Local human activities limit marine protection efficacy on Caribbean coral reefs

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Abstract

Marine ecosystems globally have suffered habitat, biodiversity and function loss in response to human activity. Marine Protected Areas (MPAs) can limit extractive activities and enhance ecosystem resilience, but do not directly address external stressors. We surveyed 48 sites within seven MPAs and nearby unprotected areas to evaluate drivers of coral reef condition in the Mexican Caribbean. We found that local human activity limits protection effectiveness. Coral cover was positively related to protection characteristics, but was significantly lower at sites with elevated local human activity. Furthermore, we predict ongoing coastal development will reduce coral cover despite expanded protection within a regionwide MPA if an effective integrated coastal zone management strategy is not implemented. Policy makers must acknowledge the detrimental impact of uncontrolled coastal development and apply stringent construction and wastewater regulations in addition to marine protection.

KEYWORDS

coastal development, coral reefs, effectiveness, eutrophication, local human threats, management, Mesoamerican Reef, protected area network

1 | INTRODUCTION

Marine ecosystems have suffered habitat, biodiversity, and function loss in response to rising human population and activity (McCauley et al., 2015). Coral reefs are particularly sensitive to perturbations as they persist within a narrow range of physicochemical conditions (Hughes et al., 2017). Reefs worldwide have experienced declines in condition and function, attributed to coral disease, overfishing and herbivore loss, eutrophication, sedimentation, and climate change (Hughes et al., 2017). However, management actions primarily target overfishing and direct physical threats through Marine Protected Area (MPA) establishment, while external stressors such as climate change and land-use change are frequently unaddressed (Hughes et al., 2017; Mora et al., 2006).

Coral communities can benefit from marine protection by two principal mechanisms. First, MPAs may regulate activities that cause physical damage, such as careless anchor use, destructive fishing and uncontrolled snorkeling and diving (e.g., Dinsdale & Harriott, 2004). Second, the positive effect of protection on herbivorous fish populations is expected to control benthic macroalgae and indirectly benefit corals by reducing competition and freeing space for recruitment and growth (Gill et al., 2017; Mumby et al., 2006a). Yet, conservation outcomes are highly variable, depending not only on MPA design and management effectiveness, but also on biological and external factors (Mora et al., 2006). Increases in coral cover are rarely observed in MPAs (Mumby & Harborne, 2010), while various studies report no significant effect of protection (e.g., Huntington, Karnauskas, & Lirman, 2011; Toth et al., 2014).

Reef degradation has been linked with anthropogenic eutrophication, sedimentation and local contamination of coastal waters at numerous sites globally including the Great Barrier Reef (GBR), Indonesia, Jamaica, and Florida (e.g., Fabricius & De'ath, 2004). Recent research has highlighted that such external stressors reduce MPA efficacy (Bégin et al., 2016; Lamb et al., 2016; Wenger et al., 2016). On the GBR, no-take reserves are ineffective in mitigating coral loss and disease due to elevated terrestrial run-off (Lamb et al., 2016; Wenger et al. 2016). In the Caribbean, benthic composition has been linked with land-use change, rather than marine protection (Bégin et al., 2016). Sedimentation increases with vegetative cover loss as a result of land-use change to agricultural or urban use, coastal dredging, and construction (Fabricius, 2005). Sediments smother corals, raise water turbidity, reducing coral photosynthetic activity, energy reserves and growth, and are linked with coral disease, reduced coral fecundity and recruitment (Jones, Bessell-Browne, Fisher, Klonowski, & Slivkoff, 2016). Anthropogenic nutrient sources include septic tanks, sewage outfalls, agricultural fertilizers and livestock (Lapointe et al., 2010). Directly, nutrients increase coral disease prevalence and severity (Vega Thurber et al., 2014). Indirectly, nutrients promote the growth of macroalgae, which compete with corals, reducing fecundity, recruitment, growth, and survival through various mechanisms (Chadwick & Morrow, 2011). Furthermore, local land-based threats can be synergistic with other stressors. For example, nutrient enrichment increases coral susceptibility to bleaching and improving water quality can ameliorate the effects of climate change on corals (Wiedenmann et al., 2013).

The Mexican Caribbean coast has experienced dramatic coastal development over the last 30–40 years. Over 10 million tourists visit annually and the local population has grown rapidly from 88,000 in 1970 to 1.3 million in 2010 (INEGI, 2010). Consequently, coastal waters of the region have experienced eutrophication and increased sedimentation levels (Arias-González et al., 2017; Baker, Rodríguez-Martínez, & Fogel, 2013). Coastal dredging, construction, and marine port construction contribute sedimentation and have been associated with nearby reef degradation (Arias-González et al., 2017). Hotels and residences are often constructed without adequate wastewater treatment facilities and due to the karstic terrain, seepage is of particular concern (Bauer-Gottwein et al., 2011; Murray, 2007). Furthermore, loss of forest and mangrove vegetation owing to hotel construction and urbanization has reduced groundwater filtration, further increasing nutrient concentrations reaching the ocean (Ellis, Romero Montero, & Hernández Gómez, 2017). Consequently, eutrophication resulting from inadequate wastewater treatment is considered a principal driver of declining reef condition in the region (Bozec, Acosta-González, Núñez-Lara, & Arias-González, 2008; Suchley, McField, & Alvarez-Filip, 2016).

Coastal development in the Mexican Caribbean has taken place despite an extensive marine protection network consisting of eight MPAs protecting over 260 km of reef. These MPAs exert little influence over land-based human activities and are generally not complemented by terrestrial protected areas as part of integrated coastal zone management (CONANP, 2017). In order to develop effective management strategies it is critical to understand marine protection performance in the context of external stressors. Here, we evaluate the impact of protection status, local human threats and other factors on Mexican Caribbean coral reef condition. This region provides an ideal model as many reefs are protected within MPAs of varying characteristics while declining reef condition has been linked to burgeoning coastal development. As elsewhere, MPA establishment and design is often driven by political and socioeconomic concerns in addition to ecosystem considerations (Marinesque, Kaplan, & Rodwell, 2012). In December 2016, after this study was conducted, the entire Mexican Caribbean was declared a biosphere reserve and consequently protection effectiveness considerations are particularly timely. Although this MPA will protect almost all Mexican Caribbean coral reef habitats, the adjacent coastline, which is planned for extensive further development, will continue to be outside protected area limits (Figures 1 and S1). To critically evaluate the capacity of expanded MPA networks to protect reefs confronted with ongoing coastal development we forecast regionwide coral cover under varying management scenarios.

2 | MATERIALS AND METHODS

Forty-eight reef sites were surveyed in the Mexican Caribbean over the period April-November 2016 (Figure 1). Sites were located within seven MPAs and nearby unprotected areas on the reef front at a mean ($\pm$ s.e.m.) depth of 11.3 ± 0.5 m (see supplemental methods for site selection details). At each site, reef benthos was surveyed using 10 videotransects of 25 m length at a swimming speed of approximately 10 m/minute. Videotransects were each sampled using 10 frame stills as photo-quadrats, which in turn were point-sampled with 50 points using the software Coral Point Count (CPCe; Kohler & Gill, 2006). A preliminary study was conducted to determinate the appropriate number of quadrats and points (see supplemental methods). Points were classified as hard coral or other benthic components. Coral bleaching incidence was recorded, but was generally low and no bleaching-induced mortality was observed.

At each site, reefscape structural complexity was visually estimated on a 0 to 5 scale by a single observer and reef rugosity was evaluated using the chain method (supplemental methods; Wilson, Graham, & Polunin, 2007). Herbivorous fish (Scaridae and Acanthuridae) abundance and total length
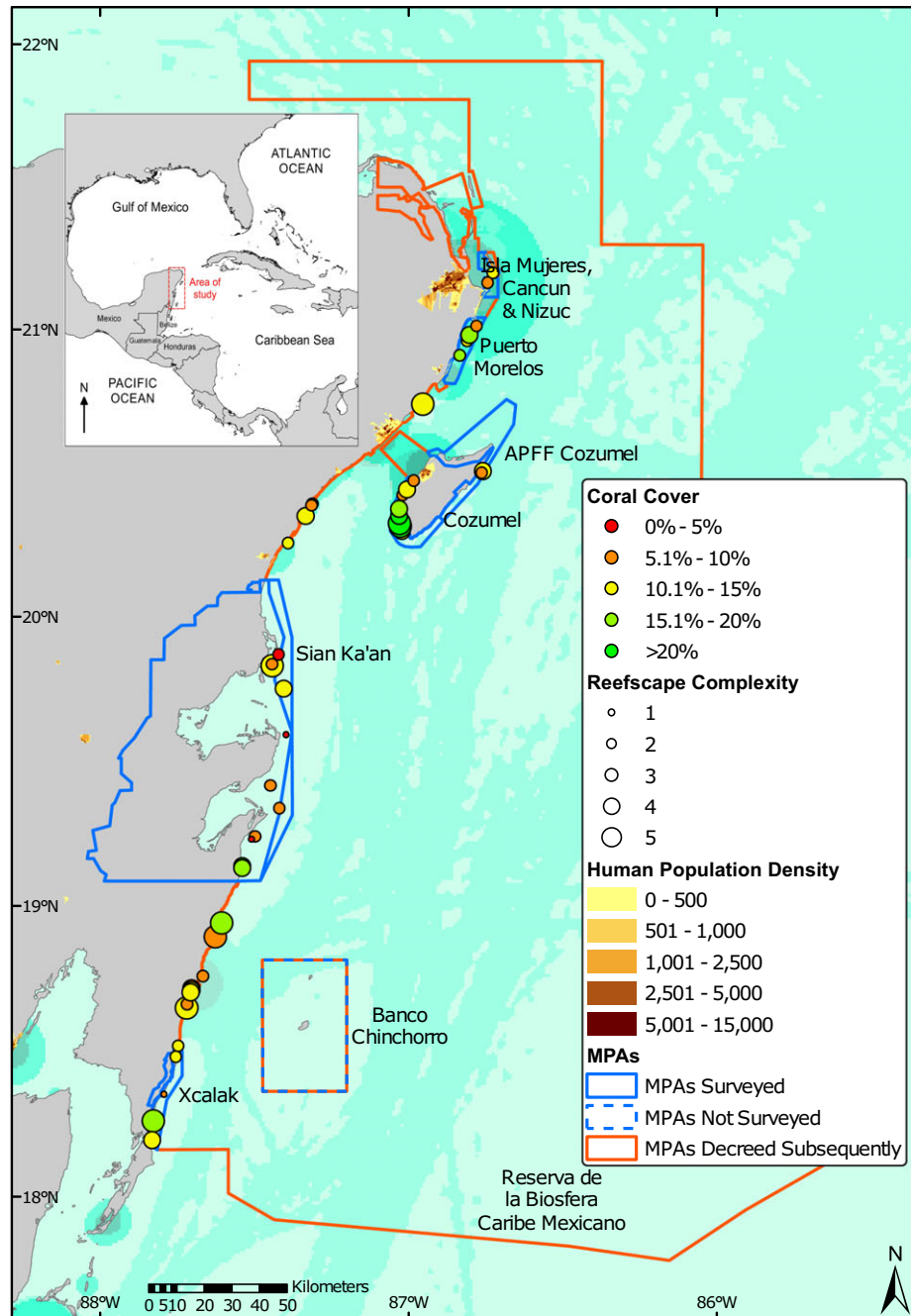
FIGURE 1 Study site location in the Mexican Caribbean. Forty-eight sites were surveyed in total. Thirty-three sites were located within 7 MPAs (blue shaded areas), of which 12 were located within complete No Take Zones where extractive practices are not permitted, and the remaining 15 sites were unprotected. Sites are identified by circles whose color reflect mean site coral cover and size reflect reef structural complexity. Urban area human population density shown by basic geostatistical area for 2010 (INEGI 2010). Marine background shade represents local human threat level (darker for higher threat) based on combined coastal development and marine pollution & damage threat from the World Resources Institute (WRI; Burke et al., 2011)

(TL), and *Diadema antillarum* sea urchin abundance were recorded in 30 m-long and 2 m-wide transects. We aimed to perform eight transects per site (range from 5 to 11). Fish abundance was converted to biomass density using standard allometric length–weight conversions. Very few sea urchins were present and were only observed at 26 of 48 sites.

We tested the effect of protection status (full No Take Zone/general use MPA/unprotected); MPA age, time since publication of management plan, size, and effectiveness; herbivorous fish biomass; *Diadema* density; fleshy macroalgal cover; reefscape structural complexity and rugosity; local human threat; wave exposure, hurricane frequency and other
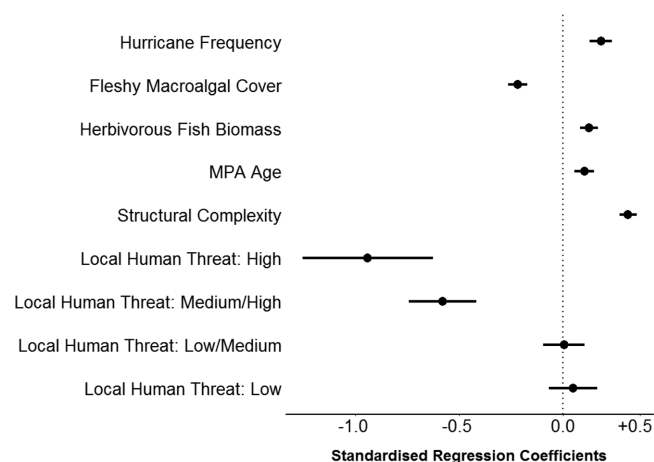
FIGURE 2 Coral cover predictors in the Mexican Caribbean. Standardized regression coefficients for predictor variables in minimum adequate binomial logit GLMM model of coral cover. The minimum adequate GLMM was refitted using z-scores for numerical predictor variables (calculated by subtracting the mean from each raw data point and then dividing by the standard deviation) to enable a comparison of predictor weights. Coefficients reflect the number of standard deviations change in the log odds of the dependent variable ($\ln(\frac{Coral\ Cover\ \%}{1-Coral\ Cover\ \%})$) for a one standard deviation increase in each predictor variable, while controlling for all other independent variables. Error bars represent one standard deviation in coefficient estimates. As Local Human Threat is a categorical variable, coefficients are not standardized but shown by category, with Medium selected as the base level and therefore not shown. There was no significant difference in model fit between the minimum adequate model and an alternative developed with separate local human threat components (coastal development and marine pollution and damage) as candidate predictor variables (chi-square test, $X^2 = 1.99$, 2 d.f., $P = 0.37$) and the combined model was retained as was more parsimonious

abiotic variables on coral cover (Table S1). Water temperature trends were not included as remote sensing data do not capture local variations at the resolution available (4 km; Chollett, Müller-Karger, Heron, Skirving, & Mumby, 2012). Furthermore, previous studies have shown that temperature is a poor predictor of spatial variation in coral reef condition in this ecoregion (Cox, Valdivia, McField, Castillo, & Bruno, 2017). Local human threat index and MPA protection variables were key to the analysis and are explained further.

The level of local human threats not related to extractive activities was estimated by integrating two component indices developed at a global scale by the World Resources Institute (WRI; Burke, Reytar, Spalding, & Perry, 2011). The advantage of using a global data source is that this approach can be replicated for any region or site worldwide. The component indices were: (1) coastal development and (2) marine-based pollution and damage threats. Watershed-based pollution threat, also available from WRI, was not considered reliable as the Yucatan peninsula has very little surface drainage due to its karstic nature. Coastal development threat

is determined based on the location and size of cities, ports, and airports, population density within 10 km of the coast, coastal population growth, and tourism growth (Burke et al., 2011). Marine-based pollution and damage threat is evaluated principally based on the distance to commercial and cruise ports scaled by shipping and passenger volumes (Burke et al., 2011). We integrated these two threat factors to generate a combined local human threat index on a five-point scale ("Low," "Medium," and "High" categories were converted to numeric equivalents -1, 0, +1, the two threats summed, and the sum ranging from -2 to +2 mapped to categories "Low," "Low/Medium," "Medium," "Medium/High," "High").

MPA age was determined as the time since formal decree, and the time since publication of management plan was also obtained (CONANP, 2017). MPA size is the total marine area protected in km^2 (CONANP, 2017). We characterized MPA effectiveness in terms of enforcement and compliance based on the 2016 Mesoamerican Reef Eco-Audit performed by the Healthy Reefs Initiative and partner organizations (Healthy Reefs Initiative, 2016). The Eco-Audit draws on input from NGOs, governmental agencies, and the private sector to classify MPAs according to three criteria: (1) the existence of an updated management plan; (2) the adequacy of personnel and equipment; and (3) the level of enforcement. The scores for the three criteria were combined to determine overall MPA effectiveness on a seven-point scale in a similar manner to the local human threat index (the three criteria each evaluated on a three-point scale were converted to numeric equivalents -1, 0, +1, and summed to give a total ranging from -3 to +3).

To model coral cover we adopted generalized linear mixed models (GLMMs) with site as a random effect. A binomial error distribution with a logit link function was adopted to account for non-normal error distribution resulting from modelling percent cover. Model assumptions were validated with residual plots and multicollinearity was eliminated by removing predictors with the highest variance inflation factors (VIFs) until all VIFs (degrees-of-freedom-adjusted GVIFs) were less than 2 (Graham, 2003). Least significant predictors were sequentially removed and models compared pairwise with chi-square tests of significant differences in residual deviance. The more parsimonious model was preferred until the chi-square test revealed a significant difference and the prior model retained as the minimum adequate model. Spline spatial correlograms were plotted to check residuals were not spatially autocorrelated. MPA predictor variables were collinear and thus only one remained in the candidate model. In order to assess the importance of MPA characteristics, alternative GLMMs were fitted retaining different MPA predictor variables during multicollinearity assessment.

The final fitted model was utilized to forecast regional coral cover in 20 years' time. The entire Mexican Caribbean was recently decreed a biosphere reserve. We assumed that this will function similarly to existing MPAs and thus

TABLE 1 Protected area management scenarios for the Mexican Caribbean. Passive, coastal zone, and comprehensive management scenarios adopted to predict regional coral cover in 20 years' time. Under each scenario, existing or improved strategies are assumed for coastal zone and herbivorous fish management, with consequences for local human threat levels and herbivorous fish biomass. We assumed that the Mexican Caribbean Biosphere Reserve will protect all surveyed sites not already protected in 2016 and thus current MPA age was increased by 20 years for all sites. All other model predictor variables were maintained constant

| Scenario	Coastal zone management strategy	Herbivorous fish management strategy	Assumptions
Passive management	Existing	Existing	Current strategy continues and adopted by the Mexican Caribbean Biosphere Reserve.
Coastal zone management	Improved	Existing	Active coastal zone management strategy to reduce the impact of local human activities. For example, improved wastewater treatment services at new hotel and residential developments, and retrofitting existing installations, would reduce nutrient run-off reaching the reefs (Murray, 2007). Prevention of mangrove destruction and sedimentation mitigation strategies for coastal construction would reduce the amount of terrestrial and coastal sediments in the water column (Ellis et al., 2017). Furthermore, marine traffic management, engine and fuel regulations would reduce local contamination. These combined actions are assumed to reduce local human threat level (after increases due to planned development) by two categories (e.g., High to Medium, Medium to Low etc.) over the 20-year forecast period.
Comprehensive management	Improved	Improved	Active strategy to reduce the impact of local human activities as per coastal zone management scenario.
			Herbivorous fish extraction banned as in other locations in the ecoregion (Kramer et al., 2015). Herbivorous fish ban assumed to increase biomass at non-No Take Zone (NTZ) sites by ratio of mean biomass at NTZ and non-NTZ sites (203%; Figure S4C), a plausible level over the 20-year forecast period given no-take protection results elsewhere (e.g., McClanahan, Graham, Calnan, & MacNeil, 2007).

forecasts were performed assuming all sites will be protected and current MPA age was increased by 20 years. Extensive urban and tourism development is planned for the coastline and its impact on regional coral cover must be considered. Based on an assessment of current threat levels and planned development, local human threat was increased to the highest category for all mainland sites north of Sian Ka'an Biosphere Reserve and those located in central Mahahual (Figure 1; supplemental methods). We then ran three forecast scenarios based on varying assumptions concerning protected area management strategy (Table 1). All statistical analyses were performed in R version 3.3.2.

3 | RESULTS

Mexican Caribbean reefs were dominated by fleshy macroalgae and turf algae/turf algae sediment mats. Mean ($\pm$s.e.m.) site fleshy macroalgal cover was $27.2 \pm 2.0\%$ (with cover ranging from 1.8% to 59.6%) and mean turf cover was $20.5 \pm 1.0\%$ (range: 5.5% to 37.5%), while mean coral cover was only $11.9 \pm 0.8\%$ (range: 2.2% to 33.2%; Figure S2). Coral cover was found to be significantly related to local human

threat, MPA age, herbivorous fish biomass, fleshy macroalgal cover, reef structural complexity, and hurricane frequency (Figure 2). Coral cover was positively correlated with MPA age, herbivorous fish biomass, reef structural complexity and hurricane frequency, and exhibited a negative relationship with fleshy macroalgal cover (Figure 3). Medium/high and high levels of local human threat were associated with lower coral cover, and these levels displayed a stronger (negative) relationship with coral cover than that between fleshy macroalgal cover and coral cover or the (positive) relationship between MPA Age and coral cover (Figure 2). *Diadema* sea urchin density was not a significant predictor of coral cover. To fully assess the importance of MPA characteristics (MPA size, effectiveness, protection status and time between formal decree and management plan publication), four alternative models were fitted, each retaining different MPA predictor variables. For all four alternatives, MPA variables were significant in the resulting models (Figure S3).

The final fitted model was utilized to forecast regional coral cover in 20 years' time (Table 1). The model predicted that if planned coastal development takes place but management strategy remains unaltered then the proportion of degraded sites with coral cover below 5% will increase substantially
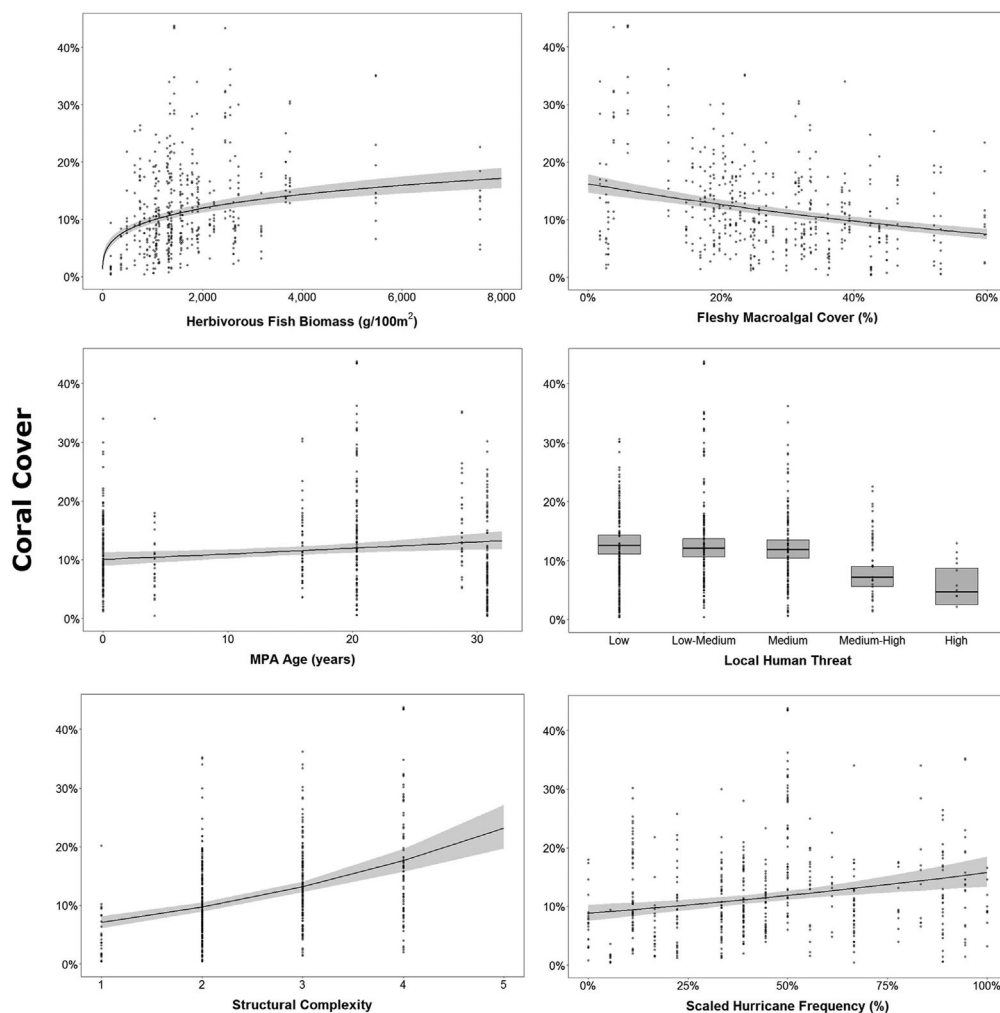
FIGURE 3 Coral cover predictor partial effects. GLMM model-predicted coral cover and actual mean transect coral cover by minimum adequate model predictor variables. Actual coral cover shown as points. Model partial effects shown as lines (with 95% confidence intervals) and determined for each predictor variable by holding all other fixed effect predictors at mean value. Structural complexity was assessed on a 0 to 5 scale. Sites with zero complexity were excluded as were not considered reefs. A single site was assigned a complexity of five, but was excluded from the analyses as fish data were not recorded. Hurricane frequency scaled by maximum and minimum observed values to give relative frequency between 0% and 100% for ease of interpretation

(Figure 4). However, if a coastal zone management strategy were implemented to reduce the impact of local human activity, then reef condition would improve beyond the current state (Figure 4). If complemented with regionwide herbivorous fish protection as part of a comprehensive management strategy, then reef condition is expected to improve further with a large proportion of sites reaching 20% coral cover or greater (Figure 4)

4 | DISCUSSION

Local human activities outweigh the effect of marine protection on coral communities in the Mexican Caribbean (Figures 2 and 4). Coral cover is positively related to marine protection characteristics including protection time, effec-

tiveness and MPA size, but is significantly reduced at sites with elevated coastal development and marine pollution and damage threat levels (Figures 1–3). This finding agrees with recent research reporting the detrimental impact of external stressors on MPA efficacy and extends it geographically (e.g., Bégin et al., 2016; Wenger et al., 2016). Further, we forecast that, despite increasing MPA coverage, highly degraded sites with very low coral cover will become increasingly common if the current management strategy continues (Table 1; Figure 4). However, integrated coastal zone management, particularly if combined with a regionwide ban on herbivorous fish extraction, could mitigate the negative impacts of planned developments and improve benthic condition beyond current levels (Figure 4).

While reef protection seeks to address human threats within MPA limits, it frequently fails to mitigate external
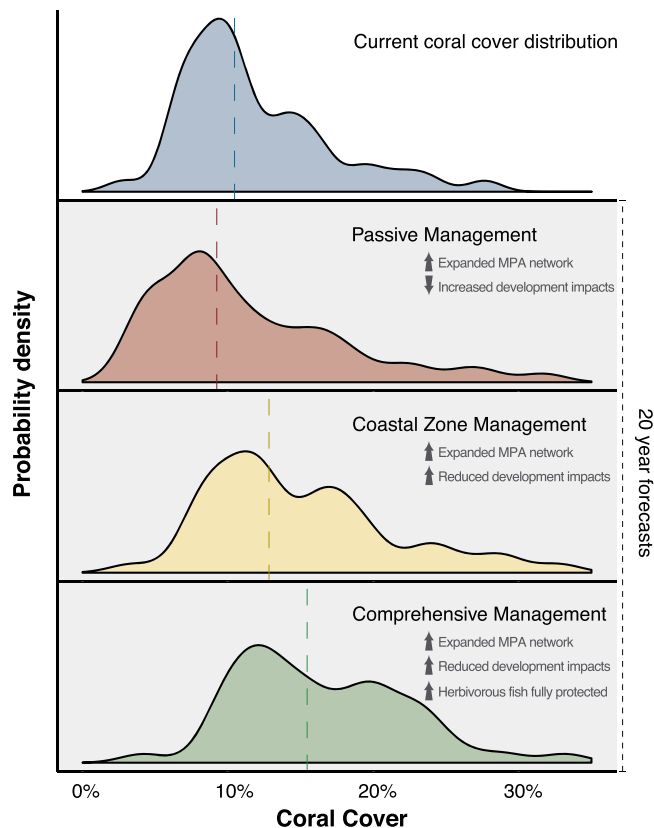
FIGURE 4 Mexican Caribbean coral cover forecasts. Three future coral cover forecast scenarios are contrasted with the current coral cover distribution. Scenarios are for 20 years in the future based on expanded marine protection in the Mexican Caribbean Biosphere Reserve and expected population and tourism growth. Three protected area management strategies are considered: (1) existing passive management with little mitigation of the impact of coastal development, (2) coastal zone management with an active strategy to reduce the impact of local human activities, (3) comprehensive management of the coastal zone and regionwide herbivorous fish protection (Table 1). Coral cover calculated using fitted GLMM model (Figure 2) for current and future scenarios. Vertical dashed lines indicate median values

threats such as climate change and local land-based human activities (Hughes et al., 2017; Mora et al., 2006). In recent decades, reef benthic condition has deteriorated at many sites despite marine protection (e.g., Huntington et al., 2011). MPA efficacy has been compromised by terrestrial sedimentation and flood run-off in both the Indo-Pacific and Caribbean basins (Bégin et al., 2016; Wenger et al., 2016). The current study took place in a region with one of the highest rates of coastal development globally. The northern coast of the Mexican Caribbean is highly developed, with major ports located across the region, and is set to develop even further (Figures 1 and S1). Here we found that despite the positive effect of the MPA network, coral cover is diminished by coastal development and marine activities (Figures 3 and S3). We hypothesize that coastal dredging, construction, and marine ports contribute sedimentation and

pollution locally while coastal development and urbanization has resulted in widescale eutrophication of coastal waters. While this reasoning is in agreement with a growing body of evidence (e.g., Arias-González et al., 2017; Bozec et al., 2008; Suchley et al., 2016), it is often not possible to identify causal factors of reef degradation due to limited and inconsistent nutrient and sediment data for many Caribbean reefs (Risk, 2014).

In the Mexican Caribbean, we observed that coral cover is positively related to protection time (Figure 2). This corresponds with other studies; however, it is important to consider selection bias as managers may preferentially protect reefs with higher coral cover (Graham et al., 2008; Selig & Bruno, 2010). Nevertheless, our finding that coral cover is related to MPA size and effectiveness (management planning, personnel and equipment, and enforcement), in addition to protection time, provides evidence for the value of MPA protection (Figure S3). In addition to marine protection and local human threats, we found other factors also influence reef condition. Both herbivorous fish biomass and fleshy macroalgal cover were significant predictors of coral cover (Figure 2), suggesting that macroalgal–coral competition is important (Chadwick & Morrow, 2011). Enhanced herbivorous fish biomass was related to no-take protection and although herbivorous fishes (parrotfishes and surgeonfishes) are not commercially targeted in Mexico, banning extractive practices can benefit populations through reduced by-catch (Figure S4C; Allison, Lubchenco, & Carr, 1998). No-take protection was also associated with lower macroalgal cover (Figure S4B); however, coral cover was not significantly correlated with no-take protection itself (Figure 2; Table S1). Given coral cover was significantly (positively) related to MPA protection (Figures 2 and S3), both direct (protection from destruction) and indirect mechanisms (related to herbivorous fish protection) may be necessary to benefit coral communities.

Coral cover was also related to reefscape structural complexity and historical hurricane frequency (Figure 2). Structural complexity influences the abundance, diversity, and trophic structure of reef fish assemblages, which in turn may benefit benthic condition due to food web integrity and enhanced ecosystem resilience (Graham & Nash, 2013). Although major hurricanes can have extensive immediate effects on reefs, less severe hurricanes and storms may be beneficial. For example, moderate hurricanes remove abundant fleshy macroalgae while not affecting robust corals (Mumby, Hedley, Zychaluk, Harborne, & Blackwell, 2006b). Hurricanes can also promote asexual coral recruitment through the creation and dispersal of coral fragments (Lirman, 2003). Furthermore, hurricanes are not responsible for historical declines in Caribbean-wide coral cover. Both impacted and nonimpacted sites suffered similar declines in the 1990s due to prior disease-driven loss of the predominant coral, *Acropora palmata* (Gardner, Côté, Gill, Grant, & Watkinson, 2005).

We found that local human threats act to reduce the efficacy of protection for Mexican Caribbean coral reefs. Given that few protected areas studied have sizeable terrestrial components (except the sparsely populated Sian Ka'an reserve; Figure 1), the protected area network currently provides insufficient protection from land-based threats. Indeed, we predict that ongoing coastal development will reduce regionwide coral cover despite expanded protection within the newly decreed Mexican Caribbean Biosphere Reserve (Figures 1 and 4). Although MPA efficacy should not be determined by the ability to mitigate threats originating outside their boundaries, these rising threats need to be considered by embedding MPAs in broader management frameworks such as coastal zone management or ridge to reef management (Table 1; Cicin-Sain & Belfiore, 2005). These are not new concepts, yet have been implemented in relatively few coral reef regions (Keller et al., 2009). Policy makers and managers globally must acknowledge the detrimental impact of uncontrolled coastal development on coral reefs. In addition to improved implementation and enforcement of herbivorous fish protection, authorities must apply more stringent controls on coastal development and wastewater treatment in order to improve coral condition and ecosystem resilience.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.