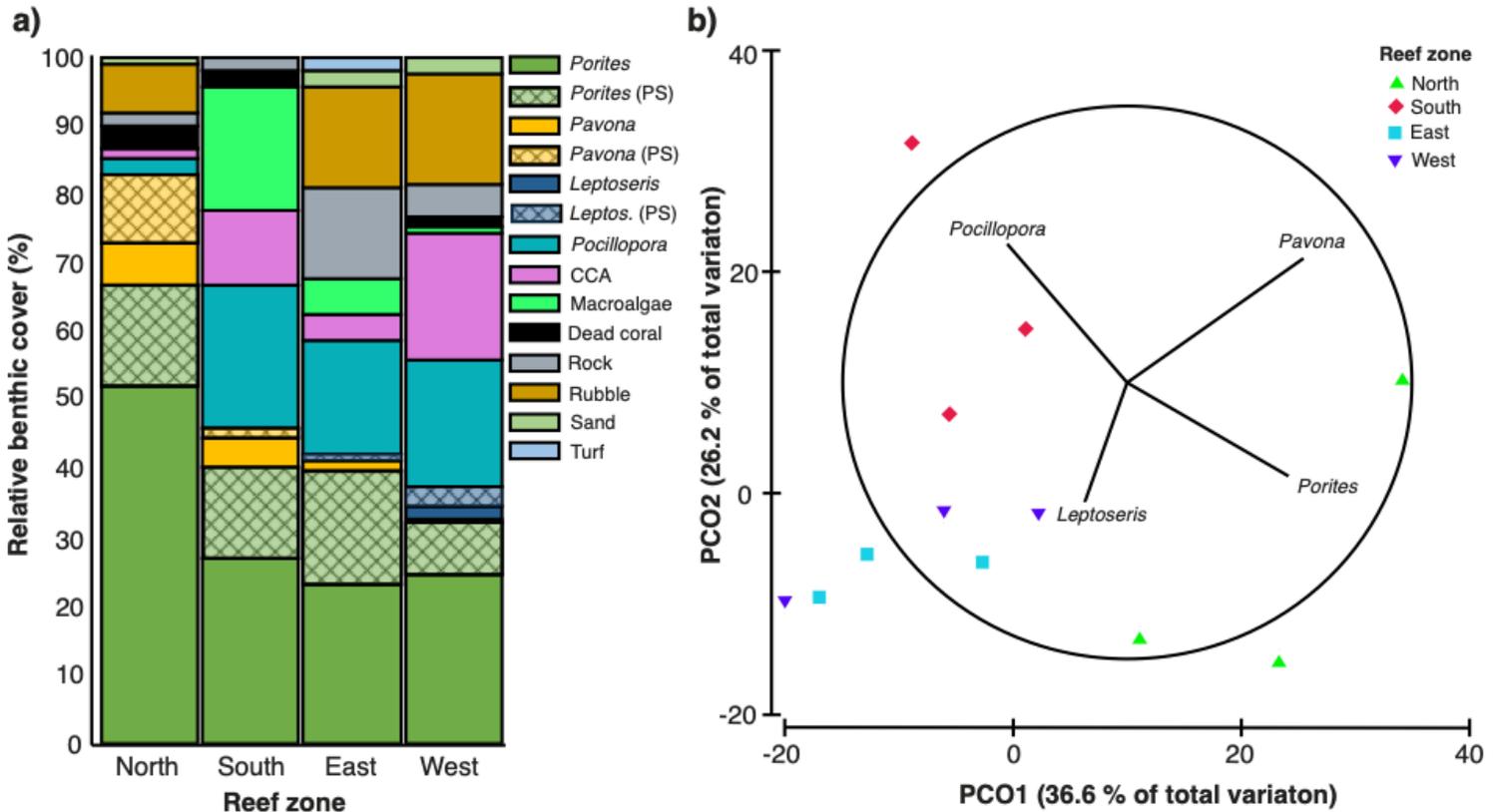
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## Figures

### Figure 1

Description of the study region and sites and coral phenotype. (a) The location of the isolated Clipperton Island in the Eastern Tropical Pacific –and (b) detailed map of the study sites. Maps adapted from van Soest et al. (2011). (c)-(f) Representative observations of massive *Porites* corals off Clipperton Island in the Eastern Tropical Pacific exhibiting trematode infection (pink spots). Close-up (c) and overview (d-f) of *Porites* coral colonies displaying pink-spotted phenotypes. Side lengths of quadrat in (b) 0.25m, and 0.5m in (a, c, d). White arrows show pink-spotted areas on affected colonies



**Figure 2**

Characterization of benthic communities of four reef zones off the remote Clipperton Island in the Eastern Tropical Pacific. (a) Percentage cover of benthic morpho-functional groups (solid colors) and the proportion of infested corals displaying a pink-spotted phenotype (grid areas) for each reef zone. (b) Ordination plot (PCoA; % of total variation explained) of benthic communities and the relationship with coral species on shallow reefs off Clipperton Island in the Eastern Tropical Pacific. CCA = Crustose coralline algae; PS = pink-spotted phenotype