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Covariates

As noted in the main text, ten covariates were chosen to describe structural, biophysical, and social characteristics of reef monitoring sites that could contribute to the variation in ecological conditions, thus confounding our analysis of MPA impacts. Each covariate is well established among experts and in well documented in the literature as factors that influence the structure of coral reef ecosystems. All covariates were ranked highly by experts as critical variables to evaluate when tracking changes in reef ecosystems through space and time.

Distance to deep water: Water depth influences fish abundance and species richness on coral reefs, and is a powerful predictor for spatial variations in fish biomass [1-3] Distance to deep water was measured as nautical distance (distance over water) from each site to the nearest 50-m depth contour [2]. We used General Bathymetric Chart of the Oceans and depth sounds from field (interpolated) bathymetry data in ArcMap to locate 50-m depth contours and measure distances [4].

Sea-surface temperature anomalies: Temperature is one of the most important physical properties of the marine environment as it exerts an influence on many physical, geochemical, and biological events and is one of the most important abiotic factors influencing the distribution of marine species. Coral reefs exposed to frequent high sea-surface temperature anomalies (SSTA) may be more resilient to future warming events [5, 6]. We calculated frequency of sea-surface temperature anomaly (SSTA) as the number of times over the previous 52 weeks that SST was greater than or equal to 1 degree C above that week's long term average value. Degree-heating-weeks data were downloaded from NODC4, Coral Reef Temperature Anomaly Database (CoRTAD5), at a spatial resolution of 4km from October 1981 to December 2010. Due to coarse locations of coral reef monitoring sites (only two decimal degree in latitude and longitude) and projection errors, Inpaint_nans6 function was used to interpolate (in cubic mode) all metrics to land area.

Reef exposure: Reefs that are protected and experience low to moderate exposure to wave action have greater fish biomass compared to reefs experiencing high wave energy [7, 8]. Wave exposure also large influences coral community structure with higher coral cover often found on sheltered reefs compared to reefs that are frequently exposed to high wave action [9, 10]. Reef exposure was noted during field surveys and classified into three categories: exposed, semi-exposed, and sheltered.

Reef slope: The slope or steepness of coral reefs determines light penetration, overhangs, settlement of sediment thus influencing the composition and abundance of both coral and fish communities [11-13]. Reef slope was noted during field surveys performed and each site was identified as either flat, slope, or wall.

Reef type: The structure of coral and fish assemblage also corresponds with type of reef [13-15]. Variation in fish communities is occurs has been well documented across the different reef types as these different reef types are exposed to a range environmental factors and support different benthic habitats [13-15]. Categories used during field surveys were fringing, patch, barrier, and atoll.

Distance to mangroves: Mangroves are a key nursery habitat for coral reef fish species and they enhance biomass of reef fish communities [16]. A global distribution of mangrove habitat was accessed from the United Nations Environment Program-World Conservation Monitoring Center (UNEP-WCMC) online tool: http://www.unep-wcmc.org/resources-and-data. Mangrove locations were detailed with 13,175 polygons in the BHS and surrounding area, lending high resolution. The minimum mangrove distance was measured between each monitoring site to the nearest nursery habitat. Nautical distance was measured.

Distance to fishing settlement:– Coral reefs accessible to nearby fishing villages will experience greater fishing pressure than remote reefs. Locations of fishing settlements were collected through household surveys (Pakiding et al., unpublished) and a rural appraisal of the region [17]. A total of 56 settlements are represented. These coordinates were loaded into ArcMap to measure nautical distance from every sites to nearest fishing settlement.

Distance to primary market: Distance to nearest fishing market is a proxy for exploitation; reefs closer to markets provide easier access for fishing boats and therefore experience more fishing compared to reefs further from markets [18, 19]. Expert consultation revealed that there are four major markets in the Birds Head Seascape: Sorong, Manokwari, Fakfak, and Kaimana Kota. Sorong, however, is the administrative capital of Raja Ampat and the predominate market for fishermen to sell their catch. Nautical distance to from Sorong to each site was measured in ArcMap.

Watershed-based pollution local threat risk: Watershed-based pollution poses a risk to coral reef ecosystems [20, 21] and was assessed by Reefs at Risk Revisited in the Coral Triangle [22]. This layer represents the estimated threat from watershed-based pollution to reefs. Erosion rates, sediment delivery, sediment trapping, and sediment dispersal were calculated and modeled for over 300,000 watersheds globally, including the Bird's Head Seascape, and were rated as either low, medium, or high threat level.

Monsoon season: Sampling sites were classified as exposed to either the northwest or southeast monsoon winds depending on their placement proxy to nearby islands during field surveys. Sites where coral reefs faced north or westerly are exposed to northwest monsoon winds, and similarly for sites facing south and easterly. Sites that are exposed to the same monsoon pattern will experience similar exposure to currents, wind, and precipitation [7, 23].

As expected with field data, not all covariates were well balanced post-matching. Field data, especially in marine systems, inherently has certain biases or inadequacies because data collection is limited by accessibility to remote habitats and resources available for carrying out such field expeditions. In the Bird's Head Seascape, the covariates that matched well in and outside protected areas, i.e., reef exposure, type, and slope, and pollution risk, were all categorical variables whereas those that did not were continuous covariates. This divergence in matching performance between categorical and continuous covariates is due, in part, to specifically imposing calipers on only categorical covariates, but also reveals that the structure of our field data contains certain biases.

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