Mapping climate resilience and vulnerability for the coral reefs of Guam to aid in prioritizing restoration sites

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Final Report

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Brief Project Summary: Climate vulnerability information is rarely available to reef and fisheries managers as spatial data layers that can be included in management planning and decision-making. Climate vulnerability can be a useful proxy for near and long-term likelihood coral transplants will survive. Since climate vulnerability information is rarely available, the process of targeting reef restoration efforts almost never accounts for climate vulnerability. Our team is generating information on climate change, resilience, and human impacts, and then combining these inputs to assess climate vulnerability in Guam. Site-level results will be interpolated to produce *spatially continuous estimates of climate vulnerability for all coral reef habitat in Guam*. Reef areas will be prioritized with resource managers and reef stakeholders in Guam by discussing and combining these datasets: coral reef climate vulnerability, an aggregate index for reef condition, social vulnerability information, and local knowledge of reef accessibility, economic and cultural value, and permitting regulations. The process of prioritizing areas for restoration proposed here ensures strategic planning precedes outplanting. This is a highly collaborative project inclusive of the agencies involved in coral reef management in Guam.

Project Results

Project objective 1. *Interpolate resilience assessment results to produce spatially continuous maps of relative resilience of coral reefs to climate change for all coral reef habitat around Guam.*

Local (University of Guam with NOAA CRCP) and regional (CRCP NCRMP) monitoring programs that survey coral reefs in Guam could never visit all of the reef habitat around Guam. Monitoring staff necessarily survey a set number of sites at the frequency their resources for collecting, compiling and reporting on monitoring data will allow. Where monitoring programs have excellent spatial coverage, and this is the case for Guam, interpolation can be used to generate information on the potential reef condition and resilience of reef areas between surveyed points. The results are spatially continuous estimates of reef condition and relative resilience that can ensure all reef areas (shallow and deep) are considered in management planning exercises. The interpolated data layer can be used with popular conservation software such as Marxan to optimize marine management and MPA network design.

The local monitoring program in Guam visited 20 shallow sites in 2016 and this project team conducted an assessment of relative resilience to climate change. We expanded the 2016 sitebased resilience assessment to include data collected since 2016, to expand spatial coverage of shallow reefs. Resilience assessment methods will follow what is shown in our NOAA CRCP TM 29 (Maynard et al. 2017a), and in the CRCP-supported *Guide to Assessing Coral Reef Resilience for Decision Support* (Maynard et al. 2017b).

We combined the local-monitoring data (/resilience assessment results) from shallow reef areas (5-11 m) with the towed-diver data collected under NOAA NCRMP (see Figures 1-3). An inverse distance weighted interpolation was then completed for each dataset (each depth) to predict values for reef condition and resilience for unmeasured locations/reef areas for both depths.

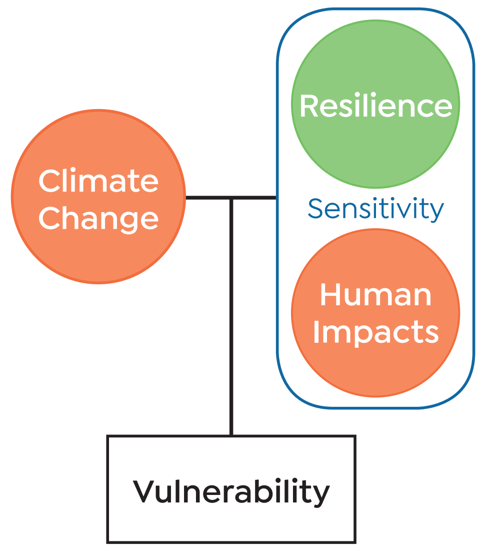
Inverse distance weighted (IDW) interpolation explicitly makes the assumption that places that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. The measured values closest to the prediction location have more influence on the predicted value than those farther away. IDW assumes that each measured point has a local influence that diminishes with distance. It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance, hence the name inverse distance weighted. Weights are proportional to the inverse of the distance (between the data point and the prediction location) raised to the power value p. As a result, as the distance increases, the weights decrease rapidly. The rate at which the weights decrease is dependent on the value of p. If $p = 0$, there is no decrease with distance, and because each weight λi is the same, the prediction will be the mean of all the data values in the search neighborhood. As p increases, the weights for distant points decrease rapidly. If the p value is very high, only the immediate surrounding points will influence the prediction. The p value will be explored in our drafts of the IDW interpolation data layer, but likely be very high, ensuring only immediately surrounding reef areas are used to predict condition and relative resilience in unmeasured areas.

<u>Spatial patterns</u>: Anthropogenic stress is lowest at the coral reefs in the far north and far south of Guam and highest mid-island on the east and west sides. Exposure to climate change is projected to be lowest (meaning annual severe bleaching (ASB) is projected to occur latest) on the reefs in the far north and highest (meaning ASB is projected to occur soonest) on the reefs mid-island on the east and west sides. Spatial patterns in relative resilience potential are very similar for the shallow (3-7 m) and deep (7.1-12 m) sites. Resilience is relatively high at the reefs in the northwest and far north and relatively low at the reefs in the southwest. Results from Objective 1 are shown in the coming pages as Figure 1 (maps of exposure and anthropogenic stress for long-term monitoring sites in Guam) and Figure 2 (maps of relative resilience potential).

Project objective 2. *Assess relative climate vulnerability for all coral reef habitat in Guam by combining resilience, climate exposure, and anthropogenic stress information.*

Changes in coral reef condition and ecosystem service provisioning over the coming decades will be determined by coral reef vulnerability, which is only partially determined by reef resilience. Coral reef vulnerability to climate change depends on the frequency and severity of climate disturbances, such as coral bleaching. Vulnerability also depends on sensitivity, which is a combination of coral reef resilience and whether resilience is compromised by human impacts.

This proposed vulnerability assessment framework (see right) is an adapted version of a vulnerability assessment framework first published in Turner et al. (2003), and then widely adopted by the Intergovernmental Panel on Climate Change. The version shown here and described in the paragraph above excludes adaptive capacity, which would typically moderate vulnerability (greater the adaptive capacity, the lower the vulnerability, everything else being equal). The adaptive capacity term is excluded because spatial variation in adaptive capacity of coral reefs (the reefs, not nearby human communities) is poorly understood. As an unknown for coral reefs in Guam, adaptive capacity is removed from the proposed assessment framework. This follows a vulnerability assessment framework this project team published in Johnson et al. (2016).



Vulnerability is relatively low in the far north and at a site in the far south. Vulnerability is relatively high mid-island on the east and west sides.

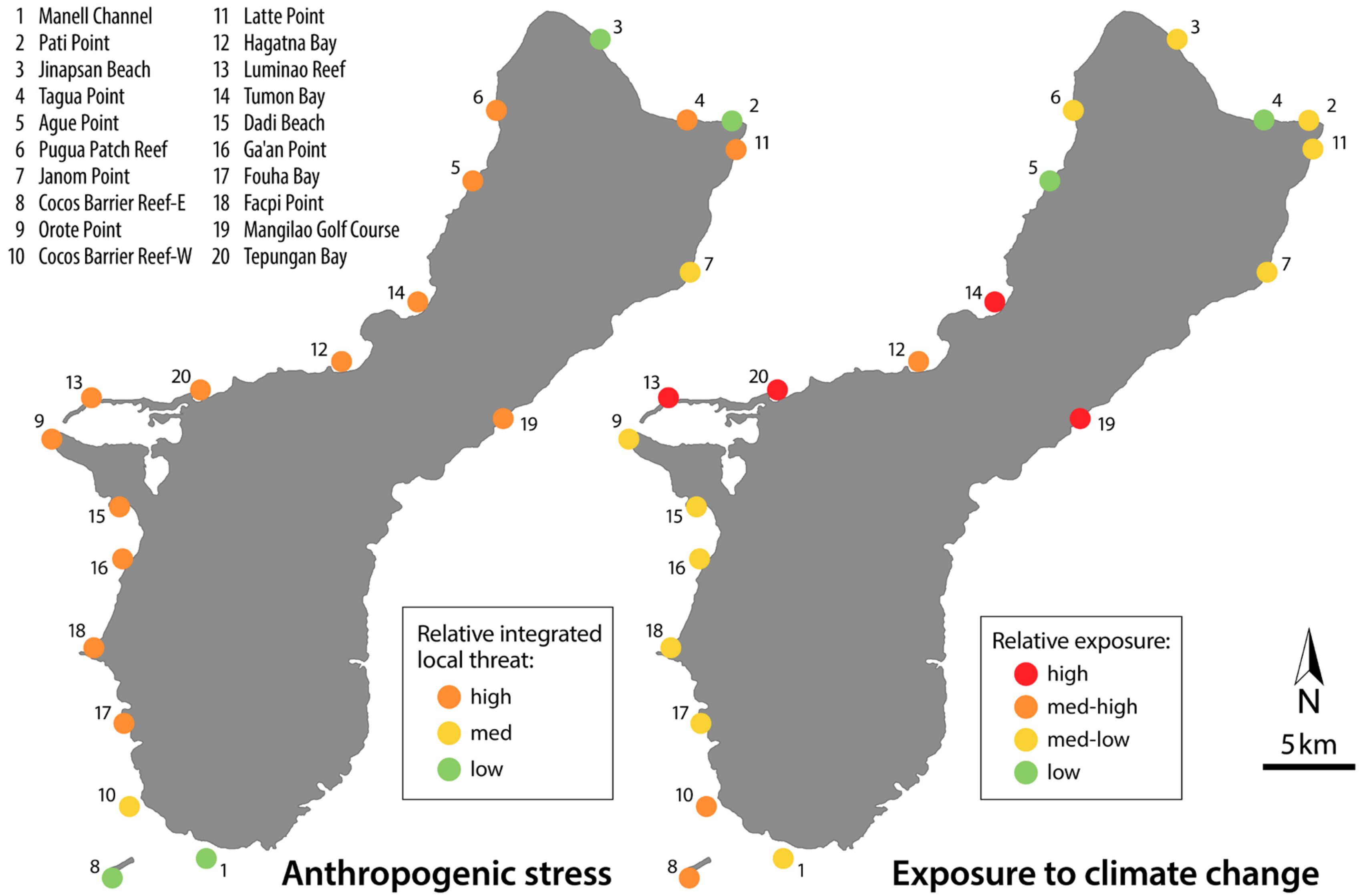


Figure 1. Anthropogenic Stress (from Reefs at Risk Revisited; Burke et al. 2011) and projected future exposure to climate change under business-as-usual fossil-fuel-aggressive emissions scenario RCP8.5.

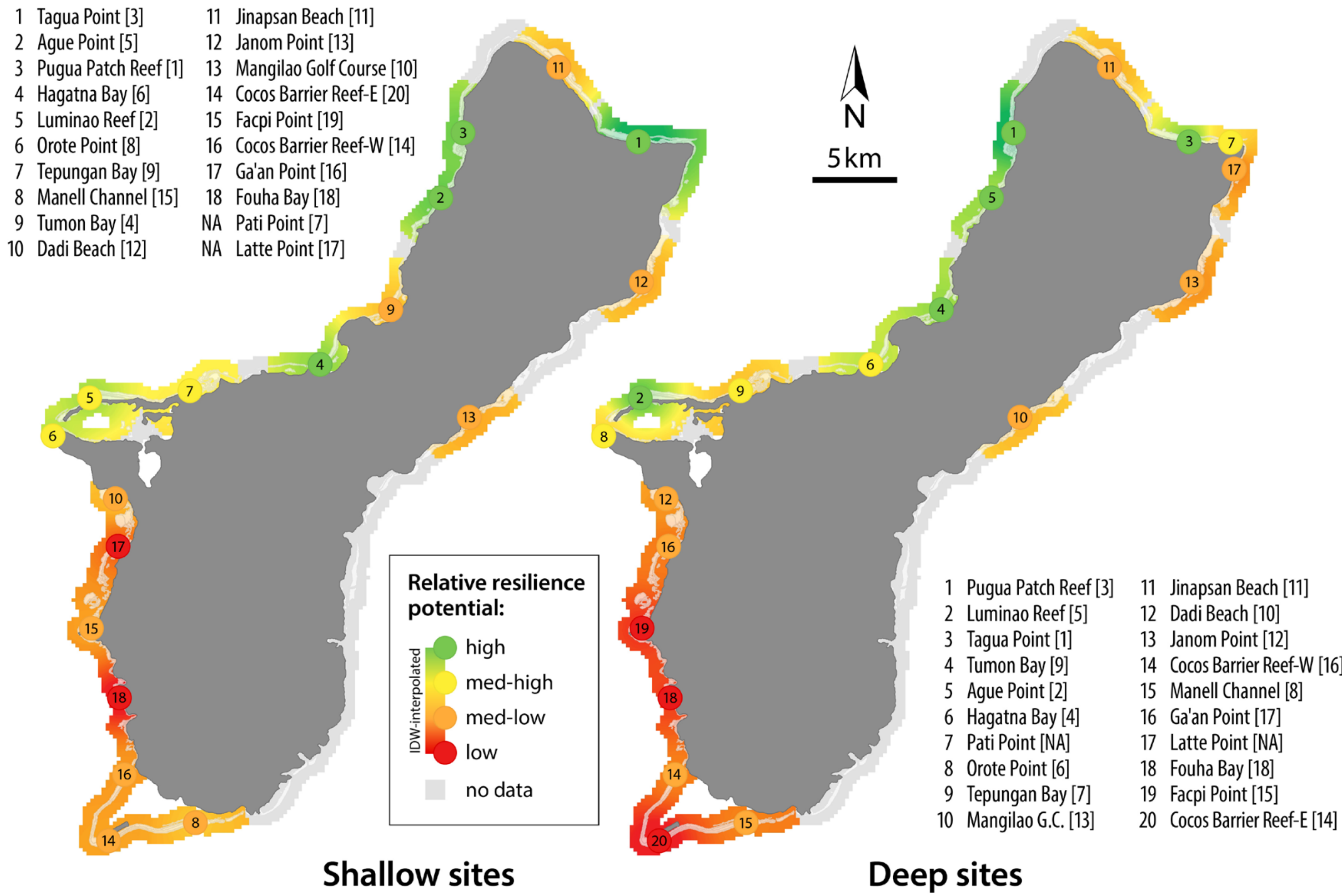


Figure 2. Relative resilience potential of shallow and deep sites in Guam; shown with IDW interpolation.

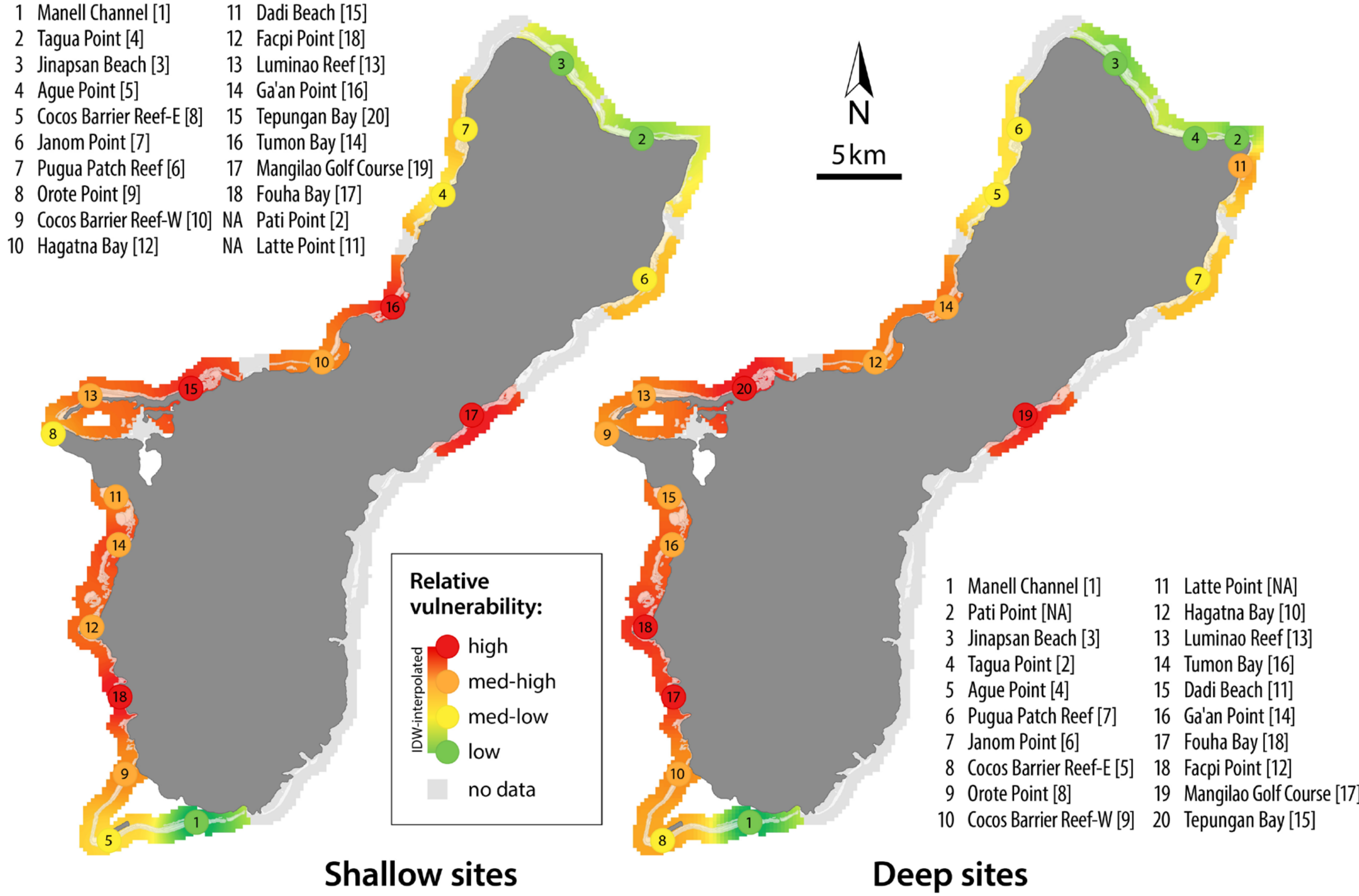


Figure 3. Relative vulnerability to climate change at shallow and deep sites in Guam; here, relative vulnerability is a function of anthropogenic stress, projected future exposure to bleaching conditions (see Figure 1), and relative resilience (see Figure 2).

Project objective 3. *Identify reef restoration priority areas based on reef climate vulnerability, social vulnerability, patterns in the severity of human impacts on reefs, economic and cultural value, and access.*

The project team collaborated with the Restoration Planning Team in March and April of 2020 to identify target areas for reef restoration. We needed to combine the vulnerability assessment outputs from Objectives 1 and 2 with other indicators identified with the Restoration Planning Team in Guam. The Planning Team in Guam included this project's leaders with Laurie Raymundo (University of Guam), Kitty Courtney (TetraTech), Jordan West (US EPA), Cherie Wagner (TNC), David Burdick (NOAA), Marie Auyong (NOAA), Jesse Cruz (Guam EPA), and Frank Roberto (Guam DOAG). Whitney Hoot and Laurie Raymundo were our primary project collaborators and we co-developed a site prioritization analysis with them for restoration on the reef flats of Guam. The text below is a summary of this broader Guam Restoration Planning Team's description of our group's work towards prioritizing restoration sites.

The team discussed a list of suggested indicators provided by this project leader. The team considered what was most important the context of restoration work and came up with a list of 14 indicators to use for systematic prioritization of restoration sites. There were seven biological/ecological indicators: water quality, herbivore biomass, coral cover, coral diversity, abundance of nuisance species, availability of suitable substrate, and presence of coral disease. There were seven socioeconomic indicators: accessibility, proximity to nursery, reef value, potential for partnerships, level of management, availability of relevant data, and whether the site is a current or planned restoration site.

The team then established a scale for each indicator - generally, they are low to high, with 1 being low and 3 being high, but some are inverse - for example, high (1) to low (3) for coral disease and abundance of nuisance species. This sets a consistent uni-directional scale where the lowest score is negative/"bad" and the highest score is positive/"good" (see table below, assembled by the Guam Restoration Planning Team with this project leader).

INDICATOR (blue = bio/eco, green = socio-econ)	**EXPLANATION**	**SCALE**
Water quality	Nutrients, silt/sediment	1 = poor/low, 2 = moderate, 3 = good/high
Herbivore biomass		1 = low, 2 = moderate, 3 = high
Coral cover		1 = low, 2 = moderate, 3 = high
Coral diversity		1 = low, 2 = moderate, 3 = high
Nuisance species abundance	Nuisance algae and shading macroalgae, cyanobacteria, Terpios sponge, coral predators	1 = high, 2 = moderate, 3 = low
Availability of suitable substrate	Substrate where restoration could occur, depth also considered	1 = low, 2 = moderate, 3 = high
Coral disease		1 = high, 2 = moderate, 3 = low
Already an existing or planned restoration site		1 = no, 3 = yes
Accessibility	Distance from staff offices, UOG Marine Lab; restrictions for access (e.g. military)	1 = difficult/low, 2 = moderate, 3 = easy/high
Proximity to nursery	Based on two existing nurseries (In Piti and Malesso Lagoon)	1 = far, 2 = moderate, 3 = close
Level of management	Marine preserve status, in NPS area, etc., level of enforcement of regs	1 = low, 2 = moderate, 3 = high
Reef value (tourism, fisheries)	Tourism, fisheries, cultural value, coastal protection	1 = low, 2 = moderate, 3 = high
Potential for partnerships		1 = low, 2 = moderate, 3 = high
Availability of data		1 = low, 2 = moderate, 3 = high

After developing our list of indicators and establishing scales, the team individually reviewed and scored each site for each indicator. After all sites were scored for the 14 indicators, we reconvened and discussed the rankings. We discussed and reassessed the values any time the range of scores for each indicator was greater than 1. Following these discussions, we had a mean value for each indicator for each site to inform our site prioritization. The team then individually scored the indicators according to how we ranked their importance for restoration site selection: 1 = low importance, 2 = moderate importance, 3 = high importance, 4 = very high/highest importance. As with the scoring of indicators, we met and discussed all indicators where the range of the score was greater than 1 and then readjusted our values after reaching consensus.

We used our indicator scores ("raw weights") to create a scaled weighting system for the indicators. We normalized the mean scores from 0-1. Then we multiplied the score for each indicator for each site by the indicator's weight (see "Summary_NormRank" - scroll to column Q). The top seven sites are highlighted in blue. Other weighting systems were examined, but did not change the rankings significantly. The table below shows the normalized rankings for the 14 indicators and the top 7 sites. The Planning Team is still considering those 7 and deciding where reef restoration will occur in the coming 1-2 years.

Site	H2O qual	Herb bio	Cor cov	Cor div	Nuis spp	Sub avail	Cor dis	Curr/plan'd	Access	Prox nur	Lev mgt	Reef val	Pot part	Data avail
Tumon Bay reef flat	2.00	3.00	2.88	2.33	1.80	3.00	1.75	3.00	2.90	1.70	2.60	3.00	2.70	3.00
Asan Piti reef flat (incl. Piti east)	2.00	2.75	2.50	2.50	1.88	2.67	2.50	3.00	2.10	2.80	2.80	3.00	3.00	2.50
Piti Bomb Holes reef flat	2.00	2.75	2.75	2.00	1.25	3.00	1.50	1.00	3.00	3.00	2.80	3.00	2.80	2.75
Tepungan Channel - Piti	2.00	2.63	1.75	1.67	1.50	2.00	3.00	3.00	3.00	2.80	2.50	2.20	2.30	2.25
Achang reef flat	2.00	2.25	2.83	2.50	2.33	3.00	3.00	3.00	1.40	2.00	1.30	1.80	2.20	3.00
Ritidian closed reef flat	3.00	2.50	2.25	2.50	1.88	2.33	2.25	1.00	1.30	1.00	2.80	2.40	2.80	1.88
Ritidian open reef flat	3.00	1.88	2.33	2.75	2.00	1.50	2.50	1.00	1.80	1.00	2.00	2.80	2.80	1.13
Malesso Pier reef flat/rim	1.00	1.50	2.25	1.33	2.33	2.00	2.00	3.00	2.90	2.80	1.20	2.30	2.80	1.75
Babi Island reef flat (in Malesso Lagoon)	2.00	1.88	1.83	1.75	2.00	2.75	3.00	3.00	1.50	1.75	1.25	1.75	2.25	1.75
Family Beach reef flat	2.00	2.06	2.75	2.00	2.00	2.00	2.00	1.00	2.70	1.20	1.50	2.30	1.75	1.50
Tanguisson reef flat	2.50	2.15	1.88	2.00	2.00	1.50	1.50	1.00	3.00	1.00	1.30	2.00	1.00	2.75
Urunao reef flat (near Ritidian)	3.00	2.00	2.00	1.50	2.50	1.50	2.00	1.00	1.13	1.00	2.00	2.30	2.10	1.00
West Hagatna reef flat	2.00	1.25	1.63	1.75	1.33	2.50	2.00	1.00	2.80	1.80	1.20	1.70	1.00	3.00
Agat Cemetery reef flat	1.00	1.20	1.88	1.83	1.75	2.33	2.50	1.00	3.00	1.20	1.20	1.70	2.20	2.00
Luminao reef flat	2.00	1.50	2.83	1.50	1.67	2.00	1.50	1.00	1.80	1.40	1.10	1.70	1.40	3.00
Ipan reef flat	1.50	1.25	1.38	1.33	2.17	1.83	1.50	3.00	2.88	1.20	1.00	2.00	1.50	1.75
Sharks Hole reef flat	2.50	1.75	2.00	2.67	2.00	2.00	1.50	1.00	1.25	1.00	1.50	1.63	1.00	1.63
Sasa Bay reef flat	1.00	2.00	1.25	1.50	1.50	1.00	2.00	1.00	1.90	1.20	2.60	1.00	2.00	1.50
Alutom south reef flat (Agat)	2.00	1.13	1.67	1.00	1.57	1.50	3.00	1.00	1.90	1.20	1.00	1.00	1.38	1.75
Dadi Beach reef flat	1.00	1.67	1.25	1.00	2.00	2.00	2.00	1.00	1.50	1.20	1.70	1.10	1.75	1.00

Project objective 4*. Communicate project results to the scientific and management community within Guam, to NOAA CRCP staff at headquarters in Silver Spring, MD, and nationally and internationally.*

We communicated extensively with the Restoration Planning Team in Guam from March to May of 2020 to complete the site prioritization analysis for reef restoration in Guam. The results were then shared with the Restoration Center (including Lani Watson and Shannon Ruseborn) in April and May of 2020. Parts of these results and this process were then published within *A Manager's Guide to Coral Reef Restoration Planning and Design*. This project leader and members of the Guam Restoration Planning Team are co-authors and contributors to the Guide, which was published as NOAA CRCP Tech Memo #36 in mid-October, 2020.

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