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Impacts of coastal development on ecosystem structure and function of Yucatan coral reefs, Mexico

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Abstract. We report the results of a multi-site comparative analysis of coral reef condition along a gradient of coastal development in the Yucatan Peninsula (Mexico). Benthic surveys and fish counts performed in 2000 were used to assess ecosystem structure and functional reef components in three regions of the State of Quintana Roo: 1) the Riviera Maya in the north, with heavy tourist development; 2) the Sian Ka'an Biosphere Reserve, a protected area with very low human density; 3) the Costa Maya in the south, with relatively little tourist development. Results showed significant differences in the ecological state of coral reefs along the coast. Northern reefs exhibited an algal-dominated state with a very low coral cover, whereas southern reefs exhibited a more balanced coverage of macroalgae and corals with extended areas of free substrate. No clear trends were apparent in the spatial patterns of the biomass of herbivorous fishes, but fish functional diversity decreased from south to north. Results suggest that massive coastal tourism development combined to a low resilience may have caused major shifts in the structure and function of coral reefs in the northern region of the Yucatan Peninsula.

Key words: Macroalgae, Herbivorous fish, Functional diversity, Tourism, Disturbance.

Introduction

Caribbean coral reefs have been suffering a regional-scale decline as a result of multiple disturbances (Gardner et al. 2003, Wilkinson 2004). Increasing coastal development calls for a better understanding of the key processes driving coral reef degradation since the causes and mechanisms leading to this decline are still debated (Aronson and Precht 2006, Mora 2008). In addition, reef management requires functional approaches to understand how disturbances affect the structure and function of coral reefs (Hughes et al. 2003, Bellwood et al. 2004).

The Mesoamerican barrier reef system is home to some of the richest biodiversity in the wider Caribbean, but it is threatened by intensive coastal development induced by fast-growing tourism industries (Kramer and Kramer 2002, Wilkinson 2002, 2004). Along the Caribbean coast of the Yucatan Peninsula (Mexico), the State of Quintana Roo has endured a massive tourism development, starting on Cancun in the 1970s and extending towards the south during the last three decades. Given the strong anthropogenic pressure, the ecological state of Quintana Roo coral reefs needs to be evaluated to search for possible impacts of coastal development.

We report the results of a multi-site comparative analysis of coral reef condition along the Quintana Roo coast. A functional approach, based on the assessment of key functional components of benthic and fish communities, was developed to evaluate the potential impacts of anthropogenic disturbances.

Material and Methods

Study area

Mexican Caribbean coral reefs extend for over 400 km along the coast of the State of Quintana Roo on the eastern side of the Yucatan Peninsula (Fig. 1).

Figure 1: The 11 study sites in the northern (N, triangles), central (C, squares) and southern (S, circles) Quintana Roo coast.

Quintana Roo reefs are referred as extended fringing reefs and vary slightly from a gentle slope with low relief in the north to better developed reefs with spur and groove formations in the south (Jordán-Dahlgren and Rodríguez-Martínez 2003, Núñez-Lara et al. 2005). According to human use and coastal development, the Quintana Roo coast can be broadly divided into 3 regions: the Riviera Maya in the north (N) with heavy coastal development, especially in Cancun; (2) the Sian Ka'an Biosphere Reserve in the central region (C) with very low human density and a protected status; the Costa Maya in the south (S) with low human density and small but rising tourism development.

Data collection

Fish counts and benthic surveys were performed (Núñez-Lara 2003) in 2000 on the 6-m deep fore-reef zone of 11 reef sites distributed in the three regions N, C and S (Fig. 1). Fish censuses were conducted on 18 replicate 50 x 2-m belt transects and species biomass was subsequently estimated from individual size using length-weight allometric relationships compiled in FishBase (Froese and Pauly 2008). Benthic coverage was assessed from digital video imagery (Osborne and Oxley 1997), video transects being later analyzed using a point sampling method. A plastic sheet marked with 13 points was laid over a monitor screen, and sessile organisms and substrate types lying beneath each point were counted on 40 regularly spaced frames. For each video transect, percentage cover of benthic components was then estimated from 520 point counts.

Finally, we gathered socio-economic indices for the coastal municipalities (the second-level administrative division in Mexico) of the Quintana Roo state for the period 2000-2002. Urban areas and road density (SEPLADER 2006), human density (INEGI 2000) and number of hotels (SEDETUR 2008) were used to quantify the anthropogenic pressure along the Yucatan coast.

Data analysis

Percentage cover of fleshy macroalgae (canopy height >1 cm), live corals (scleractinians and gorgonians) and bare substratum (i.e., free hard substrate) was compared in the regions N, C and S of the Quintana Roo coast. Total fish biomass and fish herbivore biomass (*Scaridae* and *Acanthuridae*) were also compared, as well as the number of fish species per transect. Comparisons between the three regions were performed using pairwise t-tests with the Bonferroni correction. Finally, functional diversity (species richness by functional group) was investigated by pooling fish species into 28 functional groups defined by feeding habits, size and mobility. For each reef site, we estimated the number of fish species (SR) by functional group, and mean SR per group were calculated 1) over all reef sites (global mean SR) and 2) over the reef sites of each region (regional mean SR). Deviations of regional means to the global mean were analyzed for each functional group.

Results

Indices of coastal development

Socio-economic data indicated a clear gradient of coastal development along the Quintana Roo coast (Fig. 2). Urban areas and human density decreased strongly from north to south. In addition, tourism infrastructure was far more developed in the north: the number of hotel rooms reached 25,000 in Cancun and decreased to about 15,000 along the whole Riviera Maya, then 100 and 200 in the Sian Ka'an Biosphere Reserve and in the Costa Maya respectively.

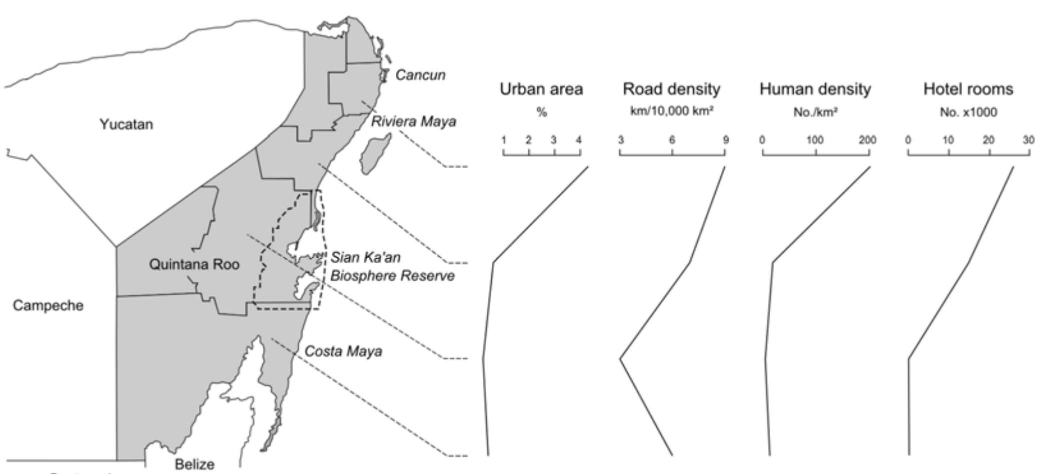

Figure 2: Indices of coastal development for the 4 coastal municipalities of the Quintana Roo state.

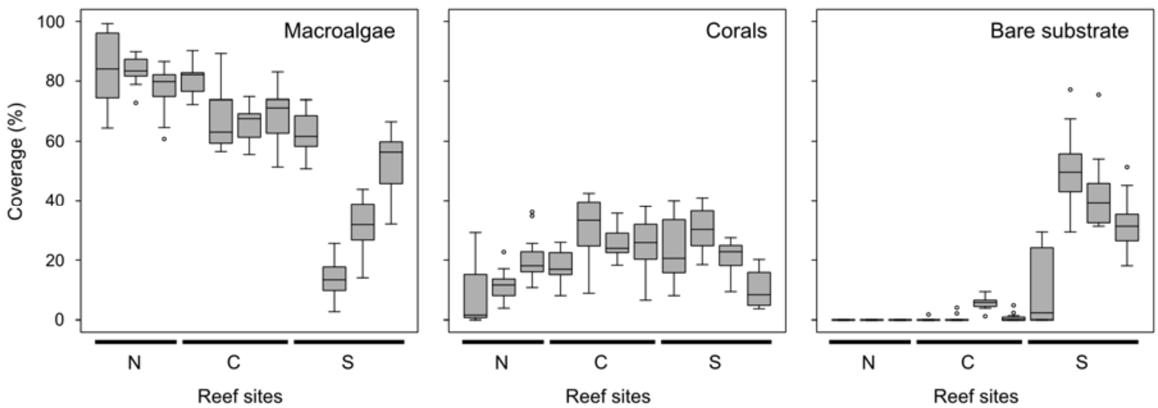

Figure 3: Benthic coverage of macroalgae, corals and bare substratum at the 11 surveyed reef sites of the Quintana Roo coast.

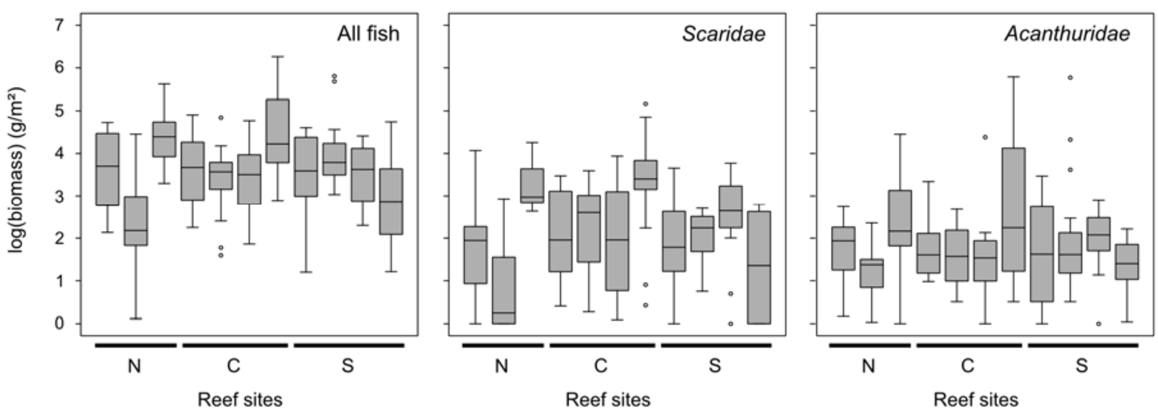

Figure 4: Total fish biomass and biomass of *Scaridae* and *Acanthuridae* at the 11 surveyed reef sites of the Quintana Roo coast.

Benthic cover

The percentage cover of macroalgae was higher in the north (Fig. 3, mean ± s.e. 82 ± 1%) and decreased significantly ($p<0.001$) in the central region (71 ± 1%), then in the south ($p<0.001$, 38 ± 3%). Maximum values were observed in the far north (10-km south to Cancun) where macroalgal cover reached 95% in several places. Coral cover was significantly lower ($p<0.001$) in the north (13 ± 1%) than the other regions (C: 25 ± 1%, S: 22 ± 1%). The coverage of bare substrate was null in the northern region and increased to the south where it reached one third (35 ± 3%) of the reef bottom.

Fish biomass

Total fish biomass (mean ± s.e. 58 ± 6 g/m²) was highly variable between and within reefs (Fig. 4) but did not vary significantly between the three regions. In average, herbivores accounted for 49% (± 3) of the total biomass of fish assemblages. Biomass of *Scaridae* was significantly higher in the central region compared to the north ($p<0.05$) and the south ($p<0.01$). The biomass of *Acanthuridae* did not vary significantly. As a result, herbivore biomass and macroalgal cover did not show a significant relationship along the Quintana Roo coast.

Fish diversity

Fish species richness (Fig. 5) was significantly lower ($p<0.01$) in the north (11.4 species/transect) than the central region (14.3 sp.) and the south (15.5 sp.).

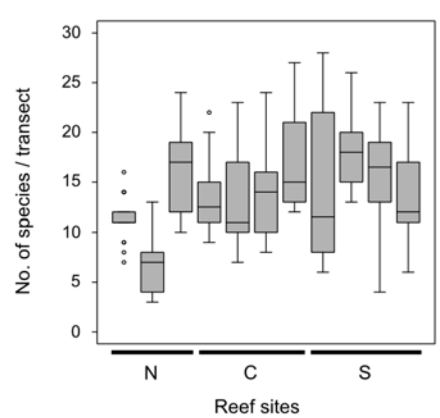

Figure 5: Fish species richness along the Quintana Roo coast.

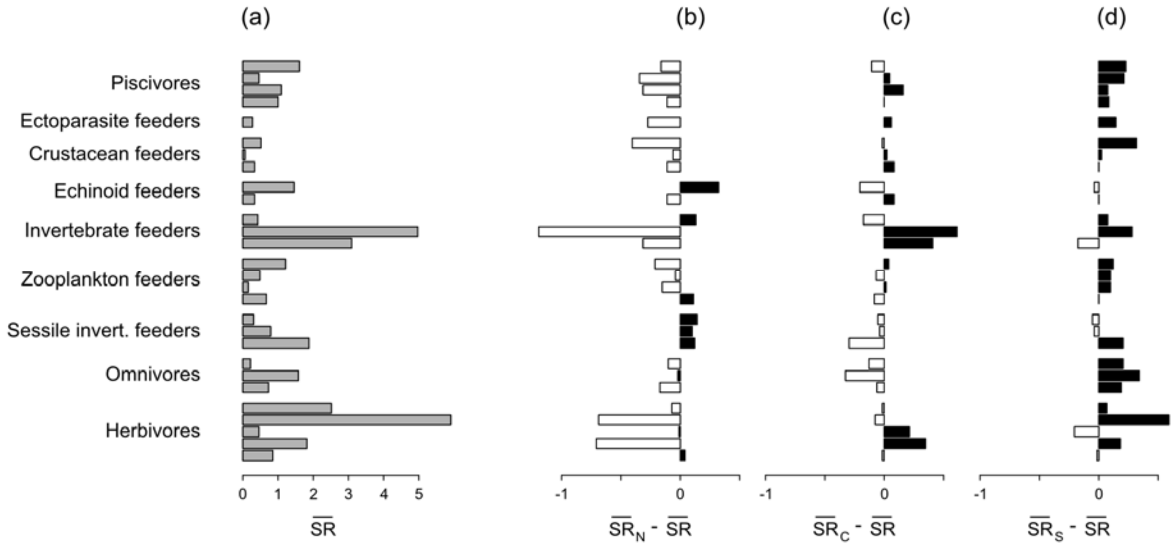

Figure 6: Fish functional diversity along the Quintana Roo coast described by (a) the global mean species richness (SR) of the 28 functional groups and deviations from the global mean SR to (b) northern, (c) central and (d) southern mean SR.

Fish functional diversity also increased from north to south (Fig. 6). Species richness of some herbivore, invertebrate feeder and high-level carnivore groups increased. Inversely, some functional groups, such as echinoid feeders and sessile-invertebrate feeders, were more speciose in the north.

Discussion

In 2000, the benthic structure of coral reefs exhibited highly contrasted patterns along the Quintana Roo coast. Northern reefs were largely dominated by macroalgae (82% mean coverage) and live coral cover was very poor (13%), whereas southern reefs exhibited a more balanced coverage of macroalgae and corals (38% and 22% respectively) with extended areas of bare substrate available for colonization. Those patterns indicate considerable changes in the equilibrium between macroalgae and corals following a north-to-south latitudinal gradient. From southern to central reefs, macroalgae progressively overwhelmed the available free space, and then overgrew corals in the northern region until they dominated and saturated the reef bottoms. Those patterns indicate a latitudinal gradient of coral-to-algae phase shift along the Quintana Roo coast. This gradient of ecological states suggests a major shift along the coast in the processes driving the equilibrium between macroalgae and corals.

In the recent decades, many Caribbean reefs have suffered major declines in coral cover leading to a phase shift from hard coral to fleshy algae dominance (Gardner et al. 2003, Pandolfi et al. 2005). Coral-to-algal phase shifts have been attributed to the reduction of herbivory as a result of diseases (mass mortality of the echinoid *Diadema antillarum*) and overfishing (Hughes 1994, Jackson et al. 2001, Mumby et al. 2007). From north to south, no clear trends were apparent in the biomass of herbivorous fishes on Yucatan reefs. Spatial information of the fishing pressure is scarce, but *Scaridae* and *Acanthuridae* are seldom targeted by Mexican fishermen. In addition, *Diadema* urchins did not recover in 2000 from the 1983-84 mass mortality event as only few isolated individuals were detected on videotransects. As a result, fishing pressure and herbivory are unlikely to have caused the benthic shifts observed along the Quintana Roo coast.

Other explanations of coral-to-algal phase shifts involve coastal development and associated nutrient enrichment (Lapointe 1997). In 2000, the Quintana Roo coast exhibited clear patterns in coastal development that fitted very well with the gradient depicted on the benthic structure. From the poorly developed coast in the south to the heavy touristic spot of Cancun in the north, urbanization, coastal population and tourism infrastructure sharply increased parallel to the latitudinal gradient of macroalgal proliferation. This suggests that tourism-driven coastal development may be the primary cause of coral-to-algal phase shifts detected along the Quintana Roo coast.

Other processes such as hurricanes and coral mortality have the potential to inverse the equilibrium between corals and algae (Ostrander et al. 2000, Aronson and Precht 2006). Coastal development may have affected reef resilience on Quintana Roo reefs and increased their susceptibility to natural disturbances. Ecosystem responses to disturbances vary according to ecosystem functions performed by organisms, and functional diversity and redundancy (i.e., the number of taxonomically distinct species that exhibit similar ecosystem functions) can be expected to strongly influence coral reef susceptibility to coral/algal phase shifts (Bellwood et al. 2004, 2006). Our results showed a lower functional redundancy in northern fish community of some key functional groups, such as herbivores and piscivores. This may indicate that northern reefs were more susceptible to anthropogenic disturbances, or that benthic shifts have impacted the species composition of fish assemblages (see also Arias-González et al., in press). Our data do not allow to conclude if the spatial patterns of functional diversity are the result or the partial cause of the ecological changes depicted on the reef benthic structure. They suggest however that the potential of reef resilience is probably lower in northern reef in face to disturbances.

In 2000, macroalgae dominated northern reefs of the Yucatan Peninsula, and coral/algal phase shifts extended towards the south. During the last decade, coastal development has grown faster, stretching from Cancun to the northern edge of the Sian Ka'an Biosphere Reserve. The expanding costal development and the low redundancy of some functional groups are unlikely to have helped northern reefs to recover. In addition, tourism economy has reached southern reefs with the construction of a cruise ship pier for the development of tourism industry in the Costa Maya. Management actions are needed to protect the last healthy reefs of Quintana Roo coast which face a massive tourism development. As reported in the present study, coral cover was higher in some reef sites of the Sian Ka'an Biosphere Reserve, despite an algal-dominated state. Such patterns may encourage the development of protected areas to help coral reefs to maintain a substantial coral cover. Finally, this study provides a reference point of coral reef condition along the Quintana Roo coast, and future management of coral reef resilience may be improved by continued assessment of ecosystem metrics and functional attributes of species.

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