Session 36

Biodiversity, biogeography and evolution of coral reef organisms

Session chairs:

Danwei Huang, huangdanwei@nus.edu.sg

Francesca Benzoni, francesca.benzoni@unimib.it

Marcelo V. Kitahara. mvkitahara@unifesp.br

James D. Reimer, jreimer@sci.u-ryukyu.ac.jp

Molly Timmers, molly.timmers@noaa.gov

Christopher Meyer, meyerc@si.edu

Forest Rohwer, frohwer@gmail.com

Gustav Paulay, paulay@flmnh.ufl.edu

Peter F. Cowman, peter.cowman@jcu.edu.au

Jennifer Hodge, jhodge@ucdavis.edu

Libby Liggins, l.liggins@massey.ac.nz

Oliver LM, Santavy DL, Bradley P (2016) Developing a multi-stressor gradient model for coral reefs of Puerto Rico. Proceedings of the 13th International Coral Reef Symposium, Honolulu: 245-257

Louis YD, Dyall SD, Bhagooli R (2016**)** Coast-reef scale physiological responses of *Acropora muricata* harboring *Symbiodinium* clade A. Proceedings of the 13th International Coral Reef Symposium, Honolulu: 258-277

Kaullysing D, Gopeechund A, Mattan-Moorgawa S, Taleb-Hossenkhan N, Kulkarni B, **Bhagooli** R (2016) Increased density of the corallivore *Drupella cornus* on *Acropora muricata* colonies overgrown by *Padina boryana*. Proceedings of the 13th International Coral Reef Symposium, Honolulu: 278-294

Developing a multi-stressor gradient model for coral reefs of Puerto Rico

Leah M. Oliver, Deborah L. Santavy, Patricia Bradley

Abstract Coral reefs worldwide are threatened by multiple anthropogenic stressors, yet understanding reef responses to multiple stressor gradients is complicated by interactive stressor effects, co-occurrence of some stressors, and inconsistent data availability. Indirect protection of aquatic life under the US Clean Water Act (CWA) may occur through requirements for effluent discharge permits and provisions for setting chemical and physical criteria based on designated waterbody uses for humans. Biological water quality criteria or "biocriteria" established under the CWA offers a direct means to protect corals. Biocriteria are quantitative thresholds or narrative descriptions of coral reef ecosystem attributes needed to maintain biological integrity. Biocriteria development involves defining the biological community associated with a wide range of ecosystem conditions ranging from a pristine, undisturbed state to severe disturbance by human activities. As part of this process for Puerto Rico, Caribbean coral reef ecosystem experts prioritized anthropogenic stressors to coral reef ecosystems as land-based sources of pollution, fishing pressure, and global climate change-related thermal anomalies. Spatial data representing these stressors were mapped, showing some areas where all three stressors were high and also areas where the magnitude of stressors contrasted. In northeast Puerto Rico, urban development around San Juan resulted in the island's highest watershed development index, which co-occurred with high fishing pressure. In contrast, southwest Puerto Rico had high fishing pressure but low watershed development and ocean temperatures compared to other coastal areas. Narrative descriptions were also developed to incorporate stressors for which spatial data is absent or limited. Future expert workshops will refine this model by developing stressor weighting factors and by considering interactive effects. This conceptual framework will contribute to developing a multi-stressor gradient model for the coral reefs of Puerto Rico, identify data needs, stimulate addition of new spatial data, and generate testable hypotheses to calibrate the stressor-response model.

Keywords: coral reefs, land-based pollution, temperature anomalies, fishing pressure, stressor gradient

Leah M. Oliver, Deborah L. Santavy
US EPA, Office of Research & Development, National Health & Environmental Effects Laboratory, Gulf Ecology Division, 1 Sabine Island Drive, Gulf Breeze, FL 32561

Patricia Bradley
Retired, US EPA, Office of Research & Development, National Health & Environmental Effects Laboratory, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, RI 02882

Corresponding author: Leah M. Oliver, oliver.leah@epa.gov

Introduction

Coral reefs are often found near coasts where multiple anthropogenic stressors co-occur at areas of high human disturbance. Stressors range in scale of influence and relative manageability from point source discharges and unrestrained coastal development to thermal anomalies and ocean acidification stemming from global climate change (Hughes and Connell 1999; Kleypas et al. 1999; Ban et al. 2014). Understanding which human-induced stressors influence important coral reef attributes is critical to effect management actions that maximize benefits to reefs and the valuable ecosystem services they provide. The US Clean Water Act (CWA) establishes a framework for regulating water quality and directs the EPA to set wastewater standards for industry, issue permits for industrial and municipal discharges, and coordinate with state and territorial governments to adopt water quality criteria to protect against harmful effects of pollutants. Chemical and physical criteria are routinely established, yet the CWA also contains a provision for states and territories to set biocriteria, which are desired states of biological resources linked to designated uses (Bradley et al. 2009). Designated uses are the formally promulgated uses for a given waterbody such as drinking water, fishing and fish consumption, swimming, and supporting aquatic life. The CWA requires that water quality be able to support the designated use(s) for a given waterbody. Based on the designated use(s), desired resource conditions may be customized, for example, biocriteria for lower quality “Class C” waters with heavy human impact may allow for some loss of ecosystem structure and function while those for higher quality “Class A” waters could require full ecosystem integrity on par with an undisturbed, undeveloped, and possibly historic condition indicative of a natural or non-degraded state (US EPA 2016). Although it is not necessary to quantify all stressors which impact biological resources, biocriteria development requires development of relevant indicators for both stressors and biological condition and a relationship established between reduced resource condition and increasing human disturbance (Karr and Chu 1997; Fore et al. 2009).

Quantitative relationships between anthropogenic stress and coral reef health have been demonstrated in the Caribbean (Fisher et al. 2008; Oliver et al. 2011; Ennis et al. 2016), Hawaii (Rodgers et al. 2012), and Indonesia (Golbuu et al. 2008), employing biological measures of coral size, taxa richness, and coral cover, and stressor estimates such as distance to disturbance and land-use based watershed indices. These studies establish stressor-response relationships for corals and set the stage for integrated stressor approaches. A conceptual model developed for wetland and stream ecosystems relating biological condition to increasing anthropogenic stressors (Fig. 1) was the basis for engaging Caribbean coral reef ecosystem experts to develop a biological condition gradient (BCG), defining attributes of coral reef ecosystems associated with conditions ranging from pristine to severely altered (Davies and Jackson 2006; Bradley et al. 2014; Santavy et al. 2016). During a structured process to assign biological attributes to different levels of the BCG, discussions included which stressors the experts believed were the

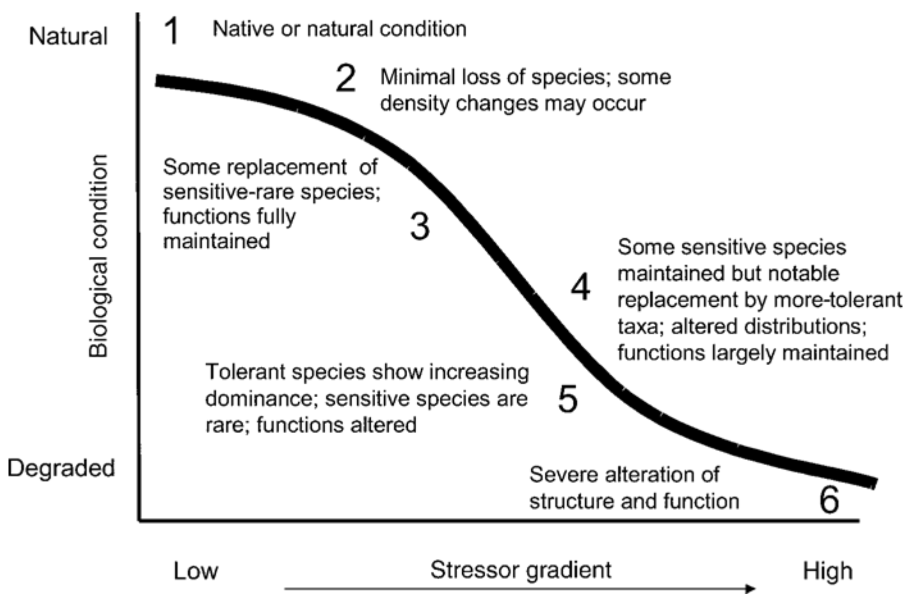

Fig. 1 Conceptual biological condition and stressor gradient model, showing general changes in ecosystem in response to increasing anthropogenic stress. Reprinted from Davies, SP and Jackson SK (2006), The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. Ecological Applications, 16: 1251–1266. doi:10.1890/1051-0761(2006)016[1251:TBCGAD]2.0.CO;2, with permission of the Ecological Society of America

most critical for coral reef ecosystems in Puerto Rico and the Caribbean. Experts identified high sea temperatures and land-based pollution as primary stressors for corals, and fishing pressure and land-based pollution for fishes. As part of the BCG development process in which anthropogenic stressor gradients are characterized and associated with different BCG levels, we sought to develop a conceptual framework for an integrated stressor gradient for Puerto Rico's coral reef ecosystems, incorporating both quantitative data and narrative descriptions.

Materials and methods

Land-Based Sources of Pollution (LBSP)

A Landscape Development Intensity Index (LDI) was calculated as a measure of land-based pollution using the method of Brown and Vivas (2005). The LDI method integrates human impact associated with specific land use/land cover (LULC) types, proportional to cumulative inputs of nonrenewable energy (Emergy). In brief, a 30m-resolution LULC dataset (Homer et al. 2007) was reclassified to Emergy coefficients (Odum 1996) blended from Brown and Vivas (2005) and Florida land use cover and classification systems (Janicki 2013) (see Table 2 in Oliver et al. 2011). LDI values were calculated for coastal Hydrologic Unit Code (HUC)-12 watersheds, and weighted for % LULC. Coastal watershed LDI values were extended into adjacent coastal segments or sea-sheds, by drawing cardinal lines from watershed borders in a 10-km offshore buffer using ArcMap v10. To address dilution of pollutants with increased distance from shore, LDI values were assigned unadjusted to coastal segments 0-2 km from shore, reduced by 50% in adjacent coastal segments 2-7 km from shore, and reduced by 70% in segments 7-10 km from shore.

Thermal anomalies

Satellite-derived, sea-surface temperature anomaly (SSTA) data was obtained from NOAA's Coral Reef Watch website (http://www.coralreefwatch.noaa.gov/satellite/bleaching5km/index.php). Annual composite, 5-km resolution SSTA files included all currently available data from 2014 – present day 2016. Files in NetCDF format were downloaded and converted to raster in ArcMap v10.3. Rasters were cropped to the geographic extent of Puerto Rico and a mean SSTA raster was calculated.

SSTA represents positive or negative deviations from average monthly climatology, which is based on historical records of mean monthly night-time SST values (Liu 2014).

Fishing pressure

Geospatial layers of fishing intensity were obtained from Manoj Shivlani (Shivlani and Koeneke 2011), who estimated commercial Puerto Rico fishing effort based on interviews with fishers. Participants were asked to map fishing areas they used, and the number of trips to each. Total fishing effort is the maximum potential number of trips to grid cells of approximate area of 3.3 km^2 for all gears including nets, lines, traps and dive gears (dive gears include spear guns and hand gathering by skin diving or scuba).

Integrated stressor index

Stressor estimates were combined by first converting the LDI and fishing effort polygon layers into rasters. Raster layers for LDI, fishing and SSTA were re-scaled from 0-1 using a linear function with the lowest values corresponding to 0 and the highest values to 1. Rasters were added using the raster calculator tool in ArcMap v10.3, Spatial Analyst toolbox.

Narrative stressor descriptions

Narrative stressor descriptions were developed for undisturbed (pristine), moderately stressed, and severely degraded states of LBSP, thermal anomalies, and fishing pressure. For LBSP these included land use characteristics for low, medium and high LDI watersheds, other conditions which were not represented by LDI such as runoff-related impaired water quality and sediment resuspension, and land conditions which exacerbate pollutant transport such as soil type and slope. Fishing pressure was described in terms of both the fishing activity and also the resulting change in fish populations which is relevant to the health of associated reef-building corals.

Results

Coastal LDI watershed values ranged from 1.2 – 5.7, with the highest values in North East Puerto Rico watersheds including the city of San Juan, the West coast near Mayaguez, and the South coast near Ponce, Santa Isabel, Salinas and Guayama (Fig. 2a). High LDI values in Northern receiving sea-sheds were driven by adjacent land areas containing dense human population and those in Western and Southern sea-sheds were driven by a combination of population and row crop agriculture.

Mean SSTA (2014 – 2016) for Puerto Rico ranged from 0.29 – 0.87°C, and a pattern of lowest SSTA on the West and South West coasts was observed (Fig. 2b).

Commercial fishing effort was highest on the West coast, Southwest near La Parguera, Cabo Rojo, and Puerto Real; and also around the central North coastal area (Fig. 2c).

Summed, rescaled stressor indices reflected high LDI and fishing pressure near San Juan on the North and South-central coasts, high fishing pressure on Southwest coast and Vieques (Fig. 2d). The West coastal area was intermediate for integrated stressor index but fishing pressure was high in the region.

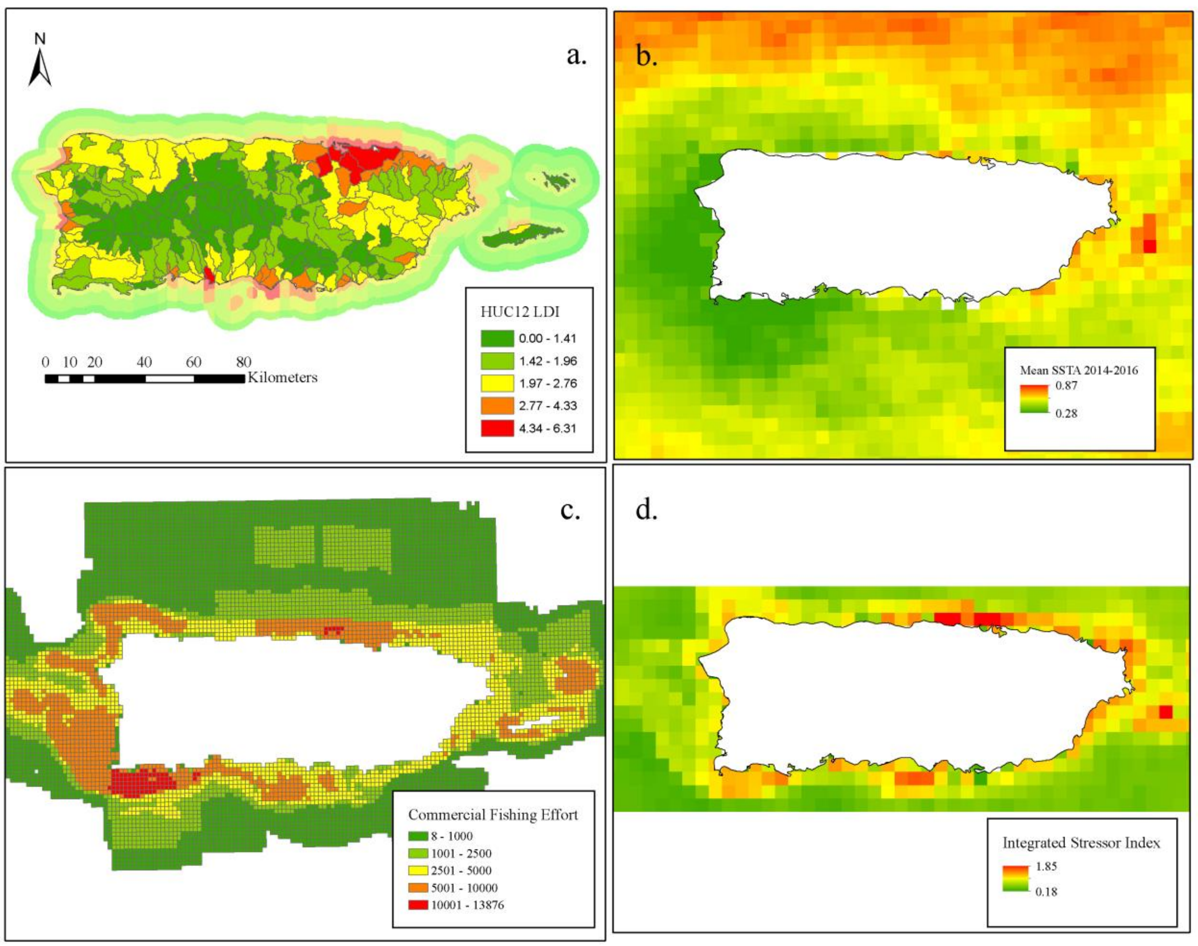

Fig. 2 **a**. Hydrologic Unit Code (HUC12) watersheds of Puerto Rico and associated LDI values. Offshore buffer zones show attenuated LDI value with increased distance from shore. **b**. NOAA Sea Surface Temperature Anomaly (SSTA), mean of monthly composites from 2014-2016. **c**. Total fishing effort modeled as maximum possible trips to each grid cell (Shivlani and Koeneke

Narrative stressor descriptions are presented in Table 1. For LBPS, soil and terrain characteristics which tend to accelerate runoff and increase sediment and pollutant transport to benthic habitats were included. Since the LDI is based on LULC, to avoid redundancy only those additional anthropogenic influences which are not LULC - related were included. Elevated temperature thresholds associated with coral bleaching were derived from literature accounts correlating bleaching with both the magnitude and duration of exposure to elevated sea surface temperature (Eakin et al. 2010; Heron et al., 2016). Fishing pressure was articulated in terms of relative fishing effort which pressures fishery sustainability, and also the resulting fish 2011). **d**. Integrated stressor index was calculated by re-scaling all three stressors (0-1) and summing for a maximum possible value of 3 community expected under varying fishing pressures in order to illustrate the indirect stress to associated corals.

Discussion

Three anthropogenic stressors (land-based sources of pollution, thermal anomalies, and fishing pressure were assembled in a spatially-explicit framework for Puerto Rico coral reef and not fisheries ecosystems, an initial step to support development of biocriteria to protect these unique and important habitats (Fore et al. 2009). Our expectation is that these stressor estimates will be fine-tuned and augmented as additional data becomes available. The LDI index was chosen as a proxy for LBSP, in part due to previous associations with coral condition in St. Croix (Oliver et al. 2011) and with wetland condition in Florida (Brown and Vivas 2005) and Ohio (Mack 2006).

However our narrative description for LBSP highlights land-based stressors which are represented in the LDI. For example, the presence of a wastewater treatment plant or coastal industry is represented in the LDI as a LULC class receiving a high LDI coefficient, but effluents originating from these facilities are not incorporated in LDI. Elevated nutrients are important coral stressors which have been associated with decline of reefs in relatively close proximity to developed coasts (Ennis et al. 2016). The LDI is based on 30-m resolution LULC data circa 2001, but 1-m resolution LULC imagery for Puerto Rico is anticipated in 2016 from the NOAA Coastal Change Analysis Program, allowing finer resolution and more current land cover for new LDI calculations, and possible application of land use changes as an indicator. In the future assumptions regarding the sea-shed transport of land-based pollutants should be refined by adjusting for ocean currents and river flow which affect distance and direction of offshore

Table 1 Narrative descriptions for three stressors representing undisturbed, moderately disturbed and severely disturbed states. For fishing pressure, both fishing activities and resulting fish community are presented. WWTP: Waste water treatment plant, BMP: best management practices

Stressor Level	Land-Based Sources of Pollution	Thermal Anomalies	Fishing Pressure
Undisturbed	Natural landscape conditions present in coastal watersheds. Coastal vegetation such as mangroves and riparian vegetation is intact. Human development absent: no impervious surfaces or facilities such as WWTPs, industries, ports or associated shipping activity. Sediment entry to coastal waters is attenuated by absorbant soil types, presence of coastal vegetation, or both. Area could be Marine Protected Area or Reserve. LDI < 1	Natural temperature regime for the area, no significant departures from normal climatology. DHW remains less than 4°C	Fishing by humans is absent Fish Community: Undisturbed. High diversity in taxa, balanced fish community in terms of size and abundance such that natural trophic interactions are sustained.
Moderately Disturbed	Low to medium density development, coastal industries and/or WWTPs may be present but if so, are compliant with discharge permits, have advanced levels of waste water treatment, and may incorporate biological filtration such as coastal wetlands. Impervious surfaces near the coast are considerable, and along with steep terrain and soils dominated by clays, result in frequent pulses of moderately elevated sediment levels to coastal benthic habitats. Agriculture activity may be broad pasture areas or moderate row crop areas, and BMPs are not universally employed to limit sediment / pollutant transport to marine environment. LDI = 2.01 – 3.0	Departures from normal temperature regime occasionally exceed 4°C-DHW but remain below 8°C-DHW	Fishing activities include a blend of commercial and recreational fishing at levels which are non-threatening to sustainable production. Effective fishing management, enforcement or some combination prevents significant loss of ecosystem functional attributes. Fish Community: Evident changes in structure due to loss of some rare native taxa; shifts in relative abundance of taxa but sensitive-ubiquitous taxa are common and abundant; ecosystem functions are fully maintained through redundant attributes of the system.
Severely Disturbed	Degraded landscape conditions include high percent impervious surface and high-density, near-coastal human development. Near-coastal row crop agriculture lacks BMPs. Sedimentation is severe due to degraded coastal and riparian vegetation and unmitigated land clearing practices, and sediment contains entrained nutrients and other chemical pollutants. Coastal WWTPs lack secondary treatment, and along with industrial discharges, 303(d)[1] listings of impaired water bodies under the CWA are common. Other human influences may include boat traffic in the form of shipping vessels, cruise ships, or recreational vessels which result in sediment resuspension in coastal benthic habitat areas. LDI > 5	Sustained elevated temperature relative to normal, periods exceeding 8°C-DHW	Intense commercial and recreational fishing pressure of reef fish species and pelagic species. Regulations to sustain fishery may be lacking or ignored; enforcement is nonexistent and illegal fishing is common. Gears used include fish traps or others with high bycatch mortality. Fish Community: Low species richness, diversity and abundance compared to other levels. Extremely high densities of tolerant opportunistic species may characterize these systems. Herbivores and apex predators are absent.

[1]Section 303(d) of the US Clean Water Act requires states and territories to submit lists of impaired waters which do not meet water quality standards.

influence, and incorporating shelf bathymetry which affects dispersal of runoff-transported sediment and other pollutants originating on land. Here, we applied simple assumptions of graded influence decay at 2, 7 and 10 km offshore which represent only a coarse estimate.

This analysis used 5-km resolution SSTA data, currently available as annual average composites from 2014 on, pending NOAA's release of additional blended satellite products which will increase retrospective spatial data presented in several ways on NOAA's Coral Reef Watch website. Although SSTA values may be positive or negative, NOAA presents positive deviations or HotSpot values, calculated by subtracting the maximum of monthly mean climatology, and a measure of "Degree Heating Weeks" (DHW) which is the sum of HotSpot values exceeding 1^{o}C for a preceding 12 week period. We demonstrate the potential for SSTA at 5-km resolution to integrate with land-based pollution and fishing data on a reef scale during a time period when thermal-anomaly related coral bleaching was not widespread in Puerto Rico. If the cooler SST values seen in western Puerto Rico (Fig. 2b) persist during a bleaching event, it is possible that corals in those areas might be afforded some degree of protection. Narrative descriptions for thermal anomalies were informed by Eakin et al. (2010) and Heron et al. (2016) who demonstrated threshold DHW values associated with coral bleaching and related mortality, and also the potential for cumulative temperature stress over time to predict coral bleaching susceptibility.

Recreational fishing pressure is thought to be at least as important as commercial landings. We show spatial variation in commercial fishing effort that will be informed by new data when the recreational component of Puerto Rico's fishing law is implemented. In the interim, narrative stressor descriptions were developed for both commercial and recreational fishing activity, including regulatory effectiveness and enforcement capability (Table 1). Indirect effects of fishing pressure on corals were also presented in terms of the associated fish community because with the exception of damage to the reef from fishing gear such as anchors or fishing line, fishing activities do not impact reef corals directly yet lead to ecological dysfunction from overall fishery decline, herbivore reduction and associated algal proliferation on the reef (Hughes et al. 2007). Similarly, model development needs to include indirect effects of climate change-associated anomalies on fish communities, related to bleaching-related coral mortality and loss of reef habitat upon which fish depend for recruitment, refugia, and feeding (Coker et al. 2012; Ainsworth and Mumby 2015).

Simple assumptions (Davies and Jackson 2006) that ecosystem structure and function gradually falter with increased anthropogenic stress represent an accepted general pattern of ecosystem response which can generate testable hypotheses to refine single and cumulative-stressor effects (Hughes and Connell 1999; Ban et al. 2014). An approach to integrate world-scale reef stressors (Halpern et al. 2008; Burke et al. 2011) was used here by summing re-scaled stressor values (Fig. 2d), but future model development needs to consider more complex stressor interactions including weighting, synergistic or antagonistic effects. Observed contrasts in stressor patterns included South West Puerto Rico with low LDI and SSTA, yet high fishing pressure (Fig. 2a, 2b, 2c) A large proportion of Puerto Rico's coral reefs are found in the South West and establishing a no-take reserve has been suggested.

Further development of this multi-stressor model will render it useful to develop biological attributes for BCG levels (US EPA 2016; Santavy et al. in review), inform management decisions, prioritize collection of reef condition data and stressor information, and support stressor-response research studies. Recent guidance for BCG development (US EPA 2016) includes approaches and challenges to defining a generalized multi-stressor axis (x-axis of the BCG, Fig. 1) to represent the cumulative impact of anthropogenic stressors to reef ecosystems ranging from a pristine state to severely disturbed by human activities. Publically available spatial datasets may be employed to represent additional stressors as has been done for the Great Lakes Environmental Indicators project (Danz et al. 2005). Quantitative information on ecosystem condition and anthropogenic stressors for Puerto Rico coral reefs is limited by comparison, but initial steps can be taken. The U.S. Virgin Islands government has identified coral reefs and reef functions as designated uses under the CWA and defined biological integrity in a narrative context (USVI 2010). The foundation exists for Puerto Rico to take similar actions for setting condition thresholds or biocriteria, to protect its valuable coral reefs.

Acknowledgements

We acknowledge Bill Fisher (US EPA Office of Research and Development, Susan Jackson (US EPA Office of Water), Manoj Shivlani (who generously provided Puerto Rico fishing pressure GIS layers), and Amy Smith (US EPA Student Services contractor, for GIS assistance). David Kline (Session No. 36 chair, ICRS 2016) and 2 anonymous reviewers provided suggestions which greatly improved the manuscript.

References

Ainsworth CH, Mumby PJ (2015) Coral-algal phase shifts alter fish communities and reduce fisheries production. Glob Chang Biol 21:165-172

Ban SS, Graham NAJ, Connolly S (2014) Evidence for multiple stressor interactions and effects on coral reefs. Glob Chang Biol 20:681-697

Bradley P, Fisher W, Bell H, Davis W, Chan V, LoBue C, Wiltse W (2009) Development and implementation of coral reef biocriteria in U.S. jurisdictions. Environ Monit Assess 150:43-51

Bradley P, Santavy DL, Gerritsen J (2014) Workshop on Biological Integrity of Coral Reefs, August 21-22, 2012, Caribbean Coral Reef Institute, Isla Magueyes, La Parguera, Puerto Rico. US Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, Narragansett, RI. EPA/600/R-13/350

Brown MT, Vivas MB (2005) Landscape development intensity index. Environ Monit Assess 101:289-309

Burke L, Reytar K, Spalding M, Perry A (2011) Reefs at risk revisited. World Resources Institute, Washington, DC

Coker DJ, Graham NAJ, Pratchett MS (2012) Interactive effects of live coral and structural complexity on the recruitment of reef fishes. Coral Reefs 31:919-927

Danz NP, Regal RR, Niemi GJ, Brady VJ, Hollenhorst T, Johnson LB, Host GE, Hanowski JM, Johnston CA, Brown T, Kingston J, Kelly JR (2005) Environmentally stratified sampling design for the development of Great Lakes environmental indicators. Environ Monit Assess 102:41-65

Davies SP, Jackson SK (2006) The biological condition gradient: A descriptive model for interpreting change in aquatic ecosystems. Ecol Appl 16:1251-1266

Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, Alvarez-Filip L, Baca B, Bartels E, Bastidas C, Bouchon C, Brandt M, Bruckner AW, Bunkley-Williams L, Cameron A, Causey BD, Chiappone M, Christensen TRL, Crabbe MJC, Day O, de la Guardia E, Diaz-Pulido G, DiResta D, Gil-Agudelo DL, Gilliam DS, Ginsburg RN, Gore S, Guzmán HM, Hendee JC, Hernández-Delgado EA, Husain E, Jeffrey CFG, Jones RJ, Jordán-Dahlgren E, Kaufman L, Kline DI, Kramer P, Lang JC, Lirman D, Mallela J, Manfrino C, Maréchal J-P, Marks K, Mihaly J, Miller WJ, Mueller EM, Muller EM, Orozco Toro CA, Oxenford HA, Ponce-Taylor D, Quinn N, Ritchie KB, Rodriguez S, Rodriguez Ramirez A, Romano S, Samhouri JF, Sánchez JA, Schmahl GP, Shank BV, Skirving WJ, Steiner

SCC, Villamizar E, Walsh SM, Walter C, Weil E, Williams EH, Woody Roberson K, Yusuf Y (2010) Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. PLoS ONE 5:e13969 [doi:10.1371/journal.pone.0013969]

Ennis RS, Brandt ME, Wilson KR, Smith TB (2016) Coral reef health response to chronic and acute changes in water quality in St. Thomas, United States Virgin Islands. Mar Pollut Bull 111:418-427

Fisher WS, Fore LS, Hutchins A, Quarles RL, Campbell JG, LoBue C, Davis WS (2008) Evaluation of stony coral indicators for coral reef management. Mar Pollut Bull 56:1737-1745

Fore LS, Karr JR, Fisher WS, Bradley P, Davis WS (2009) Heeding a call to action for US coral reefs: The untapped potential of the Clean Water Act. Mar Pollut Bull 58:1421-1423

Golbuu Y, Fabricius K, Victor S, Richmond RH (2008) Gradients in coral reef communities exposed to muddy river discharge in Pohnpei, Micronesia. Estuar Coast Shelf Sci 76:14-20

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R, Watson R (2008) A global map of human impact on marine ecosystems. Science 319:948-952

Heron SF, Johnston L, Liu G, Geiger EF, Maynard JA, De La Cour JL, Johnson S, Okano R, Benavente D, Burgess TFR, Iguel J, Perez D, Skirving WJ, Strong AE, Tirak K, Eakin CM (2016) Validation of reef-scale thermal stress satellite products for coral bleaching monitoring. Remote Sens 8(1): 59 [doi: 10.3390/rs8010059]

Homer C, Dewitz J, Fry J, Coan M, Hossain N, Larson C, Herold N, McKerrow A, VanDriel JN, Wickham J (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogramm Eng Remote Sensing 73:337-341

Hughes TP, Connell JH (1999) Multiple stressors on coral reefs: A long-term perspective, Limnol Oceanogr 44:932-940

Hughes TP, Rodrigues MJ, Bellwood DR, Ceccarelli D, Hoegh-Guldberg O, McCook L, Moltschaniwskyj N, Pratchett MS, Steneck RS, Willis B (2007) Phase shifts, herbivory, and the resilience of coral reefs to climate change. Curr Biol 17:360-365

Janicki T (2013) Land development index (LDI) and cross-walk of Florida land use cover and classification system (FLUCCS) codes to LDI values. Attachment A in: Central Florida Water Initiative's Environmental Measures Team, Development of Environmental Measures for Assessing Effects of Water Level Changes on Lakes and Wetlands in the Central Florida Water Initiative Area, Final Report November 2013

Karr JR, Chu EW (1997) Biological Monitoring and Assessment: Using Multimetric Indexes Effectively. EPA 235-R97-001, University of Washington, Seattle

Kleypas JA, Buddemeier RW, Archer D, Gattuso J-P, Langdon C, Opdyke BN (1999) Geochemical consequences of increased carbon dioxide on coral reefs. Science 284:118-120

Liu G, Heron SF, Eakin CM, Muller-Karger FE, Vega-Rodriguez M, Guild LS, De La Cour JL, Geiger EF, Skirving WJ, Burgess TFR, Strong AE, Harris A, Maturi E, Ignatov A, Sapper J, Li J, Lynds S (2014) Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA coral reef watch. Remote Sens 6:11579-11606, doi:10.3390/rs61111579

Mack JJ (2006) Landscape as a predictor of wetland condition: an evaluation of the Landscape Development Index (LDI) with a large reference wetland dataset from Ohio. Environ Monit Assess 120:221-241

Odum HT (1996) Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York, 370 pp

Oliver LM, Lehrter JC, Fisher WS (2011) Relating landscape development intensity to coral reef condition in the watersheds of St. Croix, US Virgin Islands. Mar Ecol Prog Ser 427: 293-302

Rodgers KS, Kido MH, Jokiel PL, Edmonds T, Brown, EK (2012) Use of integrated landscape indicators to evaluate the health of linked watersheds and coral reef environments in the Hawaiian Islands. Environ Manage 50:21-30

Santavy DL, Bradley P, Gerritsen J, Oliver LM (2016) The biological condition gradient, a tool used for describing the condition of US coral reef ecosystems. Proceedings of the 13th International Coral Reef Symposium, Honolulu: 552-563

Shivlani M, Koeneke R (2011) Spatial characterization of artisanal fisheries in Puerto Rico: Geographic information systems (GIS) approach for assessing the regional effort and landings. Proc of the 63rd Gulf and Caribb Fish Inst., Nov 1-5, 2010

US EPA (2016) A Practitioner's Guide to the Biological Condition Gradient: A Framework to Describe Incremental Change in Aquatic Ecosystems. EPA 842-R-16-001, Washington, DC

USVI (US Virgin Islands) (2010) United States Virgin Islands 2010 Revisions to: Water Quality Standards Title 12, Chapter 7, Government of the Virgin Islands, Department of Planning and Natural Resources, Division of Environmental Protection, 22 pp