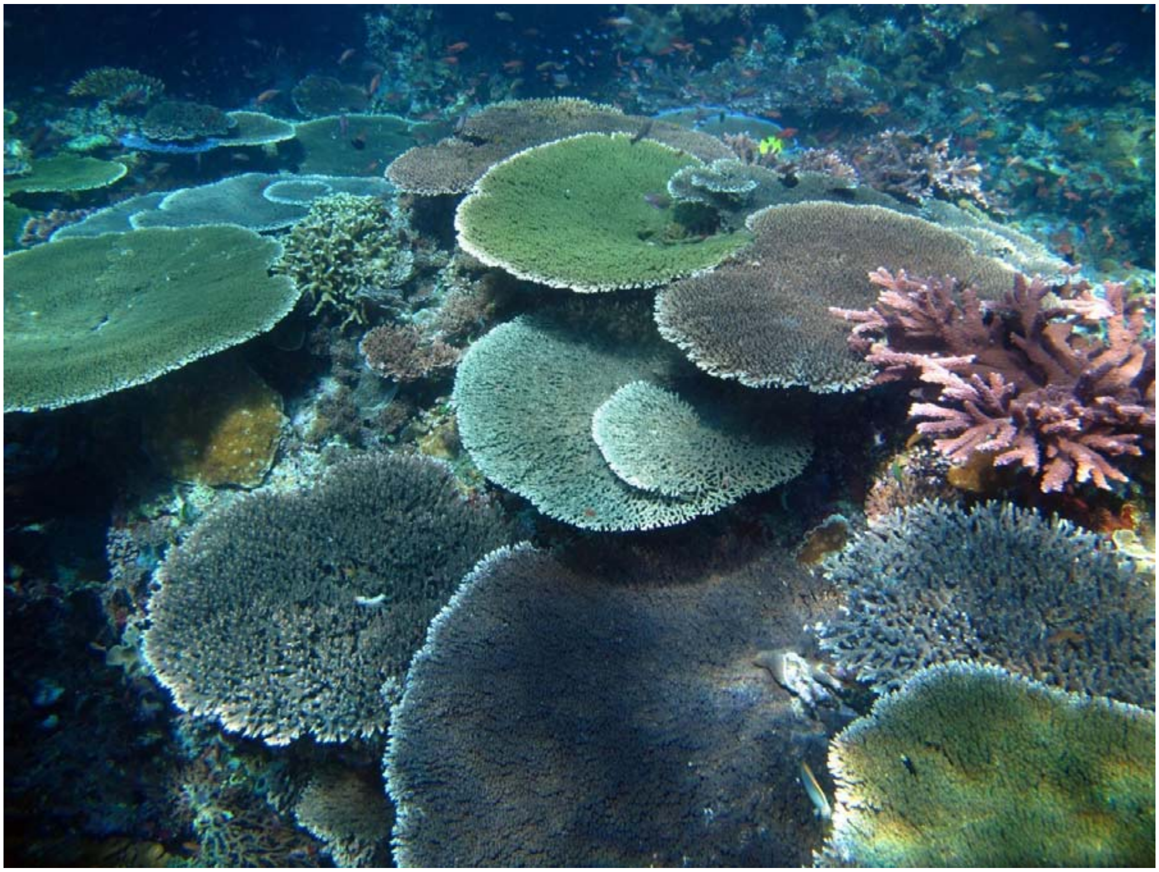
HOW-TO-GUIDE

FOR CONDUCTING RESILIENCE ASSESSMENTS



Contribution to "Integrating reef resilience and climate change vulnerability into protected area design and management in Palau and greater Micronesia." Report prepared for the Western Pacific Coral Reef Institute, University of Guam, September 2012.

Jeffrey Maynard[1,2] and Lizzie Mcleod[3]

[1]Centre de Recherches Insulaires et Observatoire de l'Environnement, Centre National de la Recherche Scientifique-Ecole Pratique des Hautes Etudes Papetoai, Moorea, Polynesie Francaise; [2]SymbioSeas, Wilmington NC 28409, USA; [3]The Nature Conservancy, Texas 78749, USA

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Introduction

Identifying and protecting coral reef ecosystems that are likely to be resilient in the face of climate change and other human stressors is a priority for marine conservation managers. The identification and incorporation of sites with high resilience potential into networks of marine protected areas (MPAs) is an important management strategy, but the ability to do so is limited by a lack of guidance for reef managers. Identifying resilient sites and assessing human stressors has huge potential to inform management decisions that can give reefs the best chance of coping with climate change (Maynard et al. 2010). Tools that help managers to determine which human stressors are responsible for a reef's susceptibility to and recovery from stress can help managers prioritize actions to control such stressors.

Resilience assessments can help managers to assess the relative resilience of coral reef sites in a management area. They can help to identify management strategies that result in the greatest improvement in the resilience of priority sites, and provide information to adaptively manage coral reefs in response to major disturbances, such as bleaching events.

The following types of information may result from a resilience assessment:

- The percentage of and spatial distribution in low, medium and high resilience sites.
- The range in resilience potential across the area; resilience potential may vary greatly amongst sites in your management area or could be very similar throughout the area.
- The sites most and least affected by anthropogenic stressor(s) that managers can address through local or broad-scale actions.
- The primary drivers of differences in resilience potential at sites in the area; i.e., which factors vary at your sites and which do not.
- Spatial variability in factors that contribute to bleaching resistance and to the processes that support recovery following all disturbances.

Information resulting from a resilience analysis has a greater likelihood of influencing management decisions if resilience assessments are well-timed and include managers in the data collection and/or analysis process. For example, a well-timed resilience assessment may be conducted when the results can be directly incorporated into a management decision-making process, such as the zoning or re-zoning of an MPA or MPA network.

Selecting indicators

A first step in undertaking a resilience analysis is to compile a list of the variables or 'indicators' to be included in the analysis. Resilience indicators are variables that can be measured or assessed that relate either directly or indirectly to the likelihood that a coral reef ecosystem will withstand or tolerate a disturbance ('resistance' here), or recover following a disturbance. Indicators used to assess the resilience of coral reef ecosystems can be broadly classified as relating to the physical environment, the ecology, and anthropogenic activities.

The focus of most published protocols designed to assess coral reef resilience (Obura and Grimsditch 2009; Maynard et al. 2010) has been on coral reefs, and not on other resident invertebrates or closely associated fish and fish communities (but see Green and Bellwood 2009). Recently, managers recognize the value of assessments that focus on key ecological processes essential for maintaining reef resilience (Green and Bellwood 2009). Indicators that assess key ecological processes and functional groups that support these include: coral population dynamics (size structure and patterns of recruitment); factors affecting coral recruitment and survivorship (e.g., water quality, benthic communities, such as macroalgae); and factors affecting the establishment and growth of macroalgal communities, particularly functional groups of herbivorous fishes (Green and Bellwood 2009).

Helpful resources for identifying resilience indicators

- IUCN's Resilience Assessment of Coral Reefs (Obura and Grimsditch 2009) contains a list of 61 resilience indicators grouped into 15 different factor groupings (http://cmsdata.iucn.org/downloads/resilience_assessment_final.pdf).
- Maynard et al. (2010) contains a sub-set (30) of IUCN's 61 indicators.
- McClanahan et al. (2012) identified 30 indicators based on Obura and Grimsditch (2009) and Maynard et al. (2010). To prioritize key resilience indicators for coral reef managers, a group of 28 scientists and managers working across all reef regions scored each of these 30 indicators for perceived importance (1-10) to both resistance and recovery, empirical evidence linking the variable to resilience (-5 to 5) from the perspective of resistance and recovery, and feasibility of measurement (1-10) (http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0042884). The list of resilience indicators and the average (+ 1 SE) scores for all variables for perceived importance, empirical evidence, and feasibility of measurement is shown below (Table 1). A site selection framework is proposed within the paper that assumes only the variables with high perceived importance and strong empirical evidence that can be feasibly measured/assessed should be included in a resilience analysis. The top ten for perceived importance and empirical evidence yielded a list of 11 variables or 'indicators': coral diversity, bleaching resistance, recruitment, coral disease, macroalgae cover, herbivore biomass, temperature variability, anthropogenic physical impacts, nutrient input, sedimentation, and fishing pressure (See Appendix 1 for how indicators influence resistance and recovery).

Table 1. Scaled importance of resilience indicators from McClanahan et al. (2012).

Ecological factor	Perceived importance (0 to 10)			Scientific evidence (−5 to +5)			Feasibility (0 to 10)
	Resilience	Resistance	Recovery	Resilience	Resistance	Recovery	
(1) Resistant coral species	**15.57**	**8.70**	**6.87**	**7.15**	**4.07**	**3.07**	**8.04**
(2) Temperature variability	**13.96**	**8.14**	5.82	**6.14**	**3.64**	2.50	**7.71**
Stress-resistant symbionts	**13.39**	**7.75**	5.64	**5.36**	**3.36**	2.00	3.19
(3)Nutrients(pollution)	**13.25**	**6.04**	**7.21**	**5.59**	**2.44**	**3.15**	5.63
(4) Sedimentation	**12.63**	**5.59**	**7.04**	**4.78**	**2.20**	**2.58**	6.73
(5) Coral diversity	**12.43**	**6.04**	6.39	4.11	**2.04**	2.07	**7.07**
(6) Herbivore biomass	**11.75**	4.29	**7.46**	**4.96**	1.64	**3.32**	**7.44**
(7) Physical human impacts	**11.67**	4.89	6.78	**4.81**	**1.96**	**2.85**	6.38
(8) Coral disease	**11.59**	**6.06**	5.54	3.81	**2.31**	1.50	6.43
Tidal mixing	**11.58**	**6.46**	5.13	4.41	**2.50**	1.91	4.83
(9) Macroalgae	11.46	3.89	**7.57**	**4.70**	1.33	**3.37**	**8.48**
(10) Recruitment	11.43	3.46	**7.96**	**4.89**	1.04	**3.86**	6.67
(11) Fishing pressure	11.39	4.32	7.07	**4.43**	1.46	**2.96**	**7.04**
Herbivore diversity	11.00	4.36	6.64	4.00	1.54	2.46	**7.33**
Habitat complexity	10.64	**5.08**	5.56	2.81	1.29	1.52	6.04
Connectivity	10.61	3.04	**7.57**	3.13	0.61	2.52	2.70
Mature colonies	10.39	4.21	6.18	2.81	1.07	1.74	**7.07**
Light (stress)	10.27	**6.31**	3.96	3.15	**2.31**	0.84	6.04
Coral size class distribution	10.08	4.81	5.27	2.58	1.19	1.38	6.88
Substrate suitability	10.00	2.39	**7.61**	2.93	0.36	**2.57**	6.52
Upwelling	9.83	5.04	4.78	2.63	1.46	1.17	4.71
Coral growth rate	9.79	2.71	**7.07**	1.79	−0.46	2.26	4.37
Proximity of other coastal habitats	9.67	4.04	5.63	3.39	1.36	2.04	**7.14**
Hard coral cover	9.50	3.71	5.79	3.14	0.88	2.27	**8.82**
Rapidly growing species	9.36	2.64	**6.71**	2.14	−0.64	**2.79**	6.89
Topographic complexity	9.19	4.74	4.44	2.26	1.22	1.04	6.19
Physical impacts	9.16	4.04	5.12	3.24	1.31	1.93	6.82
Wind mixing	8.00	4.00	4.00	2.71	1.52	1.19	4.45
Crustose coralline algae	7.81	2.54	5.27	0.35	0.00	0.35	6.62
Bioerosion rate	7.54	3.29	4.25	2.07	0.82	1.25	4.57
Exotics and invasives	7.00	3.04	3.96	2.42	0.92	1.50	5.00

Summary of the scaled perceived importance, scientific evidence, and feasibility of measurement for the top 31 factors. Perceived importance and feasibility are based on responses from 28 coral reef experts. Scientific evidence is based on a review of the journal literature with a distinct objective scale based on the level of evidence (see SI methods). Resilience scores are the sum of resistance and recovery scores. Values in bold indicate the top 10 values in each column; the 11 ecological factor names in bold indicate the feasible (feasibility>5) ecological factors which ranked among the top ten factors for perceived importance or empirical evidence of resilience.

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There are two primary considerations to take account of when finalizing the indicators to be used in a resilience assessment:

1. *All* of the indicators selected should be strongly related to the likelihood that a given site will resist and/or recover from disturbances. With each indicator included in the assessment, the importance of each individual indicator is diluted. Therefore, variables should not be included that are likely to be far less important than other variables. Further, there is no published and defensible weighting scheme for resilience indicators that applies to reef areas globally, so all indicators should be equally weighted in the analysis. Local knowledge should be used to develop the list of indicators as some indicators are likely to be more important for resistance and recovery in some areas than others.
2. The rigorous measurement or assessment of all variables needs to be within the resource budget and expertise and capabilities of your group.

Based on the considerations above, a final list of 9-15 resilience indicators is likely. It is possible that there will be several variables on your list when considering point 1 just above that have to be taken off the list following considering point 2. If this is the case, you may not want to complete an analysis, or you may want to postpone until you can compile the resources and/or capability to do the analysis.

Data Collection

Once the variables to be included in the resilience assessment have been selected, they need to be measured or assessed, usually via a combination of in-water field surveys and desktop analysis. Completing the field surveys efficiently and safely is likely to require a minimum of two 2-diver (or snorkeler) teams, a safety officer/lookout, and boat captain. The desktop analyses are likely to require a minimum of a GIS software package like those produced by ESRI (ArcGIS 9.0+, and the related ArcINFO), the MS Office software package.

There will be at least as many defensible methodologies for measuring or assessing the variables included in an analysis as there will be variables. Decisions regarding methodologies to use for each of the selected variables should take account of the following considerations. The method needs to: 1) be within the resource budget of the project managers and capability levels of those collecting the data, 2) be standardized as much as is possible to methodologies used by your group in the past or by other groups in your area, and 3) will ideally be consistent for all sites in the analysis.

The following case study outlines methods recently applied in a resilience assessment conducted in Saipan. These methods are included to provide examples of rigorous methodologies that can be used, but are not intended to be prescriptive (See “Helpful resources for assessing/measuring resilience variables” for examples of resilience assessments and resources for methods)

Case Study: Resilience assessment methods applied in Saipan

The following resilience assessment methods were applied using the site selection framework proposed by McClanahan et al. (2012). The methods used to measure or assess each of the 11 recommended variables are described below. Variables are categorized as having been measured in the field or assessed using a desktop analysis. The results of the resilience analysis in Saipan are included in Appendix 2.

Fieldwork

Variables assessed in the field include: coral diversity, recruitment, bleaching resistance, herbivore biomass and macroalgae cover, coral disease, and anthropogenic physical impacts (i.e., anchor and fin damage). Survey methodologies and units for each are described below.

Coral diversity: All corals were identified to species within 16, 0.25 m^2 quadrats randomly placed along three 50 m line transects laid sequentially with 10-20 m gaps along the same depth (8-10 m for reef sites, 2-4 for lagoon sites). A total species count – species richness – was produced, and the abundance of each species was derived. Simpson's Index of Diversity (unitless, ranging from 0 to 1) was calculated. This index asks the likelihood that two randomly sampled individuals will *not* be of the same species; the greater the likelihood (closer to 1) the higher the diversity. The formula for Simpson's Index is given below, where n = the total number of organisms of a particular species, and N = the total number of organisms of all species.

$$D = \frac{\sum n(n-1)}{N(N-1)}$$

Recruitment: The geometric mean (two longest lengths averaged) of all corals within 16, 0.25 m^2 quadrats (see Coral diversity for transect information) was calculated. Recruits were considered to be corals with a geometric mean <4cm. The density of recruits was calculated for each site and became the final recruitment measure; sum total of recruits across all quadrats divided by 4 (for meters) yielding 'recruits/m^2'.

Bleaching resistance: Every coral species identified during the surveys was given a bleaching susceptibility score from 0 to 10; the higher the score the more susceptible the species to thermally-induced bleaching. Rankings were produced using an expert focus group that reviewed the literature, as well as data from the only well documented bleaching event in Saipan – the 2001 event. Species with a susceptibility score of 4 or less were considered resistant for this analysis. The proportion (%) of the community made up of bleaching resistant corals was then calculated for each site. The community of corals at each site was considered to be the species identified using the quadrats described in the Coral diversity section above.

Herbivore biomass: Nine 5-minute stationary point counts (SPC, circle with 9 m diameter) were conducted at each site. All fish larger than 5 cm in body length were identified to species, and their length was estimated in cm. The weight of each fish in grams was then calculated using the standard equation – $W = aL^b$, where W is weight, L is length, and a and b are coefficients specific to each species. The coefficients used were sourced from NOAA's Coral Reef Ecosystem Division, are up-to-date and are mostly standard across the globe for all of the fish species identified. Species were classified as herbivores using IUCN's classification for these species and when not available were classified as herbivores if known to be herbivorous in Saipan and/or elsewhere. Herbivore biomass was calculated for each SPC at each site following summing, and converting to kg/100 m^2. The average herbivore biomass was used here and based on averaging across all nine SPCs.

Macroalgae cover: Three 50 m point-intercept transects were laid as described in the Coral diversity section. At 50 cm intervals (100 per transect, 300 per site) the benthos was categorized as live coral, dead coral, soft coral, sand, rubble, crustose coralline algae (CCA), pavement (bare hard substrate without CCA), macroalgae, turfing algae, and other invertebrates (i.e., sponges and sea stars). Macroalgae cover was calculated as the average (across transects) percent of the points identified classified as macroalgae.

Coral disease: All observations of coral disease were to be identified and described within 1 meter either side of the three 50-m transects (see Coral diversity section), so three 100 m^2 belt transects. No coral disease was identified or described at any of the sites during these surveys so coral disease is not included in the resilience analysis.

Anthropogenic physical impacts: All instances of anchor or fin damage were to be documented, described and photographed but no such damage was observed at any of the sites.

Desktop

Variables assessed using remote sensing and GIS software include: temperature variability, nutrient input, sedimentation, and fishing pressure. The methodologies used to assess each are described below.

Summer temperature variability: Summer is defined as the three-month period containing the month with the highest average temperatures or the 'maximum monthly mean' as the middle month. The standard deviation of summer temperatures was calculated for 1982-2010 using NOAA's Pathfinder dataset (available at: http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/). Time series data can be requested via the website for any area of interest. Databasing technologies have to be used to extract data for the waypoints of your survey sites.

Pollution and Sedimentation Proxies: A proxy for pollution loading was developed using geographic information system (GIS) layers pertaining to watershed size, topography, and discharge flow direction. Digital elevation models (i.e., topographic data) were first used to define watershed boundaries and likely flow patterns for discharge waters. Subsequently, each site was attributed to an adjacent watershed. The proxy for pollution loading was then calculated as a continuous variable by measuring the watershed size. Thus, it was assumed that watershed size was a disproportional contributor to overall pollution loading. A proxy for sedimentation was generated by incorporating United States Forest Service GIS layers pertaining to land use (http://www.fs.usda.gov/r5). Land use categories were simplified into three classes: 1) barren land/urbanized vegetation/highly developed, 2) shrubs, and 3) vegetation with canopy cover. The sedimentation proxy was estimated by the percent cover of class 1 within each watershed.

Fishing access: Several proxies were considered to accurately depict fishing pressure: 1) wave exposure, 2) distance to shoreline access, 3) distance to nearest large population center, and 4) number of people in the nearest population center. We examined several combinations of the above noted variables for their ability to match an expert survey on perceived differences in relative fishing pressure, whereby local fishers and fishery managers were asked to evaluate fishing pressure at our survey sites as being low, medium or high. Our preliminary analysis found that wave exposure alone most closely matched the results of the survey. This seems logical given that fishing pressure on Saipan is largely driven by accessibility, which is driven to a great extent by the average wave height.

Wave exposure was estimated by using long-term wind datasets, and GIS layers pertaining to varying angles of exposure for each survey site. For each site, fetch (i.e., distance of unobstructed open water) was first estimated for each site within 16 quadrants (i.e., 0 to 360 degrees, equally distributed into 16 bins). Fully develop sea conditions were considered if unobstructed exposure existed for 20 km or greater. Ten-year long-term windspeed averages were calculated from Saipan airport data (http://www7.ncdc.noaa.gov/), and used as inputs to calculate wave height as following Ekebom et al. (2003). Specifically, mean height was calculated by:

$$H_m = 0.019\, U^{1.1}\, F^{.45} \qquad (1)$$

Where H_m is the wave height (m) for each quadrant, U is the windspeed at an elevation of 10m, and F is the fetch (km). Windspeed corrections for varying elevations were made following Ekebom et al. (2003). Last, wave height was converted to energy following:

$$E = (1/8)\rho g H^2 \qquad (2)$$

Where ρ is the water density (kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), and H is the wave height (m). This process resulted in continuous data on wave exposure, used here to describe ‘access’ to the fishery.

Helpful resources for assessing/measuring resilience variables

- The Global Coral Reef Monitoring Network’s Methods for Ecological Monitoring of Coral Reefs (GCRMN 2004) (http://www.icran.org/pdf/Methods_Ecological_Monitoring.pdf). The benefits of various monitoring methods are described in this publication, which could be useful in weighing options.

- IUCN's Resilience Assessment of Coral Reefs (Obura and Grimsditch 2009) provides guidance on the survey design and field methods of a resilience assessment (http://cmsdata.iucn.org/downloads/resilience_assessment_final.pdf)

Examples of resilience assessments include:

- Assessing coral resilience and bleaching impacts in the Indonesian archipelago (http://www.conservationgateway.org/Files/Pages/assessing-coral-resilienc.aspx)
- Coral Reef Resilience Assessment of the Pemba Channel Conservation Area, Tanzania (http://cmsdata.iucn.org/downloads/pemba_report___final.pdf)
- Coral Reef Resilience Assessment of the Nosy Hara Marine Protected Area, Northwest Madagascar (http://cmsdata.iucn.org/downloads/resilience_assessment_madagascar.pdf)
- Coral Reef Resilience Assessment of the Bonaire National Marine Park, Netherlands Antilles (http://data.iucn.org/dbtw-wpd/edocs/2011-008.pdf)

Data analysis

Data should be stored so that site summaries can be produced for each individual site, and so that all raw data can be viewed for all sites within the same spreadsheet or table. The Excel file template and Appendix 2 contain example tables. When the final data table is compiled, the resilience potential of all sites can be calculated, as can combined scores for anthropogenic stress. Methods for each calculation are below.

Calculating Resilience potential

To calculate resilience potential (the final output) values for each variable are first anchored to the maximum value for: Option 1 - the variable with the max value among the pool of sites, or; Option 2 – the max value for the region. Option 1 maximizes differentiation of the sites locally, while Option 2 ensures results can be compared across the entire region. For each variable, the site with the maximum value (in the region or just locally) is given a score of 1. All other values for that variable - all of the sites with less than the max value - are normalized to the score of 1 by dividing by the maximum value. For example, if the maximum bleaching resistance value in the region or locally is 64%, the site with 64% receives a 1 and the site with 60% receives a 0.94 (or 60 divided by 64). Anchoring values to the max value helps make clear exactly how different one site's value is from others.

To produce a composite score, the scale for the anchored and normalized scores must always be the same - 0 to 1 – and be uni-directional; i.e., a high score is always a good score. This requires producing the inverse of the anchored score for, as examples: macroalgae cover, nutrient input, sedimentation and fishing pressure since high levels of these are a negative rather than a positive for reef resilience. For these, 1 minus the anchored score results in the final score so highest values are given a zero or the worst possible score for those variables.

Normalizing to a standard scale ensures the scores can all be combined into the composite resilience score, which is the average of all of the anchored and normalized scores. That score is one final 'resilience potential score'. An alternate – used to produce the final rankings - can also be produced by using the anchoring and normalizing procedure again whereby the site with the highest resilience score receives a 1 and so on. As with the variables, this can be set to the highest resilience score for any pool of sites, which could be the local analysis or one that includes sites from across a region or management area. Sites are then ranked from highest to lowest resilience score or anchored resilience score. Using the rankings to identify the sites within all tables and on maps can aid with interpretation. Low, medium and high groupings can be set by equally dividing the range of scores into three equal bins (as in Maynard et al. 2010) or other criteria can be set. In the example from Saipan in Appendix 2, anchored resilience scores of 0.8 to 1 represent high (relative) resilience potential, 0.6-0.79 medium, and low is <0.6. Coloring these classifications green, yellow and red may also aid in interpretation though any colors can be set for the table and mapping outputs.

A principal components analysis (PCA) can be undertaken to test whether differences between sites in final resilience scores are consistently driven by a few rather than all of the variables examined. A PCA is made possible by using scores that are uni-directional, anchored and normalized. The PCA results can be extremely valuable and potentially indicate that some variables are very strong drivers of differences in the calculated resilience potential and some may not factor into the analysis at all.

A composite score can also be produced for anthropogenic stress by averaging the anchored scores for all variables used that relate directly to human activity. Examples from the site selection framework proposed by McClanahan et al. (2012) include fishing pressure, nutrient input, sedimentation and anthropogenic physical impacts. For consistency, such that the composite score for resilience potential can be calculated, high scores are good scores for these variables, so a high score equals low stress. As with resilience potential, scores from 0.8 to 1 are high scores or good scores (low stress), 0.6-0.79 medium, and scores of <0.6 are low and equate to high stress. The larger numbers signifying low stress is counterintuitive and an unfortunate effect of needing all anchored scores to be uni-directional for a composite score to be produced. An arrow describing stress and figure captions can help with interpretation of the maps that describe the anthropogenic stressors. Using red to denote sites with high stress and to denote sites with low resilience potential, and green for low stress and high resilience potential, can help ensure results presentation via maps and tables is intuitive.

References

Ekebom, J., P. Laihonen, and T. Suominen. 2003. A GIS-based step-wise procedure for assessing physical exposure in fragmented archipelagos. *Estuarine, Coastal and Shelf Science* 57(5):887-898.

Green, A.L., and D.R. Bellwood. 2009. Monitoring functional groups of herbivorous reef fishes as indicators of coral reef resilience - A practical guide for coral reef managers in the Asia Pacific region. IUCN Working Group on Climate Change and Coral Reefs. IUCN, Gland, Switzerland.

Maynard, J. A., P. A. Marshall, J. E. Johnson, and S. Harman, 2010. Building resilience into practical conservation: identifying local management responses to global climate change in the southern Great Barrier Reef. *Coral Reefs* 29(2): 381-391.

McClanahan, T.R., S.D. Donner, J.A. Maynard, M.A. MacNeil, N.A.J. Graham, *et al.* 2012. Prioritizing key resilience indicators to support coral reef management in a changing climate. *PLoS ONE* 7(8): e42884. doi:10.1371/journal.pone.0042884.

Obura D, and G. Grimsditch. 2009. Assessment protocol for coral reefs focusing on coral bleaching and thermal stress. Gland, Switzerland: IUCN.

Appendix 1. Empirical evidence for factors relating to resistance and recovery of coral reefs based on McClanahan et al. (2012). See McClanahan et al. (2012) Tables S1 and S2 for references for scientific evidence of indicators.

Resilience Indicator	Scientific evidence for effect of resilience indicators on coral resistance and recovery
Coral diversity	Coral diversity may increase resistance, but this likely depends on the species composition and their species-specific sensitivities or tolerances to disturbance. Overall, the association between diversity and resistance remains unclear. There is limited evidence that coral diversity promotes recovery following disturbance.
Bleaching resistance	Resistant species (e.g. massive corals) are often not impacted by disturbance and a high abundance of resistant species, by definition, confers resistance. Resistant species, such as massive corals that remain after a disturbance, can continue to grow and reproduce to promote recovery, although these are often slow-growing species and coral recovery may depend more on the recolonization of fast-growing branching and plating species.
Recruitment	Mixed evidence surrounds the thermal sensitivity of coral recruits and small size classes, compared to larger corals, with some evidence suggesting small corals bleach more severely, while a great number of studies suggest coral recruits and small size classes are more resistant to bleaching and mortality. High rates of successful coral recruitment and survival enhance coral recovery rates following disturbance.
Coral disease	Few studies have directly tested how disease affects bleaching sensitivity. Instead, research has focused on the effect of temperature on pathogen virulence, how disease outbreaks follow bleaching episodes (suggesting corals are more susceptible), and how disease might become more common as climate change continues. There is little evidence that high levels of disease impede recovery from bleaching. However, disease outbreaks often follow episodes of mass bleaching, which would imply slower recovery as corals expend resources to combat infection.
Macroalgae cover	The impact of macroalgae on resistance is not clear though potential factors are generally negative. Factors can work to counteract one another. For example, macroalgae can reduce growth rates, shade can reduce bleaching, and disease transmission from algae can divert coral resources. Macroalgae is a significant factor limiting the recovery of corals following disturbance by increasing competition for benthic substrate, allelopathy and by trapping sediment that smothers coral recruits.
Herbivore biomass	No clear evidence the herbivory increases resistance. It is possible that reduced algal competition might help corals withstand other stressors but no clear evidence Most studies have linked increased herbivory to reduced macroalgal cover and an increase in coral recruitment despite higher corallivory. One study has gone further and shown that increased herbivore biomass led to a reversal in the reef trajectory from one of coral decline to coral recovery. Relative importance of fish and urchins varies geographically and with fishing intensity.
Temperature variability	Temperature variability, or the previous exposure of corals to different thermal regimes, has been demonstrated to increase resistance to bleaching in both field observations and experimental manipulations. Temperature variability is thought to be important but how past temperature exposure affects their rate of recovery from thermal stress events is not well studied. Corals with thermally tolerant symbionts exhibit slower growth rates, potentially making them less able to recover and re-grow following bleaching events.
Anthropogenic physical impacts	Several studies have illustrated that there is a strong negative relationship between anthropogenic physical impacts (especially reef trampling and/or diving, ship groundings and coral mining/dredging) to coral reefs and their ability to resist stressors. Physical destruction may not kill coral colonies entirely, but even partial mortality and weakening increases susceptibility to thermally induced coral bleaching, disease outbreak or and reduce the reproductive potential of individuals. However, the degree of resistance exhibited by coral reefs or colonies may be dependent on the scale and frequency of the disturbance. There is mixed evidence on the impact of physical anthropogenic disturbances on coral reef

	recovery. Most studies have linked anthropogenic physical impacts to coral lower growth rates, lower reproductive potential, fewer coral recruits, lower and survivorship and increased disease incidence. Conversely, other studies have found that these impacts (e.g. trampling, displacement of coral boulders, anchor damage, ship groundings, blast fishing, nuclear blasts and snorkeling/diving damage) created new coral habitat available for colonization by corals and certain fish species post impact.
Nutrient input	Field and experimental evidence suggests that nutrient pollution can reduce coral reef resistance to stress, but differences have been observed based on coral species, morphology, type of nutrient, level of nutrients and local context. Nutrient pollution is associated with decreased recovery following disturbance but studies recognize the challenge of separating the effects of multiple stressors, such sedimentation, overfishing from pure nutrients
Sedimentation	The effects of increased sediments on corals, widely studied in both classical recent literatures are linked to resistance properties of corals. In synergy with SST, increased sediment and nutrients have been shown to decrease the thermal tolerance of corals causing bleaching during marginal increase in SST. There is scientific evidence that can sediments can limit the recovery of coral reefs. It has been shown that sediment can smother corals tissue, and limit coral larvae settlement impairing coral recovery. Additionally sediments can also inhibit recovery and growth of inshore reefs in deposition areas, and as a result can modify the zonation of coral reefs
Fishing pressure	The ability to definitively link fishing pressure and resistance is difficult, due to the indirect impact of fishing pressure on corals and problems quantifying fishing pressure Increased coral recruitment and growth have been demonstrated on some reefs protected from fishing whereas no evidence has been found in others.

Appendix 2. Resilience analysis example from Saipan in CNMI, Micronesia.

The case study example from Saipan, CNMI, presented here was developed in collaboration with NOAA and CNMI's Division of Environmental Quality with critical contributions from Peter Houk, Steven McKagan, Steven Johnson, Gabby Ahmadia and Lindsey Harriman.

This example shows the results of a field-based resilience analysis conducted at 35 sites in the lagoon, bay, and outer reef sites of Saipan. The 11 variables recommended in the site selection framework posed within McClanahan et al. (2012) were all measured or assessed. The methods for each variable are described below the tables and map. Nine variables were included in the final analysis as all sites received the same scores for coral disease and anthro physical impacts as neither was observed during surveys. The first table below, Table A, shows the raw values for all variables for all sites. Table B then shows the anchored scores for each variable for all sites, calculated by assigning the site with the max value a 1 and dividing all other values by the max value. The resilience score is the average of all of the anchored scores for the variables. A final anchored resilience score is also shown whereby the max resilience score is assigned a 1 and all other scores are assessed relative to the max score. Here, sites are considered to have high resilience if the anchored resilience score is 0.8-1.0, medium if between 0.6 and 0.79, and low if <0.6. There are many mapping options for the final data; here we show the low, medium and high ranking classifications in Figure A. Combined anthropogenic stress is also calculated for each site by averaging the anchored scores for the variables directly related to human activities. Like the resilience score, this combined score for anthropogenic stress has been anchored to the max value and all other scores assessed relative to that score (scale of 0-1.0). The scales for all anthropogenic stressors are flipped to match that of all of the other variables whereby a high score is a good score. Thus the site with the highest fishing access based on wave exposure, or highest sedimentation levels receives a 0. The anthropogenic stress results are shown in Table C.

Table A. Raw values for all variables included in the Saipan resilience analysis. Values for each variable are anchored to the max value and assessed relative to that value – see the anchored scores in Table B.

Site Names	Coral Diversity	Recruitment	Bleaching Resistance	Temperature variability	Herbivore biomass	Macroalgae cover*	Nutrient input*	Sedimentation*	Fishing access*
Forbidden Island	0.93	9.75	64.99	0.96	1.95	0.00	2.46	1.57	1440
Bird Island	0.95	5.81	59.91	0.98	3.33	0.00	5.18	2.28	550
Lanyas	0.94	11.00	59.66	0.96	1.18	0.00	2.04	1.43	142
Nanasu Reef	0.92	7.44	53.85	0.99	3.01	6.00	3.97	1.99	1429
MMT - Managaha MPA	0.79	7.58	71.23	0.96	1.48	9.33	2.04	1.43	12
Obyan Beach	0.95	13.50	59.27	0.95	2.65	0.00	4.41	2.10	54
South Laolao	0.95	10.46	73.95	0.95	0.47	24.61	3.22	1.80	1671
Laolao Bay East	0.93	14.31	81.79	0.96	1.25	1.00	3.67	1.92	20
Agingan Point	0.91	13.50	66.80	0.97	0.67	0.00	2.28	1.51	130
Oleai Rocks	0.92	10.69	58.52	0.94	1.47	0.00	2.04	1.43	100
Laolao Bay Mids	0.91	8.44	63.76	0.96	1.98	0.50	2.83	1.68	85
North Dakota	0.94	10.31	64.53	0.96	0.65	0.00	3.97	1.99	616
Old Man By the Sea	0.94	4.75	69.79	0.94	1.27	6.00	7.16	2.68	1397
Point Break Reef	0.92	10.92	61.98	0.95	0.90	0.00	2.04	1.43	119
Pau Pau	0.94	11.06	54.07	0.96	1.07	0.00	2.04	1.43	107
Achu Dangkulu	0.94	8.94	67.74	0.96	0.30	0.00	2.04	1.43	443
Boy Scout	0.94	10.06	70.68	0.95	1.19	0.00	4.20	2.05	57
South Dakota	0.95	4.81	80.95	0.95	0.51	33.67	3.25	1.80	1405
Wing Beach	0.94	10.88	50.59	0.98	0.57	0.00	2.04	1.43	139
Lighthouse Reef	0.95	6.42	71.85	0.94	1.02	0.00	2.04	1.43	38
Ladder Beach	0.96	10.19	54.15	0.95	0.48	0.00	2.34	1.53	223
MMT - Outside Grand Hotel	0.95	6.93	69.66	0.95	0.77	0.00	2.04	1.43	113
Elbow Reef	0.96	6.69	62.98	0.96	0.36	0.00	2.04	1.43	448
Oleai Staghorn	0.69	2.50	88.46	0.94	2.06	11.33	2.04	1.43	7
Coral Ocean Point	0.96	9.50	51.36	0.95	0.65	0.00	5.30	2.30	103
Achugao	0.94	9.06	40.07	0.95	0.26	0.00	2.04	1.43	107
Tanapag Staghorn	0.78	4.88	82.67	0.96	0.78	10.67	6.59	2.57	7
MMT - Managaha Patch Reef	0.92	5.08	64.71	0.95	1.34	4.00	27.45	5.24	30
Pak Pak Beach	0.90	3.38	45.45	0.95	0.13	3.00	2.04	1.43	16
Tuturam	0.95	8.38	72.17	0.95	0.45	72.44	4.57	2.14	614
Tank Beach	0.96	6.13	68.75	0.95	0.26	0.35	27.72	5.26	1771
Peysonnelia Reef	0.79	8.56	85.95	0.94	0.48	0.33	19.95	4.47	137
Marianas Resort	0.43	0.94	20.00	0.96	0.88	22.33	2.34	1.53	7
Quartermaster Staghorn	0.10	1.06	20.00	0.94	1.42	32.33	2.04	1.43	10
Fishing Base Staghorn	0.00	0.00	0.00	0.95	0.42	0.00	2.62	1.62	13

Table B. Anchored scores for all variables, the resilience score (average score for all variables) and final anchored resilience scores and rankings.

Resilience Score:
= High
= Medium
= Low

Site Names	Rank	Anchored Resilience Score	Resilience Score	Coral Diversity	Recruitment	Bleaching Resistance	Temperature variability	Herbivore biomass	Macroalgae cover*	Nutrient input*	Sedimentation*	Fishing access*
Forbidden Island	1	1.00	0.84	0.96	0.68	0.73	0.97	0.59	1.00	0.91	0.70	1
Bird Island	2	0.99	0.83	0.98	0.41	0.68	0.99	1.00	1.00	0.81	0.57	1
Lanyas	3	0.98	0.82	0.98	0.77	0.67	0.97	0.35	1.00	0.93	0.73	1
Nanasu Reef	4	0.95	0.80	0.95	0.52	0.61	1.00	0.90	0.92	0.86	0.62	0.81
MMT - Managaha MPA	5	0.94	0.79	0.82	0.53	0.81	0.97	0.44	0.87	0.93	0.73	1
Obyan Beach	6	0.90	0.76	0.98	0.94	0.67	0.96	0.79	1.00	0.84	0.60	0.03
South Laolao	7	0.90	0.76	0.99	0.73	0.84	0.96	0.14	0.66	0.88	0.66	0.94
Laolao Bay East	8	0.89	0.75	0.96	1.00	0.92	0.97	0.37	0.99	0.87	0.64	0.01
Agingan Point	9	0.86	0.72	0.94	0.94	0.76	0.98	0.20	1.00	0.92	0.71	0.07
Oleai Rocks	10	0.86	0.72	0.96	0.75	0.66	0.95	0.44	1.00	0.93	0.73	0.06
Laolao Bay Mids	11	0.85	0.72	0.95	0.59	0.72	0.97	0.60	0.99	0.90	0.68	0.05
North Dakota	12	0.85	0.71	0.98	0.72	0.73	0.97	0.20	1.00	0.86	0.62	0.35
Old Man By the Sea	13	0.84	0.71	0.97	0.33	0.79	0.95	0.38	0.92	0.74	0.49	0.79
Point Break Reef	14	0.84	0.71	0.95	0.76	0.70	0.96	0.27	1.00	0.93	0.73	0.07
Pau Pau	15	0.84	0.71	0.97	0.77	0.61	0.97	0.32	1.00	0.93	0.73	0.06
Achu Dangkulu	16	0.84	0.70	0.98	0.62	0.77	0.97	0.09	1.00	0.93	0.73	0.25
Boy Scout	17	0.83	0.70	0.98	0.70	0.80	0.96	0.36	1.00	0.85	0.61	0.03
South Dakota	18	0.82	0.69	0.98	0.34	0.92	0.96	0.15	0.54	0.88	0.66	0.79
Wing Beach	19	0.82	0.69	0.98	0.76	0.57	0.99	0.17	1.00	0.93	0.73	0.08
Lighthouse Reef	20	0.82	0.69	0.99	0.45	0.81	0.95	0.31	1.00	0.93	0.73	0.02
Ladder Beach	21	0.82	0.69	1.00	0.71	0.61	0.96	0.14	1.00	0.92	0.71	0.13
MMT - Outside Grand Hotel	22	0.82	0.68	0.98	0.48	0.79	0.96	0.23	1.00	0.93	0.73	0.06
Elbow Reef	23	0.82	0.68	1.00	0.47	0.71	0.97	0.11	1.00	0.93	0.73	0.25
Oleai Staghorn	24	0.79	0.66	0.72	0.17	1.00	0.95	0.62	0.84	0.93	0.73	0
Coral Ocean Point	25	0.77	0.65	1.00	0.66	0.58	0.96	0.20	1.00	0.81	0.56	0.06
Achugao	26	0.77	0.65	0.97	0.63	0.45	0.96	0.08	1.00	0.93	0.73	0.06
Tanapag Staghorn	27	0.72	0.60	0.80	0.34	0.93	0.97	0.24	0.85	0.76	0.51	0
MMT - Managaha Patch Reef	28	0.71	0.60	0.95	0.36	0.73	0.96	0.40	0.94	0.01	0.00	1
Pak Pak Beach	29	0.70	0.59	0.93	0.24	0.51	0.96	0.04	0.96	0.93	0.73	0.01
Tuturam	30	0.70	0.58	0.98	0.59	0.82	0.96	0.13	0.00	0.84	0.59	0.35
Tank Beach	31	0.69	0.58	0.99	0.43	0.78	0.96	0.08	1.00	0.00	0.00	1
Peysonnelia Reef	32	0.66	0.55	0.82	0.60	0.97	0.95	0.14	1.00	0.28	0.15	0.08
Marianas Resort	33	0.57	0.48	0.45	0.07	0.23	0.97	0.26	0.69	0.92	0.71	0
Quartermaster Staghorn	34	0.53	0.44	0.10	0.07	0.23	0.95	0.42	0.55	0.93	0.73	0.01
Fishing Base Staghorn	35	0.49	0.41	0.00	0.00	0.00	0.96	0.13	1.00	0.91	0.69	0.01

Figure A. Map showing the locations of the survey sites and the spatial distribution of low, medium and high resilience sites.

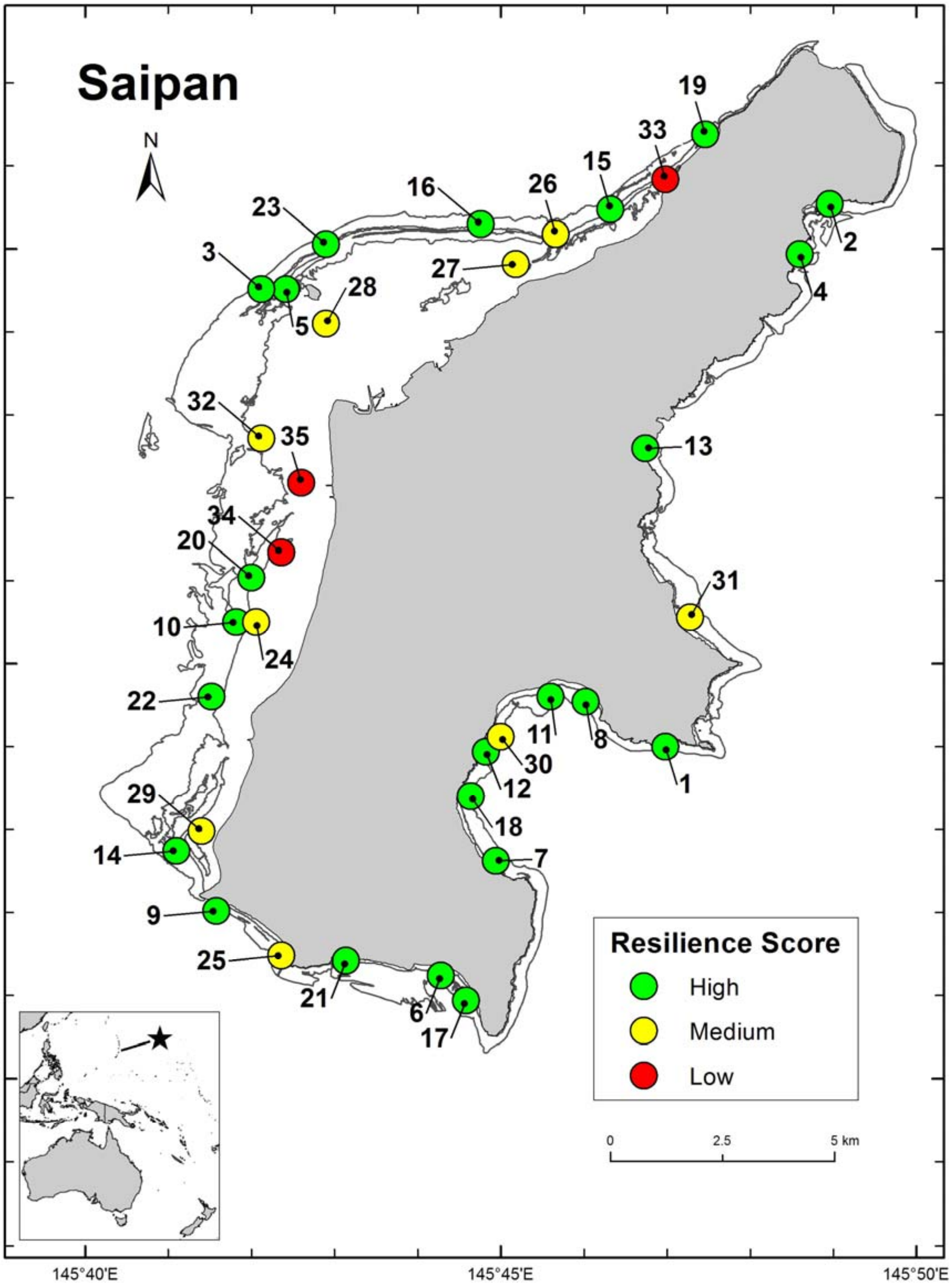

Table C. Combined anthropogenic stress scores and low, medium and high classifications for anthropogenic stress for all sites.

Anthropogenic Stress:
- Green = Low
- Yellow = Medium
- Red = High

Site Names	Resilience rank	Anchored score	Average score	LMH	Nutrient input	Sedimentation	Fishing access
Forbidden Island	1	0.98	0.87	L	0.91	0.70	1.00
Bird Island	2	0.90	0.79	L	0.81	0.57	1.00
Lanyas	3	1.00	0.89	L	0.93	0.73	1.00
Nanasu Reef	4	0.86	0.76	L	0.86	0.62	0.81
MMT - Managaha MPA	5	1.00	0.89	L	0.93	0.73	1.00
Obyan Beach	6	0.55	0.49	H	0.84	0.60	0.03
South Laolao	7	0.94	0.83	L	0.88	0.66	0.94
Laolao Bay East	8	0.57	0.51	H	0.87	0.64	0.01
Agingan Point	9	0.64	0.57	M	0.92	0.71	0.07
Oleai Rocks	10	0.64	0.57	M	0.93	0.73	0.06
Laolao Bay Mids	11	0.61	0.54	M	0.90	0.68	0.05
North Dakota	12	0.69	0.61	M	0.86	0.62	0.35
Old Man By the Sea	13	0.76	0.67	M	0.74	0.49	0.79
Point Break Reef	14	0.65	0.57	M	0.93	0.73	0.07
Pau Pau	15	0.65	0.57	M	0.93	0.73	0.06
Achu Dangkulu	16	0.72	0.64	M	0.93	0.73	0.25
Boy Scout	17	0.56	0.50	H	0.85	0.61	0.03
South Dakota	18	0.88	0.78	L	0.88	0.66	0.79
Wing Beach	19	0.65	0.58	M	0.93	0.73	0.08
Lighthouse Reef	20	0.63	0.56	M	0.93	0.73	0.02
Ladder Beach	21	0.66	0.58	M	0.92	0.71	0.13
MMT - Outside Grand Hotel	22	0.65	0.57	M	0.93	0.73	0.06
Elbow Reef	23	0.72	0.64	M	0.93	0.73	0.25
Oleai Staghorn	24	0.62	0.55	M	0.93	0.73	0.00
Coral Ocean Point	25	0.54	0.48	H	0.81	0.56	0.06
Achugao	26	0.65	0.57	M	0.93	0.73	0.06
Tanapag Staghorn	27	0.48	0.43	H	0.76	0.51	0.00
MMT - Managaha Patch Reef	28	0.38	0.34	H	0.01	0.00	1.00
Pak Pak Beach	29	0.63	0.55	M	0.93	0.73	0.01
Tuturam	30	0.67	0.59	M	0.84	0.59	0.35
Tank Beach	31	0.38	0.33	H	0.00	0.00	1.00
Peysonnelia Reef	32	0.19	0.17	H	0.28	0.15	0.08
Marianas Resort	33	0.61	0.54	M	0.92	0.71	0.00
Quartermaster Staghorn	34	0.63	0.55	M	0.93	0.73	0.01
Fishing Base Staghorn	35	0.60	0.54	M	0.91	0.69	0.01