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Coral assemblages are structured along a turbidity gradient on the Southwestern Gulf of Mexico, Veracruz

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ABSTRACT

Corals on the reef corridor of the southwestern Gulf of Mexico have evolved on a terrigenous shallow continental shelf under the influence of several natural river systems. As a result, water turbidity on these reefs can be high, with visibility as low as <1 m, depending on reef location and season. Using a presence-absence species database from field surveys, literature search, and satellite data on sea surface temperature, turbidity and chlorophyll-a, the coral species composition and environmental variables were analyzed for the three main reef systems of the reef corridor of the southwestern Gulf of Mexico. Completeness of the data set was assessed using species accumulation curves and non-parametric estimators of species richness. Differences in coral assemblages' composition between the reef systems were investigated using univariate (ANOVA) and multivariate (nMDS, ANOSIM, SIMPER) analyses and the relationship between the assemblages and environmental data was assessed using a forward selection process in canonical correspondence analysis (CCA) to eliminate non-significant environmental variables. The northern and central Veracruz reef systems share a similar number of coral species ($p=0.78$ mult. comp.) and both showed higher species richness than the southern system ($p<0.001$ mult. comp.). In terms of the assemblages' structure, significant differences were found (ANOSIM $R=0.3$, $p=0.001$) with larger average dissimilitude between north-south (75.4% SIMPER) and central-south (74.2%) than north-central (27%) comparisons. Only environmental variables related to water turbidity and productivity were significant on the final CCA configuration, which showed a gradient of increasing turbidity from north to south. Reef geomorphology and the effect of turbidity help explain differences in coral assemblages' composition. More studies are necessary to establish if turbidity could function as a refuge for future environmental stress. Each Veracruz reef system is at the same time unique and shares a pool of coral species. To protect these ecosystems it is necessary to effectively manage water quality and consider coral diversity on the reef corridor of the southwestern Gulf of Mexico.

1. Introduction

Coral reefs are diverse ecosystems that provide ecological goods and services for a large proportion of the world's population (Moberg and Folke, 1999). Unfortunately, reefs are on global decline, with coral cover lost in most oceans, for example in the Great Barrier Reef (GBR) (Bruno et al., 2007), in the Caribbean Sea (Gardner et al., 2003; Andrefouet and Guzmán, 2005) and in the Gulf of Mexico (Tunnell, 1988; Burman et al., 2012; Horta-Puga et al., 2015). The causes for coral cover loss include local and global factors, like coral bleaching and disease, tropical storms, overfishing, coastal pollution and their interactions (Hughes et al., 2007, 2010). One major global environmental threat to coral reefs is the increase in water temperature that, together with light stress, triggers bleaching events and subsequent disease epizootics that lead to coral mortality (Harvell et al., 2001; Loya et al., 2001; Williams and Miller, 2005; Miller et al., 2006; Muller et al., 2008; Brown and Dunne, 2015). Bruno and Valdivia (2016) suggest that global factors are the main drivers of biological change on reefs, but regional and local factors play an important role (Salas-Pérez et al., 2008; Riegl and Tsounis, 2014; Anthony et al., 2015). For example, Kennedy et al. (2013) estimated that the adequate management of fisheries and water quality can help delay reef decline in a business-as-usual global context. Examples of fast recovering or well preserved (high coral cover) reefs exist in some world ocean locations (Idjadi et al., 2006; Roff and Mumby, 2012; Gilmour et al., 2013; Manzello et al., 2014). Identifying the factors that contribute to these coral reefs conservation is an important task that can help in management-decision making with a better understanding of the mechanisms that cause or prevent decline (van Woesik, 2002; McClanahan et al., 2006; Mumby and Steneck, 2008). In that sense, coral-reef refugia can be

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defined as areas in which the environment or the coral assemblages have remained unaltered compared to surrounding areas where decline in coral assemblages has been driven by environmental change. Examples may include: moderate to deep reef areas, reefs that are distant from pollution sources, areas with cooler or turbid waters, high-latitude areas and areas where corals present some physiological characteristic that make them more resilient (Glynn, 1996; West and Salm, 2003; Fine and Tchernov, 2007; Bongaerts et al., 2010; Smith et al., 2014). Most of these proposed coral refugia include some protection from thermal or irradiance stress. Moderate but long-lasting water turbidity occurs on many reef locations around the world and it can offer protection from thermal stress by blocking light, thus reducing pressure to the symbiont's photosystem II (Iglesias-Prieto and Trench, 1997; Cacciapaglia and van Woesik, 2016). Extreme turbidity will not have a beneficial effect and can be deleterious (Loya, 1976; van Woesik and Done, 1997; Dikou and van Woesik, 2006). The reefs along the coast of Veracruz, Mexico develop next to approximately 450 km of coastline in the Gulf of Mexico. More than 60 named reefs are currently known (Jordán-Dahlgren and Rodríguez-Martínez, 2003; Tunnell, 2007; Ortiz-Lozano et al., 2013). These reefs vary on reef geomorphology (emergent platforms, submerged reef banks and fringing reefs), size (from a few hundred to several km in length) and distance: 1) to the coast, 2) to populated areas and 3) to river discharges (from a few m to several km) (Salas-Pérez and Granados-Barba, 2008; Salas-Pérez et al., 2015). Due to the influence of several rivers, water can become turbid several months per year but the degree and duration of water turbidity is variable along the coast (Salas-Pérez et al., 2008; Carriquiry and Horta-Puga, 2010; Horta-Puga et al., 2015). This study describes patterns of scleractinian coral diversity along the coast of Veracruz using univariate and multivariate techniques. In addition, a stepwise procedure in canonical correspondence analysis tests the relationship of the coral assemblages with satellite-derived environmental variables (sea surface temperature, positive and negative temperature anomalies, chlorophyll-a, diffuse attenuation coefficient (Kd490 and KdPAR) and irradiance at 5 m depth) and identifies the most influential environmental variables that correlate with the coral assemblages. Variables that surrogate for water turbidity were more influential in the structure of the coral assemblages, with this information this study seeks to establish which reefs and coral species could potentially benefit from turbidity in a time of rapid climate change.

2. Material and methods

2.1. Corals of the reef corridor of the southwestern Gulf of Mexico

A database of Scleractinian corals at the study area (Fig. 1) was assembled with information from two sources: 1) direct field observations and 2) literature research. Field observations were the result of several years of work by the Coral Reef Laboratory of the "Universidad Veracruzana" at Tuxpan, Veracruz. In general, field observations were made using 1) 5 m-diameter circles, 2) 50 m long line-intercept transects and 3) reconnaissance dives. The observations were made in all reef habitats (fore reef, back reef, reef lagoon and reef crest where present) at depths from 1 to 20 m for the Lobos-Tuxpan ("Sistema Arrecifal Lobos-Tuxpan", SALT) and Los Tuxtlas ("Sistema arrecifal Los Tuxtlas", SAT) reef systems. Coral species presence was established for each sampled reef, identification was made in situ by trained divers; in case of taxonomic uncertainty, a sample of the coral skeleton was collected for laboratory identification. Emergent reefs of the northern system have been sampled intensely and a great effort has been devoted to the more recently discovered submerged platforms. On the other hand, the Los Tuxtlas reef system has received little attention until recently, and this is the first report of a Scleratinian species list for 32 SAT reef formations. A literature search completed field observations for the species lists of the SALT and SAT. The species list for the reefs of the Veracruz reef system ("Sistema Arrecifal Veracruzano", SAV) was compiled from published sources that included information from the leeward, windward and reef crest zones of most (80%) reefs from the SAV. The SAV is one of the best studied reef systems in the Mexican part of the Gulf of Mexico due to the historical and commercial importance of the Veracruz City and port (Horta-Puga et al., 2007, 2015).

2.2. Environmental variables

Monthly time series from 2008 to 2011 of environmental data (sea surface temperature (SST), chlorophyll-a (Chl-a) concentration and diffuse attenuation coefficient) were obtained from an ocean area adjacent to a reef (Salas-Pérez et al., 2015). Data were downloaded from http://upwell.pfeg.noaa.gov/erddap/griddap/erdMGk490mday.html. Given the spatial resolution of the environmental data and the clumped distribution of the reefs, not every reef was associated to an environmental value. Instead a local group of reefs was associated to a local environmental value by selecting ocean coordinates close to the group centroid. The downloaded environmental variables were examined for outliers. Positive and negative temperature anomalies were calculated by subtracting the four-year (total length of the time series) mean to each SST value in the time series. The diffuse attenuation coefficient (K_{dPAR}) of photosynthetically active radiation and the amount of PAR at 5 m (PAR5m) depth were calculated from the K_{d490} measurements using the formulas presented in Cacciapaglia and van Woesik (2015). Turbidity was assessed by K_{dPAR} that indicates how strongly light intensity in the blue to green region of the spectrum penetrates within the water column, in addition K_{dPAR} and PAR5m represent the attenuation (K_{dPAR}) and the amount of photosynthetically active radiation (PAR5m in) at 5 m deep in the water column. The Chl-a data was used as a surrogate to productivity and river discharge. A mean value for each environmental variable was calculated from the data downloaded for the ocean area. Given that we were interested in differences in large spatial scales a yearly mean for each environmental variable at each reef or reef group was used. The time series used- 2008–2011- had no mayor environmental stress (e.g. large storm or hurricane events). A matrix of environmental data by reefs or group of reefs was obtained for use in canonical correspondence analysis.

3. Data analysis

3.1. Data sets completeness

In evaluating the completeness of the species data sets, species accumulation curves were performed using the number of sampled reefs for each reef system. In addition, the number of unseen species were estimated using three non-parametric estimators (Chao, first order jackknife and bootstrap; Bunge and Fitzpatrick, 1993; Smith and van Belle, 1984). These analyses were done in R (R Core Team, 2016) using the "vegan" library (Oksanen et al., 2013).

3.2. Coral assemblages

To identify the reef system with significantly higher species richness, the mean number of Scleractinian and Milleporid species was compared between the three reef systems: (Lobos-Tuxpan (SALT), Veracruz (SAV) and los Tuxtlas (SAT)) with a one-way analysis of variance. The assumptions of normality and homogeneity of variances were checked with Shapiro-Wilks and Levene tests. Multiple comparisons were made using a Tukey post hoc test. The analysis was done with R (R Core Team, 2016) using the "lawstat" library (Gastwirth et al., 2013). The reef and species matrix was used to calculate a Sørensen-disimilarity matrix between the reefs. To identify reefs with similar coral species the Sørensen matrix was used to perform a non-