# Integrating reef resilience and climate change vulnerability into protected area design and management in the Commonwealth of the Northern Mariana Islands (CNMI) and greater Micronesia

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## Executive Summary

Severe thermal stress events have already caused coral mortality in Micronesia, and climate models suggest the reefs of Micronesia, including CNMI, will suffer increased thermal stress. The project team identified thermal variability and the average frequency of thermal stress events likely to induce a bleaching response over the last two decades, and projected rates of temperature increase across Micronesia using climate models. Historical remote sensing data suggests that the average frequency of thermal stress events per decade ranges from 2-5 events. Based on climate model outputs, a >3°C change in temperature is projected for reefs across Micronesia by 2100, bleaching conditions are projected to occur annually by 2050, and bleaching conditions are projected to occur 2x per decade by 2025.

To complement the remote sensing and modeling outputs, resilience assessments were completed for reef sites across Saipan by using established resilience protocols and historical SST data and bleaching records. Variables assessed included: coral diversity, recruitment, bleaching resistance, thermal variability, herbivore biomass and macroalgae cover, coral disease, nutrient input, sedimentation, fishing access (proxy for fishing pressure), and anthropogenic physical impacts (i.e., anchor and fin damage). Each site was ranked based on resilience indicators and anthropogenic stressors to produce a relative resilience ranking.

The results of the rankings will be used to inform management decisions in Saipan and associated management strategies. Tools were developed and shared with partners to help build the capacity of local resource managers to address the threat of climate change in the region. Specifically, a "How-to-guide" to conduct resilience assessments was developed and a suite of GIS data layers were produced for each indicator independently and combined indicators for resilience and anthropogenic stress.

Finally, based on the results of the analysis, a number of management recommendations and next steps were identified to support coral reef and coastal managers working in Saipan. The ability to identify potentially resilient sites and human impacts will be critical to inform management decisions that provide reefs with the best chance of coping with climate change and other human impacts. The results of this work provide essential case studies to help coral reefs managers around the world operationalize reef resilience to inform management decisions.

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## Introduction

The majority of people in Micronesia depend on healthy ecosystems for their livelihoods and for the provision of essential services, such as food and clean drinking water. The human connection to the environment is a core value in Micronesia. Consequently, resilience to the climate change impacts projected for the region is critical for the preservation of sustainable livelihoods, natural heritage, customs, and traditions and hence a major priority for resource managers and policy makers in the region. Countries in Micronesia have declared their commitment to respond to the threats posed by climate change by conserving marine and coastal resources through the Micronesia Challenge (MC).

The protection of coral reef ecosystems is essential to meeting the MC's goal to effectively conserve near-shore marine resources. Coral reefs are among the most vulnerable ecosystems to climate change (Hughes et al. 2003). The corals that form the structure of reefs bleach and can die when temperatures are anomalously high; 16% of the world's coral reefs were lost during the 1998 bleaching event alone (Wilkinson 2000). Sea surface temperatures (SSTs) only 1°C warmer than the maximum monthly mean (Glynn and D'Croz 1990) can cause coral bleaching.

In CNMI, severe bleaching events have already caused coral mortality (Starmer 2005). Projected rates of temperature increase under fossil-fuel aggressive emissions scenarios (e.g., IPCC A1F1) suggest harmful thermal stress events will occur annually after 2050 (Donner et al. 2005), if not before (Donner 2009). Recent evidence suggests that the growth rate of $CO_2$ emissions since 2000 has been greater than was projected in the most fossil-fuel aggressive emissions scenario (Raupach et al. 2007). Consequently, frequent harmful thermal stress events may occur sooner than expected.

Importantly, the degree to which sites will be exposed to temperature stress likely to induce a bleaching response (i.e., vulnerability) is likely to be high at local and regional scales as the climate changes. There are two inter-related reasons this is true. (1) The difference between the bleaching threshold – maximum monthly mean plus 1°C – and average summer temperatures varies greatly on the scale of tens of kilometers over coral reef areas (Maynard et al. 2008). Sites where the difference between the bleaching threshold and average summer temperatures is greatest need to experience high rates of temperature increase to bleach frequently. (2) The outputs of climate models indicate that rates of temperature increase vary greatly in different parts of the west Pacific (Delecluse et al. 1998).

Sites where the difference between the bleaching threshold and average summer temperature is greatest *and* projected rates of temperature increase are relatively low are likely to be less vulnerable to climate change. Our team identified these locations at 4km resolution for all of Micronesia and presents the results as interactive mapping tools. Managers in CNMI have requested such tools to guide decisions regarding the design and management of new and existing conservation investments.

Further, we assessed the resilience of reef sites in CNMI by using protocols based on measuring biophysical and ecological criteria (see Maynard et al. 2010; McClanahan et al. 2012), and analyzing historical SST data and bleaching records. This way, we can identify the sites that the climate modeling described above suggests have lower relative vulnerability. Our local resource manager partners in CNMI are now able to integrate resilience and vulnerability to climate change in protected area planning and management.

Reducing anthropogenic stress is critical to supporting the natural resilience of reefs and reducing vulnerability to climate-related impacts like mass bleaching (Mcleod et al. 2009). The innovative approach we implemented represents a critical contribution to meeting the challenge of responding to the climate change threat. The work conducted was highly collaborative with local resource managers in CNMI.

## Objectives

The overarching objective of this project was to provide practical tools for marine conservation planners and policy makers in CNMI and greater Micronesia. Specific objectives:

1. Identify priority areas for conservation throughout Micronesia
2. Assess the relative resilience of priority areas identified in CNMI
3. Deliver tools that build the capacity of local resource managers to address the threat of climate change
4. Share project outputs with international scientific and management communities

## Results

The results below, for the remote sensing and climate modeling analysis and field-based resilience assessment, address the first three objectives described above. The remote sensing and climate modeling are described first, as project phase 1. The field-based resilience analysis is described next, as project phase 2. Project phase 3 describes management recommendations and capacity building and addresses objectives three and four above.

### *Phase 1 – Remote sensing and climate modeling*

### Remote sensing

We assessed coral bleaching thresholds across Micronesia (in degree heating weeks) using the NOAA Pathfinder dataset (4 km resolution). The thresholds for bleaching were based upon previous observations of coral bleaching prevalence in relation to observed thermal stress (van Hooidonk and Huber 2009a) across Micronesia, and globally. Using a 1x1$^{o}$ global grid, all observations of bleaching between 1990 and 2007 (obtained from reefbase.org) were compared to annual maximum degree heating weeks (DHW). For each location, an optimal threshold in DHWs was selected that resulted in the highest Peirce skill score. The Peirce skill score is defined as the difference between the hit-rate and false alarm-rate, and therefore this threshold maximizes the ability to discriminate between events and non-events. The global mean threshold for the occurrence of coral bleaching was 6.1 DHWs. Based on the limited bleaching observations in Micronesia (van Hooidonk and Huber 2009b) and the uncertainty inherent in the local optimal threshold found, we elected to project bleaching using the global average of optimized thresholds (6.1 DHWs).

*Average frequency of thermal stress events 1982 – 2010*

Thermal stress events likely to induce a bleaching response were classified by the above noted threshold of 6 DHWs.

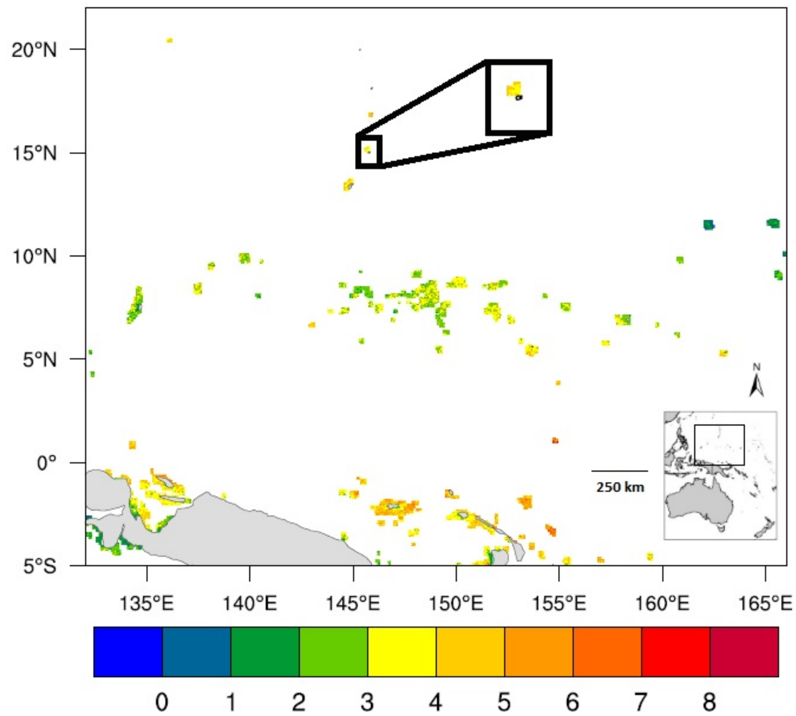


**Figure 1. Map of the average frequency of thermal stress events likely to induce a bleaching response (e.g., >6 DHWs) per decade, using data collected between 1982 and 2010. The inset box shows Saipan and CNMI; the unit for the legend is number of thermal stress events.**

The frequency of thermal stress events/decade across Micronesia ranges from 2 to 5, with the highest observed frequency of events in the south, and the lowest frequency of events in the east (Figure 1). Bleaching is likely to be a more important driver of habitat condition and ecosystem dynamics on reefs where thermal stress event frequency is high relative to other sites in the region.

*Summertime temperature variability 1982 – 2010*

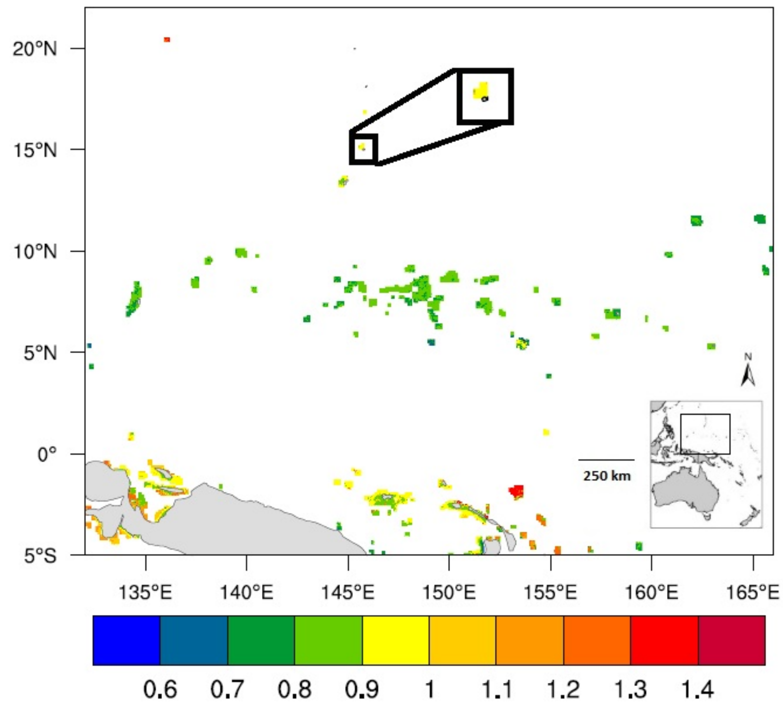


**Figure 2. Map of variability between 1982 and 2010 in the summer temperatures, defined as the three-month period containing the month with the highest annual temperature as the middle month. The inset box shows Saipan and CNMI; the unit for the legend is degrees Celsius.**

Variability is expressed as the standard deviation in summertime (3 hottest months**)** temperatures between 1982-2010 across Micronesia (Figure 2). During similarly stressful events, reefs with high variability in temperatures during the summer period have been observed to bleach less severely than reefs with low temperature variability (Guest et al. 2010). It is unknown, however, how variable temperatures need to be for an increase in temperature tolerance to be noted. Whether there is a thermal threshold beyond which there is no benefit from past temperature variability is also unknown, but is likely. The spatial variation in summertime temperature variability is low across Micronesia with nearly all sites having a standard deviation between 0.7 and 0.9. This suggests that at the regional scale, the ability to identify potential refugia based on reef areas with high thermal variability is limited.

## Climate modeling

The most current climate models (IPCC AR5 model ensemble) were used for this analysis, and modeled sea surface temperature (SST) data was retrieved for the relative concentration pathway experiments (RCP 2.6 and 8.5). RCP2.6 represents a conservative future with reductions in emissions, whereas RCP 8.5 is characterized by business-as-usual aggressive emissions growth. For the RCP2.6 experiment, the following models were used: CNRM-CM5, MPI-ESM-LR, MRI-CGCM3, NorESM1-M, GISS-E2-R, and HadGEM2-ES. Although the number of models available for the RCP 2.6 will increase, only the previously listed models were available at the time that this project phase was completed. The following RCP8.5 experiment ensemble members were included in this analysis: CSIRO-Mk3-6-0, IPSL-CM5A-LR, MPI-ESM-LR, inmcm4, MIROC5, NorESM1-M, GISS-E2-R, HadGEM2-CC, and HadGEM2-ES. The modeled SST data and associated projections of thermal stress events were used to produce four outputs for each of the RCP experiments used (RCP 2.6 and RCP 8.5).

We assessed when the RCP2.6 and 8.5 outputs suggest minor and moderate bleaching annually throughout Micronesia. For a 6 DHW threshold (minor bleaching) under RCP2.6, 115 of 120 sites (climate model pixels where reefs occur) in Micronesia experience these conditions annually by 2032. For an 8 DHW threshold (moderate bleaching) under RCP2.6, 46 of 120 sites experience these conditions annually by 2030 – the rest are not projected to experience these conditions during this century under this RCP experiment. Under RCP8.5, all 120 pixels experience conditions consistent with minor (6 DHWs) and moderate (8 DHWs) bleaching in 2025 and 2033, respectively.

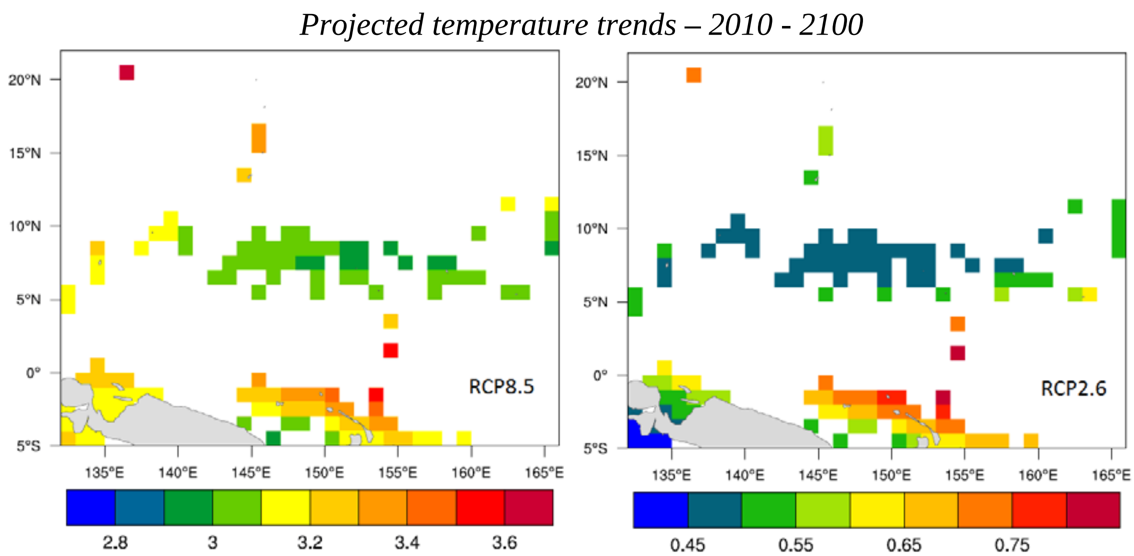


**Figure 3. Projected temperature trends in degrees Celsius this century under RCP8.5 and RCP2.6.**

The left panel (RCP 8.5) shows that the projected changes in temperature are higher in northern and southern parts of Micronesia, and projected changes are lower in central and eastern Micronesia. In the RCP 2.6 scenario (right panel), projected changes in temperature across Micronesia are about 1/6$^{th}$ of what is projected in RCP8.5; i.e., the projected change in temperature across many reefs in central Micronesia (much of the Federated States of Micronesia) is about ~.5°C under the RCP 2.6 compared to ~3°C under the RCP 8.5. The right panel (RCP 2.6) shows that the projected changes in temperature are higher in southern parts of Micronesia, and projected changes are lower in central Micronesia. In CNMI, the RCP2.6 projections suggest that the change in temperature by 2100 will be ~0.60°C and the RCP 8.5 projections suggest ~3.4°C change in temperature. The mean trend in temperature between 2010 and 2100 for all coral reef pixels in Micronesia is 3.13°C/century.

*Frequency of thermal stress events – RCP8.5*

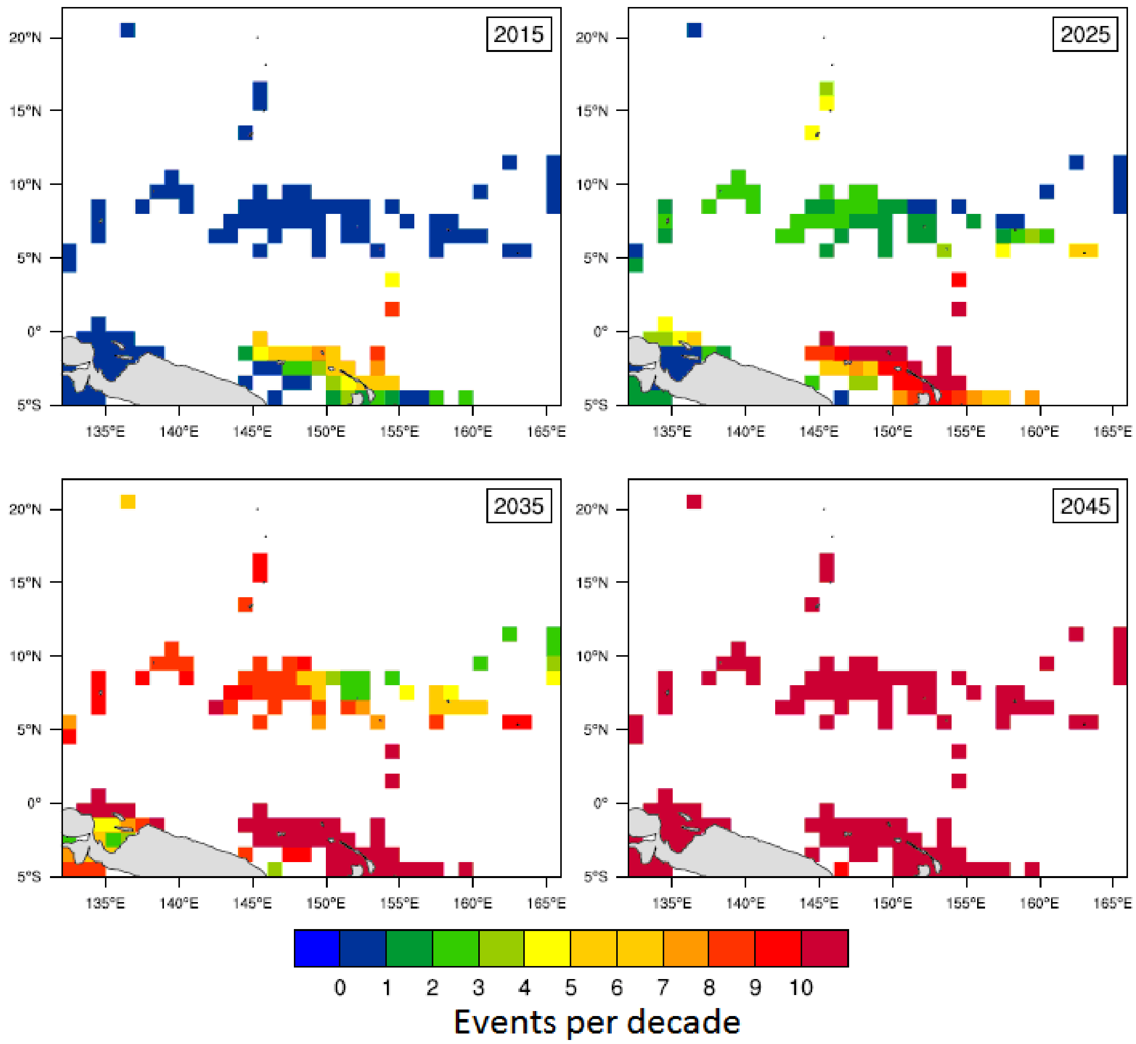


**Figure 4. Frequency of thermal stress events likely to induce a bleaching response projected for each of the coming four decades under RCP8.5.**

The figure above demonstrates that under the more aggressive RCP8.5 experiment, between 2045 and 2054, all reef areas in Micronesia experience annual bleaching conditions.

*Frequency of thermal stress events – RCP2.6*

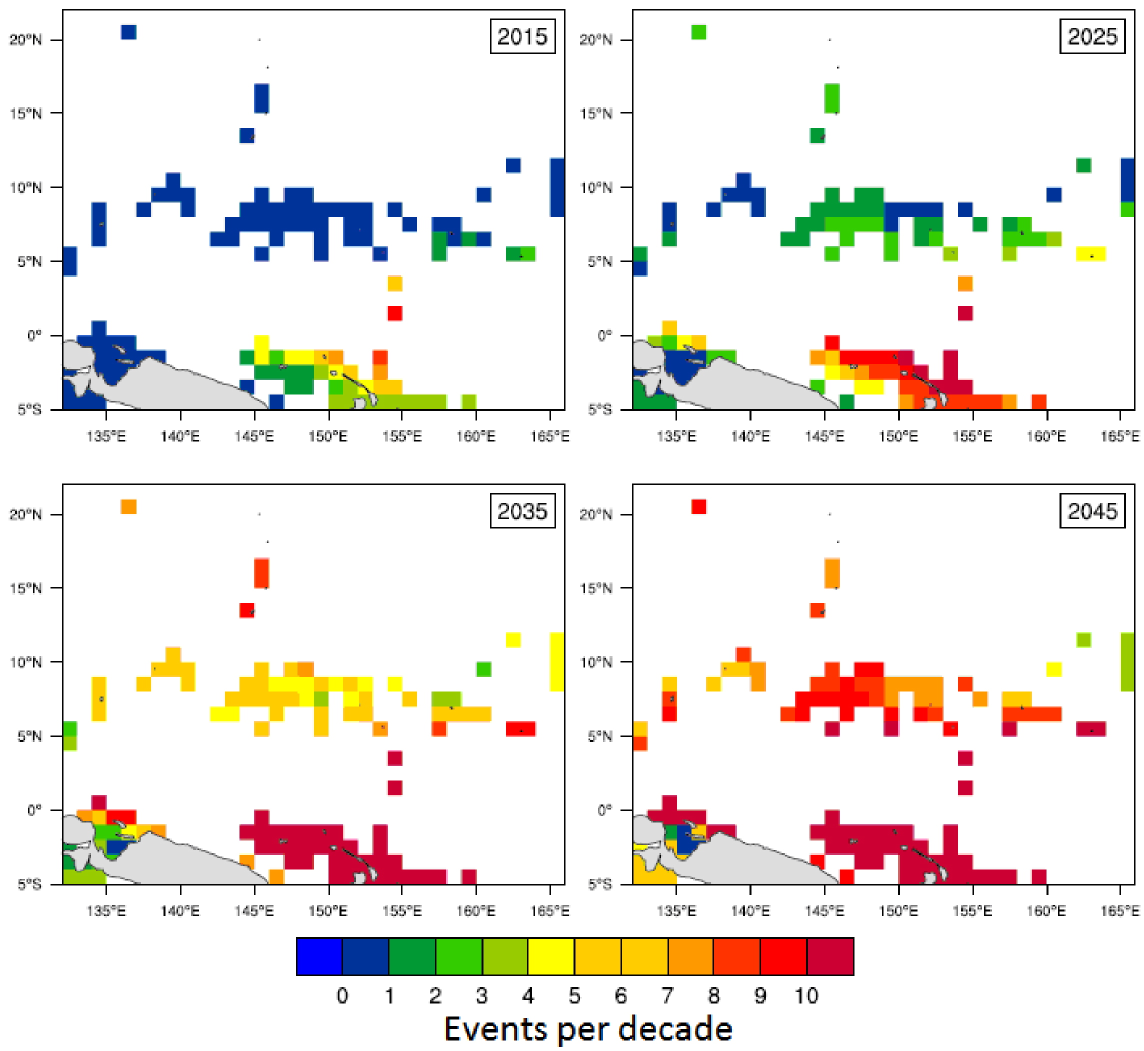


**Figure 5. Frequency of thermal stress events likely to induce a bleaching response projected for each of the coming four decades under RCP2.6.**

The figure above demonstrates that even under the more conservative RCP2.6 (i.e., drastic reductions in greenhouse gas emissions and stabilization), reefs throughout Micronesia experience severe thermal stress 7 to 10 times between 2045 and 2054.

*Onset of decade projected to have at least two thermal stress events likely to induce a bleaching response – RCP2.6 and 8.5*

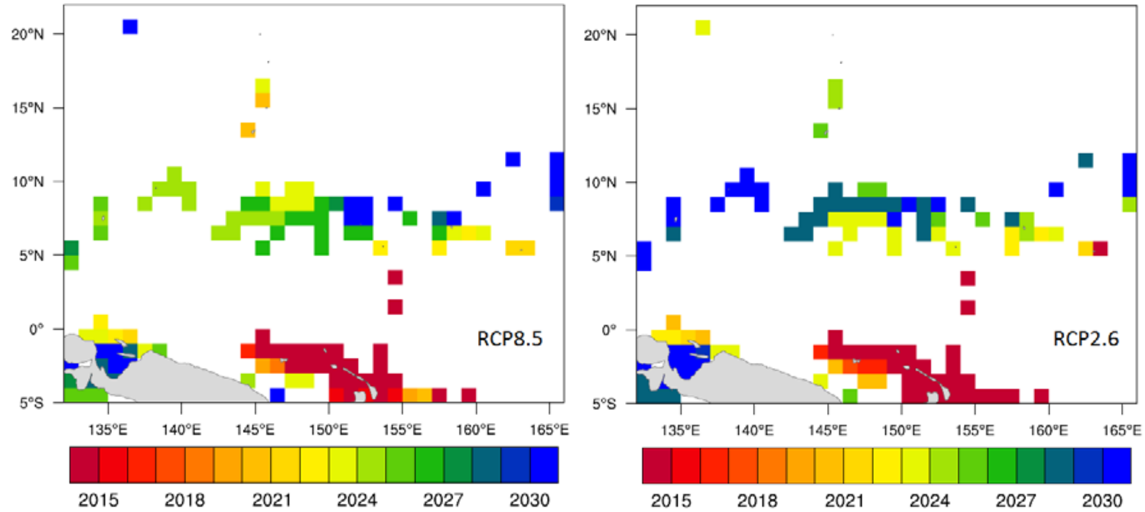


**Figure 6. Projected year marking the onset of a decade projected to have at least two thermal stress events likely to induce a bleaching response under RCP8.5 and 2.6.**

The left panel (RCP 8.5) shows that at least two thermal stress events likely to induce bleaching response are projected per decade *before* 2030 for reef areas across Micronesia. For CNMI, the models suggest that reefs are projected to experience 2 thermal stress events per decade by ~2020. In other words, based on the model projections, in less than a decade, CNMI is likely to experience repeated thermal stress events sufficient to cause reefs to rapidly degrade. However, there will be a lot of spatial variability on how these conditions affect coral reef communities at fine scales, reinforcing the need to identify potentially resistant/resilience coral reef areas. The right panel (RCP 2.6) shows that at least two thermal stress events likely to induce a bleaching response are projected per decade by 2030 for reef areas across Micronesia under RCP 2.6. This amounts to an average return time between thermal stress events of 5 years or less, allowing little time for reefs to recover if major bleaching occurs. For CNMI, under the RCP 2.6 and 8.5, reefs are projected to experience two thermal stress events per decade by 2020-2025.

*Annual thermal stress events likely to induce a bleaching response – RCP2.6 and 8.5*

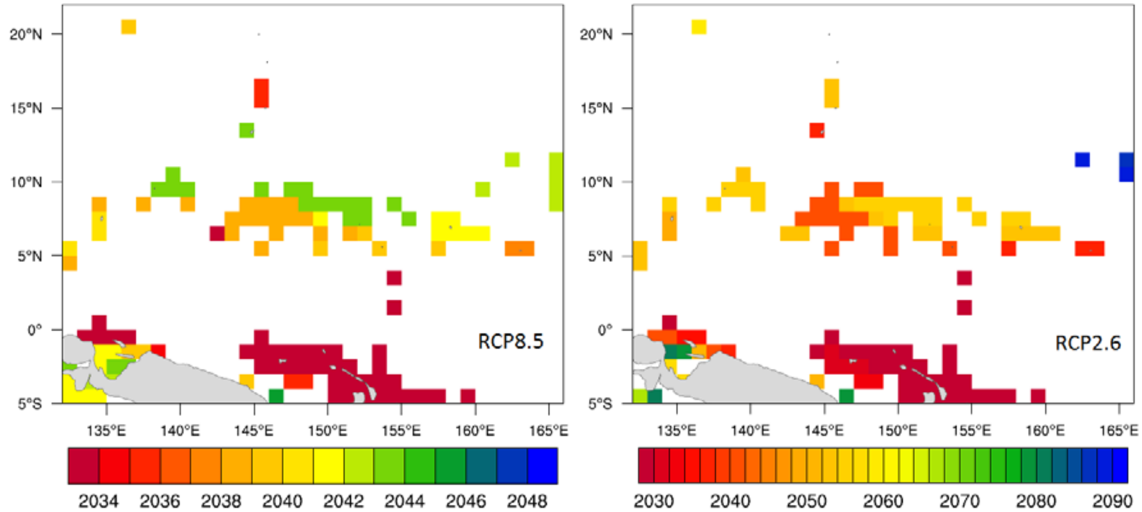


**Figure 7. Projected year marking the onset of a decade projected to have ten thermal stress events likely to induce a bleaching response (annual bleaching conditions) under RCP8.5 and 2.6.**

The left panel (RCP 8.5) shows that much of Micronesia (including CNMI) is projected to experience annual thermal stress events likely to induce a bleaching response by 2040 and by 2060 under RCP 2.6 (right panel). CNMI is projected to experience these events by the middle of the century.

***Phase 2 – Field-based resilience assessments***

Resilience assessments were conducted for 35 locations around Saipan using standard field-based protocols (Appendix 1). Resilience scores ranged from 0.84 (Forbidden Island) to 0.45 (Fishing Base Staghorn) (Figure 8; Table 1). High resilience scores were found for 23 sites (~65% of sites ranged between 0.8 and 1.0, based upon anchored resiliency scores), medium resiliency scores were found for 9 sites (26% of sites ranged between 0.6 and 0.79), and low resiliency scores were found for 3 sites (9% of sites scored <0.59) (Table 1). Principle components analysis (PCA) indicated that high and medium resilience sites were distinguished from low resilience sites by having higher coral diversity, recruitment, and bleaching resistance (Figure 9). Conversely, low resilience sites were characterized by high fishing access, nutrient input and sedimentation, and low coral diversity (Figure 9). This can be seen in the spatial patterns in resilience potential around Saipan (Figures 10 and 11). Most outer reef sites have similar resilience scores and the low resilience sites are all in the lagoon where fishing access is greatest and coral diversity lowest (see sites numbered 33, 34 and 35; Figure 11).

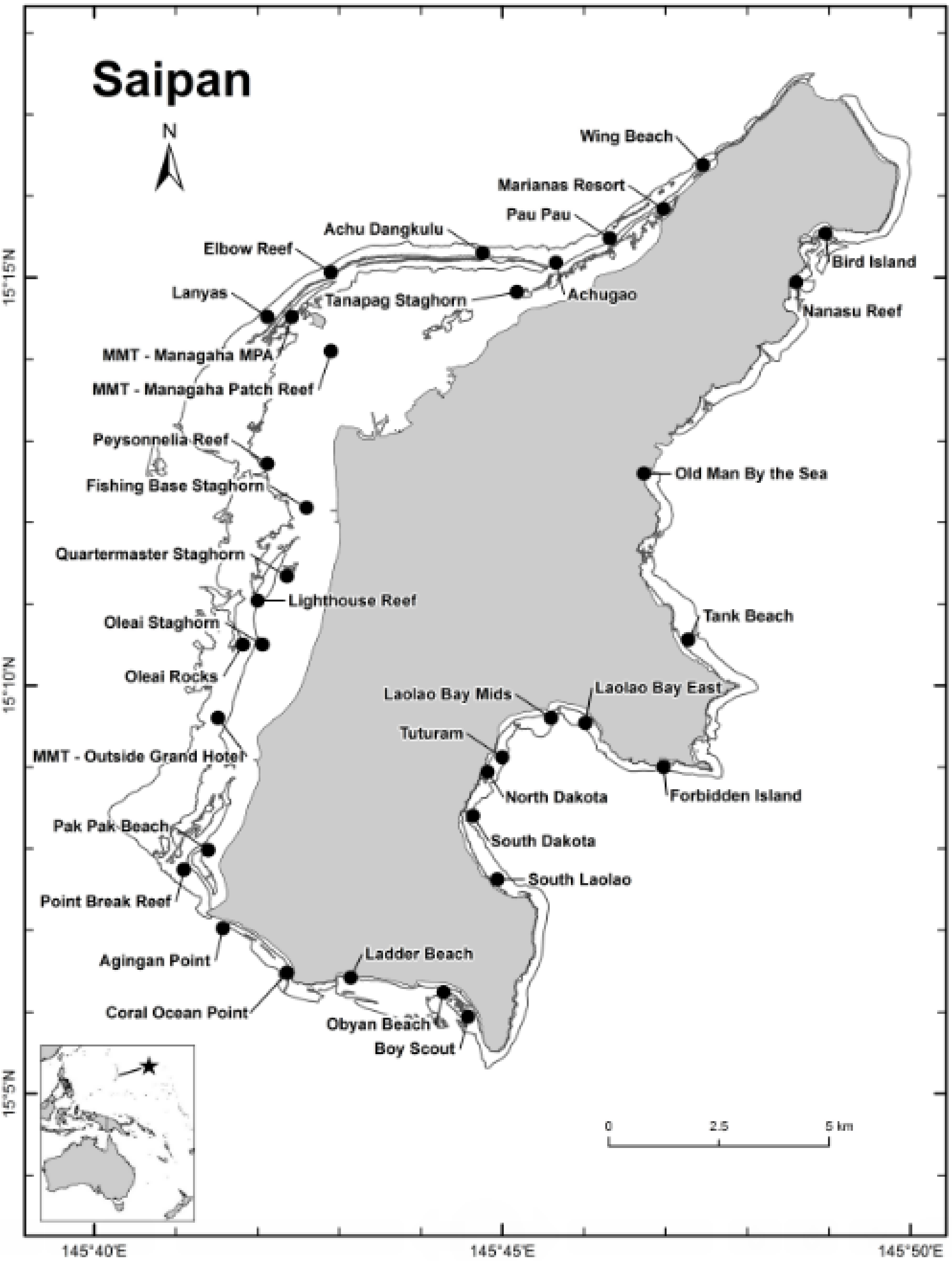


**Figure 8. Site Map - Locations and names of all 35 survey sites; sites were surveyed between March and May of 2012.**

**Table 1. Summary of anchored scores for all variables and the final resilience and anchored resilience scores.** * denotes variables where scales had to be reversed such that high scores are always good scores (e.g., scores close to 1 mean low or no macroalgae cover, nutrient input, sedimentation or fishing access).

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 | 1.00 |
| Bird Island | 2 | 0.99 | 0.83 | 0.98 | 0.41 | 0.68 | 0.99 | 1.00 | 1.00 | 0.81 | 0.57 | 1.00 |
| Lanyas | 3 | 0.98 | 0.82 | 0.98 | 0.77 | 0.67 | 0.97 | 0.35 | 1.00 | 0.93 | 0.73 | 1.00 |
| Nanasu Reef | 4 | 0.95 | 0.81 | 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 | 1.00 |
| 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 | 0.74 | 0.99 | 0.73 | 0.84 | 0.96 | 0.14 | 0.66 | 0.88 | 0.66 | 0.94 |
| Laolao Bay East | 8 | 0.89 | 0.76 | 0.96 | 1.00 | 0.92 | 0.97 | 0.37 | 0.99 | 0.87 | 0.64 | 0.01 |
| Agingan Point | 9 | 0.86 | 0.75 | 0.94 | 0.94 | 0.76 | 0.98 | 0.20 | 1.00 | 0.92 | 0.71 | 0.07 |
| Oleai Rocks | 10 | 0.86 | 0.78 | 0.96 | 0.75 | 0.66 | 0.95 | 0.44 | 1.00 | 0.93 | 0.73 | 0.06 |
| Laolao Bay Mids | 11 | 0.85 | 0.73 | 0.95 | 0.59 | 0.72 | 0.97 | 0.60 | 0.99 | 0.90 | 0.68 | 0.05 |
| North Dakota | 12 | 0.85 | 0.76 | 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 | 0.75 | 0.95 | 0.76 | 0.70 | 0.96 | 0.27 | 1.00 | 0.93 | 0.73 | 0.07 |
| Pau Pau | 15 | 0.84 | 0.75 | 0.97 | 0.77 | 0.61 | 0.97 | 0.32 | 1.00 | 0.93 | 0.73 | 0.06 |
| Achu Dangkulu | 16 | 0.84 | 0.76 | 0.98 | 0.62 | 0.77 | 0.97 | 0.09 | 1.00 | 0.93 | 0.73 | 0.25 |
| Boy Scout | 17 | 0.83 | 0.74 | 0.98 | 0.70 | 0.80 | 0.96 | 0.36 | 1.00 | 0.85 | 0.61 | 0.03 |
| South Dakota | 18 | 0.82 | 0.68 | 0.98 | 0.34 | 0.92 | 0.96 | 0.15 | 0.54 | 0.88 | 0.66 | 0.79 |
| Wing Beach | 19 | 0.82 | 0.70 | 0.98 | 0.76 | 0.57 | 0.99 | 0.17 | 1.00 | 0.93 | 0.73 | 0.08 |
| Lighthouse Reef | 20 | 0.82 | 0.75 | 0.99 | 0.45 | 0.81 | 0.95 | 0.31 | 1.00 | 0.93 | 0.73 | 0.02 |
| Ladder Beach | 21 | 0.82 | 0.70 | 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 | 0.74 | 0.98 | 0.48 | 0.79 | 0.96 | 0.23 | 1.00 | 0.93 | 0.73 | 0.06 |
| Elbow Reef | 23 | 0.82 | 0.75 | 1.00 | 0.47 | 0.71 | 0.97 | 0.11 | 1.00 | 0.93 | 0.73 | 0.25 |
| Oleai Staghorn | 24 | 0.79 | 0.72 | 0.72 | 0.17 | 1.00 | 0.95 | 0.62 | 0.84 | 0.93 | 0.73 | 0.00 |
| Coral Ocean Point | 25 | 0.77 | 0.67 | 1.00 | 0.66 | 0.58 | 0.96 | 0.20 | 1.00 | 0.81 | 0.56 | 0.06 |
| Achugao | 26 | 0.77 | 0.70 | 0.97 | 0.63 | 0.45 | 0.96 | 0.08 | 1.00 | 0.93 | 0.73 | 0.06 |
| Tanapag Staghorn | 27 | 0.72 | 0.63 | 0.80 | 0.34 | 0.93 | 0.97 | 0.24 | 0.85 | 0.76 | 0.51 | 0.00 |
| 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 | 1.00 |
| Pak Pak Beach | 29 | 0.70 | 0.60 | 0.93 | 0.24 | 0.51 | 0.96 | 0.04 | 0.96 | 0.93 | 0.73 | 0.01 |
| Tuturam | 30 | 0.70 | 0.62 | 0.98 | 0.59 | 0.82 | 0.96 | 0.13 | 0.00 | 0.84 | 0.59 | 0.35 |
| Tank Beach | 31 | 0.69 | 0.55 | 0.99 | 0.43 | 0.78 | 0.96 | 0.08 | 1.00 | 0.00 | 0.00 | 1.00 |
| Peysonnelia Reef | 32 | 0.66 | 0.62 | 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 | 0.00 |
| Quartermaster Staghorn | 34 | 0.53 | 0.50 | 0.10 | 0.07 | 0.23 | 0.95 | 0.42 | 0.55 | 0.93 | 0.73 | 0.01 |
| Fishing Base Staghorn | 35 | 0.49 | 0.45 | 0.00 | 0.00 | 0.00 | 0.96 | 0.13 | 1.00 | 0.91 | 0.69 | 0.01 |

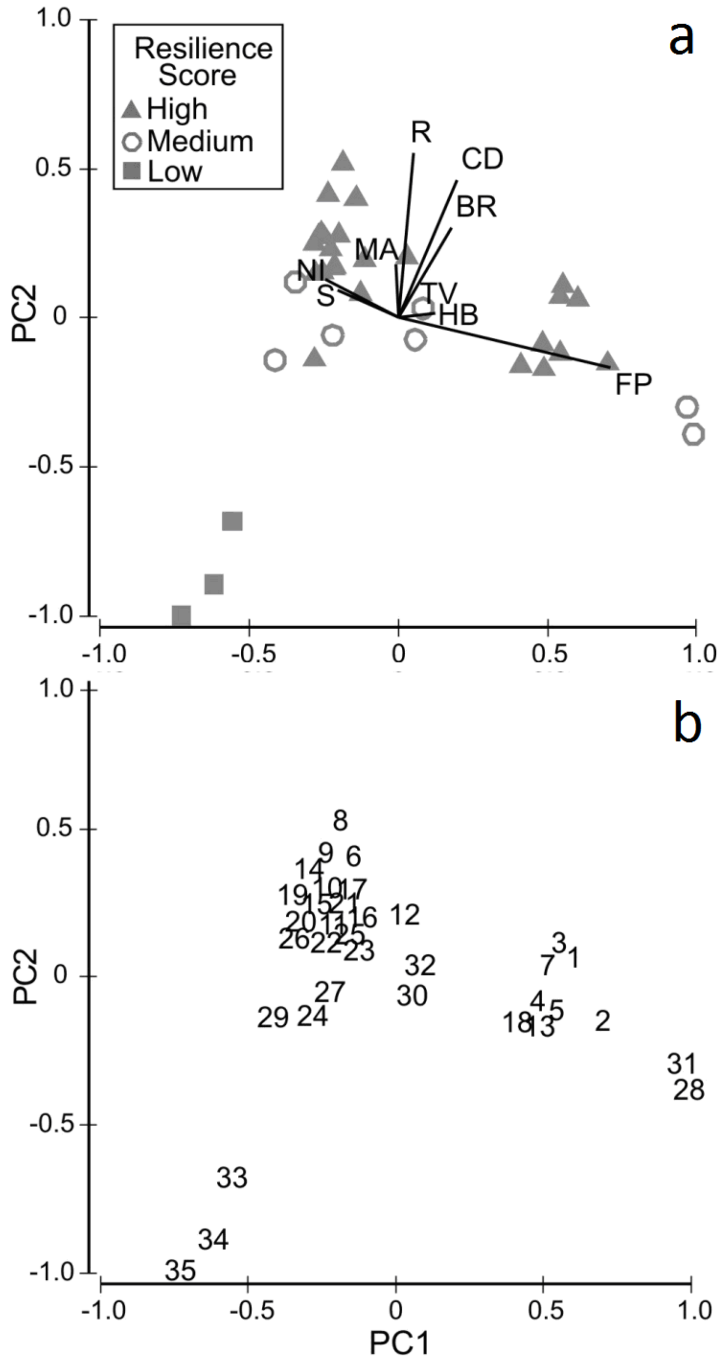


**Figure 9. Principle components analysis (PCA) results indicating that coral diversity, bleaching resistance, recruitment, macroalgae cover, and the three anthropogenic stressors – fishing access, nutrient input, and sedimentation – all distinguish the low, medium and high resilience sites (a). The positions of each site (numbers are resilience rankings) along the PC axes are shown in (b).**

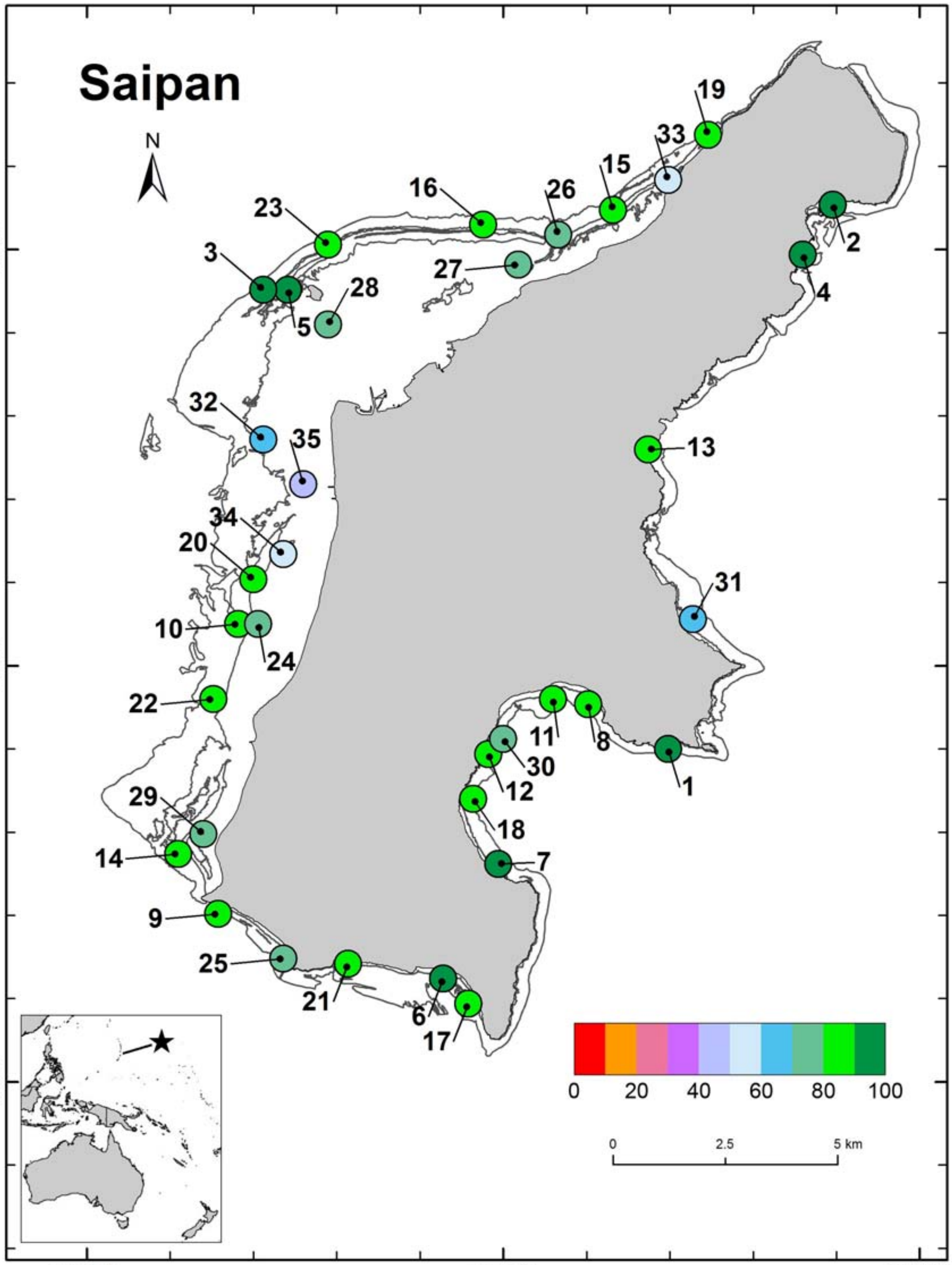


**Figure 10. Anchored resilience scores for the survey sites.** Shades of green indicate the high resilience sites and blues indicate the medium and low resilience sites.

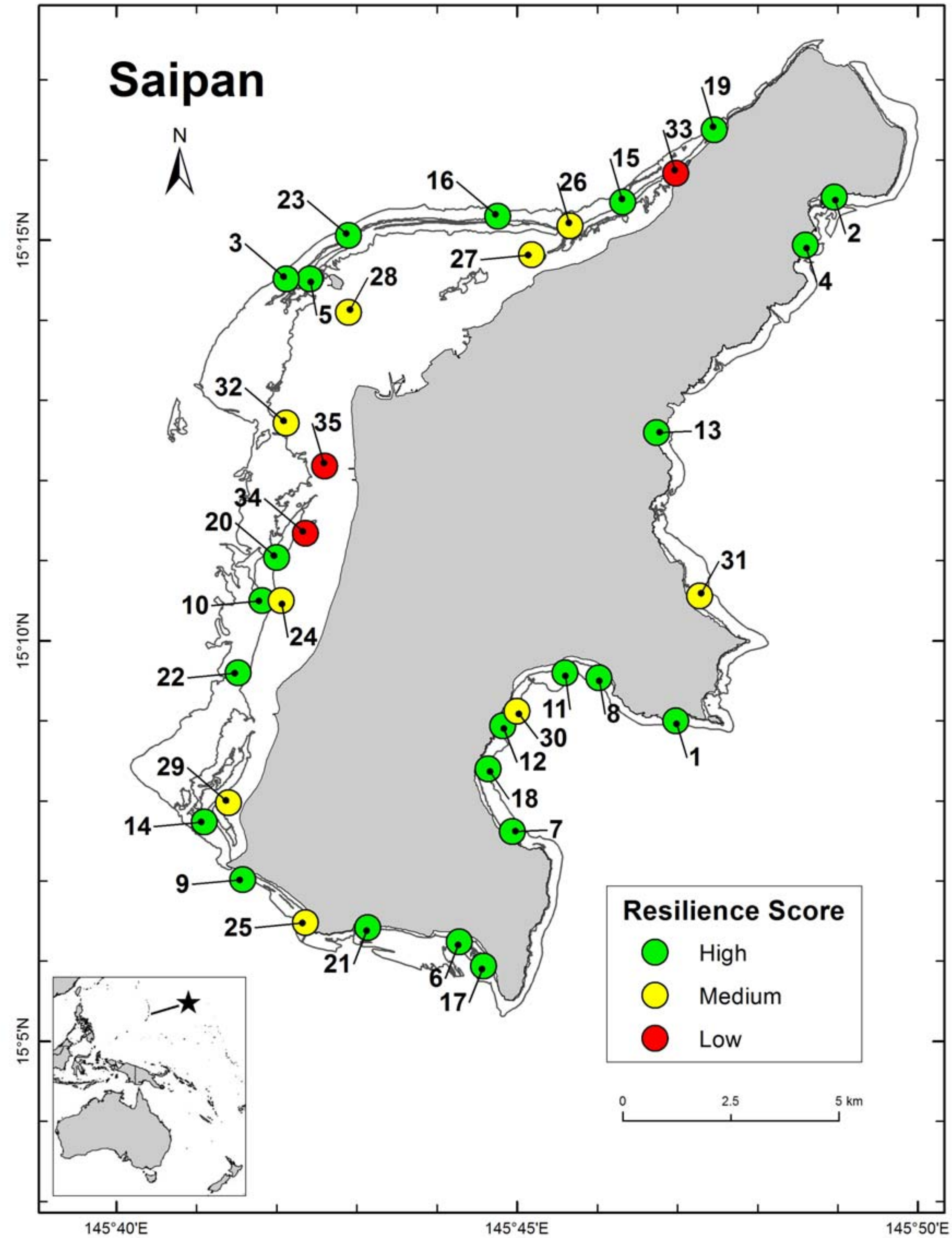


**Figure 11. Resilience scores classified as high (0.8-1.0), medium (0.6-0.79) and low (<0.6).**

Anthropogenic stress scores were produced by averaging anchored scores for nutrient input, sedimentation and fishing access. Then anchoring these scores allowed us to describe anthropogenic stress at each site relative to the site assessed as having the lowest anthropogenic stress of all of the surveyed sites. This process yielded 7 sites with low anthropogenic stress (1.0-0.8), 20 with medium (0.79-0.6), and 8 with high (<0.6); these are shown as green, yellow and red respectively in Table 2 and Figure 12. The mechanisms through which nutrients and sediments are transported to reefs are similar so the spatial patterns in these stressors are also very similar. Spatial variability around Saipan in nutrient input and sedimentation is far greater than with fishing access, which is assessed as being high at most of the surveyed sites (see Figure 12). Fishing accesss here is calculated using wave exposure as a proxy for access so many sites in LaoLao Bay, the south, lagoon and western outer reef are assessed here as having high fishing access. High levels of combined anthropogenic stress (nutrient input, sedimentation and fishing access;  red in Table 2 and Figure 12) are found at locations exposed to run-off that are easy to access due to low wave exposure. There are 8 of these locations: Obyan Beach, LaoLao Bay East, Boy Scout, Coral Ocean Point, Tanapag Staghorn, Managaha Patch Reef, Tank Beach, and Peysonnelia Reef. Three of these sites – Obyan Beach, LaoLao Bay East and Boy Scout – have high resilience so can be considered priorities for local-scale actions to reduce the three anthropogenic stressors.

**Table 2. Average scores for anthropogenic stress (nutrient input, sedimentation and fishing access), and anchored score for anthropogenic stress set to the site with the lowest anthropogenic stress.** Anthropogenic stress is rated as low (anchored score of 1-0.8), medium (0.79-0.6) and high (<0.6).

Anthropogenic Stress:
= Low
= Medium
= 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 |

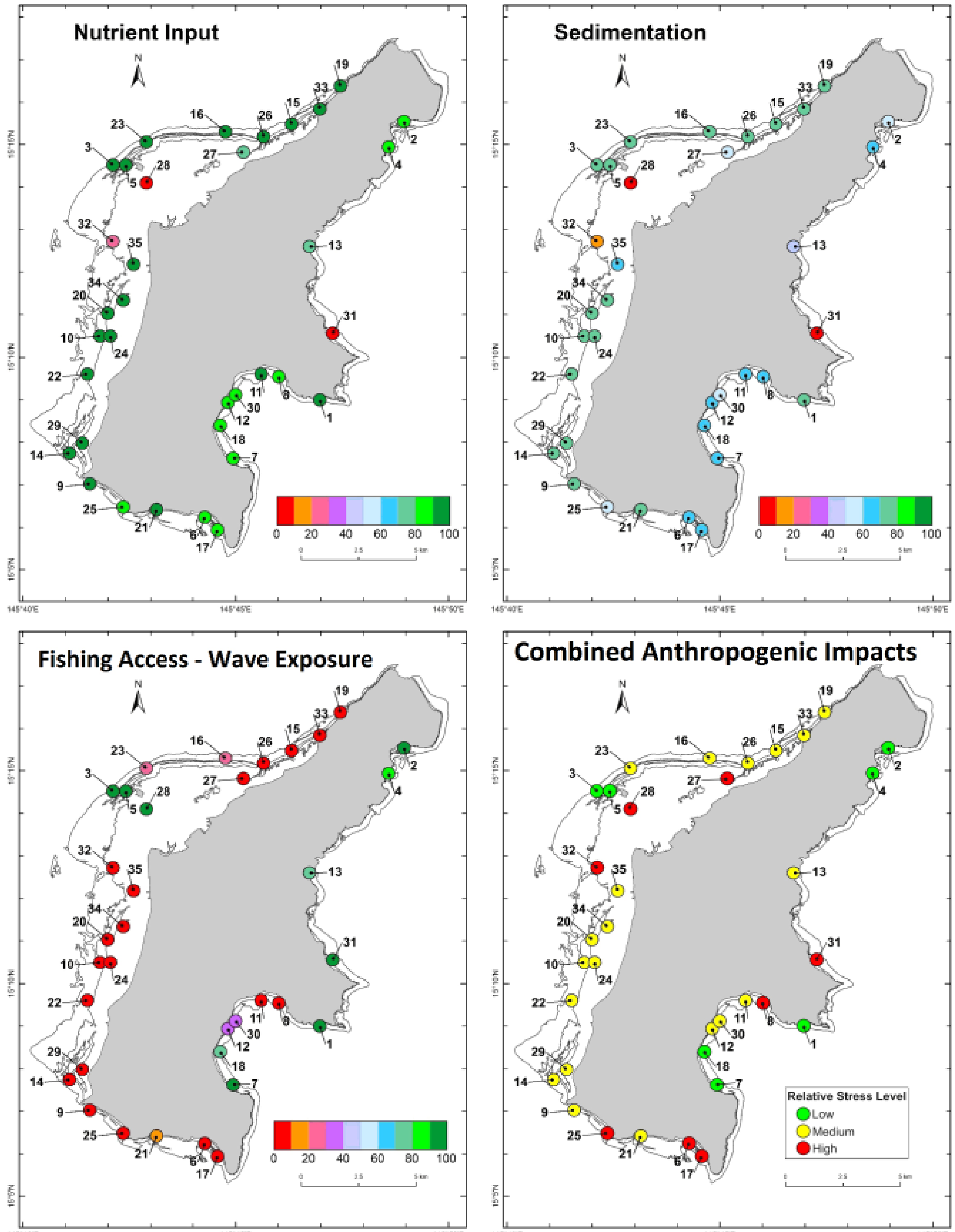


**Figure 12. Maps for each of the three individual anthropogenic stressors and the combined anthropogenic stress scores (see Table 2) for low, medium and high classifications.**

For locations highly susceptible to bleaching, factors such as herbivore biomass and fishing access are particularly important. Herbivory is important at locations with high susceptibility to bleaching (relative to other sites in the area) because herbivores can reduce the cover of macroalgae which is a major competitor of corals. Healthy herbivore populations can help facilitate the recovery of coral populations following bleaching or other disturbance events that cause coral mortality.

Seven locations (20% of those surveyed) are highly susceptible to bleaching (i.e., sites where the bleaching resistance (anchored) score is less than 0.60; Table 3). Bleaching resistance here is the percentage of the community made up by coral species that are generally resistant to bleaching. These bleaching susceptible locations will recover more slowly if processes like herbivory are not intact. Herbivore biomass is less than 50% of that seen at the site with the max herbivore biomass (anchored scores <0.5, Table 3). Further, fishing access based on wave exposure is high at all seven of these locations. These locations are likely to be amongst the most vulnerable surveyed given their sensitivity to bleaching and their accessibility to fishers, which may lengthen recovery timeframes between disturbance events. These sites warrant special attention during management and conservation planning.

**Table 3. Vulnerable sites with low scores for bleaching resistance, low herbivore biomass and high fishing access based on wave exposure.**

| Rank | Site name | Bleaching resistance | Herbivore biomass | Fishing Access |
|---|---|---|---|---|
| 35 | Fishing Base Staghorn | 0 | 0.13 | 0.01 |
| 33 | Marianas Resort | 0.23 | 0.26 | 0 |
| 34 | Quartermaster Staghorn | 0.23 | 0.42 | 0.01 |
| 26 | Achugao | 0.45 | 0.08 | 0.06 |
| 29 | Pak Pak Beach | 0.51 | 0.04 | 0.01 |
| 19 | Wing Beach | 0.57 | 0.17 | 0.08 |
| 25 | Coral Ocean Point | 0.58 | 0.2 | 0.06 |

*Phase 3 - Management recommendations and capacity building*

## Management recommendations

Key results relevant to managers from the remote sensing and climate modeling include a >3°C change in temperature projected for all sites in Micronesia by 2100; bleaching conditions projected to occur annually at all sites by 2050; and bleaching conditions projected to occur 2x per decade at all sites by 2025. There are spatial patterns in the year when reefs are projected to experience annual and 2x per decade bleaching conditions that are similar between the two emissions scenarios (RCP 2.6 and 8.5). The far eastern portion of Micronesia is projected to experience annual and 2x per decade bleaching conditions later than the rest of Micronesia; coral reefs in this area could represent regional conservation priorities. However, climate projections are highly uncertain. Based on our results from project phase 1, we suggest that managers build resilience into marine managed areas across Micronesia to reduce the risk of coral reefs succumbing to a combination of climate-related and other human stressors.

Based on the resilience analysis above, our team has made the following suggestions to coral reef and coastal managers working in CNMI:

- Obyan Beach, LaoLao Bay East, Agingan Point, and Oleai rocks are the four sites with resilience scores in the top ten that are currently unprotected, and have high fishing access based on wave exposure. These are strong candidates for area based management since they have high resilience potential and are not protected from fishing by wave exposure. Further, coral diversity is extremely high at these locations. Another benefit of protecting these sites is that they are also likely to create positive growth opportunities for local dive and snorkel-based tourism operations.

- There are three sites with high resilience scores that have high anthropogenic stress: Obyan Beach, LaoLao Bay East, and Boy Scout. These warrant special consideration from managers as they represent priorities for targeted actions to reduce anthropogenic stress, specifically reducing nutrient input, sedimentation, and fishing access.

- The largest driver of the relative resilience rankings is a proxy for fishing pressure (fishing access based on wave exposure), and can be addressed through management action. Without exception, the sites with high resilience scores have low fishing access based on wave exposure, high herbivore biomass and low macroalgae cover. Suites of actions to reduce any pressure due to access, implemented where possible and appropriate, will increase resilience potential at many sites around Saipan and need to be an ongoing management consideration.

- All of the sites assessed as having low or medium resilience have very low scores for one or more of: nutrient input, sedimentation, and fishing access. Scores for all of the other variables vary less among the pool of sites than these three anthropogenic stressors. Whole-of-island and local-scale targeted actions to reduce these stressors will maximize the number of healthy reef sites around Saipan as the frequency of climate-related disturbances increases.

- The three sites with low relative resilience – Marianas Resort, Quartermaster Staghorn, and Fishing Base Staghorn – are all highly vulnerable to temperature-induced bleaching. This is also true for Achugao, Pak Pak Beach, Wing Beach, and Coral Ocean Point. At all seven of these locations, bleaching resistance is low (<0.6), herbivore biomass is less than half of that seen at the site with the max biomass, and fishing access is high. These are vulnerable locations that warrant special consideration from managers. Three of these – Marianas Resport, Quartermaster Staghorn and Fishing Base Staghorn - are also critical lagoonal nursery habitats for fish. These areas could be a focus of community monitoring programs given their vulnerability and accessibility. People participating in the monitoring can help keep trash off these reefs, and provide early warnings of bleaching impacts at these sites if bleaching is observed.

- The analysis approach of anchoring scores to local maxima means the analysis results are sensitive to the pool of sites included in the analysis; including more sites may raise the maxima, meaning sites with current high relative scores may have medium or low relative scores and vice versa. This is critically important in CNMI where most of the territory's population resides on one island, Saipan. Surveying the reefs around the lesser populated islands, like Tinian and Rota, is an important next step. Such surveys would reveal the extent to which habitat condition and reef resiliency differ between Saipan and other locations with lower anthropogenic stress (see next steps section below).

**Building local and global capacity to address climate change**

This project contributed to building local and global capacity to address climate change by producing tools (vulnerability maps, GIS data layers, "how-to-guide") to help managers assess climate impacts and resilience and to share project outputs with international scientific and management communities (project objectives 3 and 4). The vulnerability maps produced from the desktop study (remote sensing and climate projections) and field based resilience assessment will help to ensure that vulnerability to climate change is a consideration to inform marine conservation efforts in CNMI. To build capacity to conduct future resilience analyses, a "how-to-guide" (Attachment 5) was prepared to provide a detailed explanation of how to conduct a resilience assessment including selection of resilience indicators and methods for collecting and analyzing data.

All product outputs including: raw data in excel, how-to-guide, vulnerability maps, GIS geodatabases and shapefiles for all resilience and anthropogenic indicators have been shared with local partners in CNMI (Pacific Marine Resources Institute, CNMI Division of Environmental Quality, CNMI Division of Fish and Wildlife, CNMI Coastal Resources Management Office) including MCT. Once the regional MC database is completed, the datasets from this project (historical SSTs, bleaching thresholds, climate projections, and bleaching and resilience indicators) and coral reef vulnerability maps will be added.

A number of presentations were delivered by the project team in CNMI to share project results. A presentation was given to the CNMI Climate Change Working Group in July 2012 and highlighted anthropogenic impacts in Saipan based on project results (links between fishing pressure and herbivore biomass), and a presentation was delivered to the CNMI Watershed Working Group in August 2012 focusing on the watershed management implications of the study (e.g., nutrient pollution, sedimentation). The project results were also highlighted at the U.S. Coral Reef Task Force in August in American Samoa.

Additionally, the Nature Conservancy's Reef Resilience Network provides the latest tools, innovations, and insights to support coral reef practitioners and managers worldwide. One of the central tools of the Network, the Reef Resilience Toolkit, is currently under revision with an anticipated launch of January 2013. The data analysis methods and summary of these project results have been contributed to the toolkit and will be included in the associated resilience trainings to ensure that the resilience approach implemented through this project will be accessible to coral reef managers worldwide.

**Next steps**

The lead investigator, J. Maynard, will continue to work closely with managers from CNMI's Division of Environmental Quality and the local NOAA fisheries field office for at least 18 months from this report's submission date. The team will work together to provide guidance for local managers based on the implications of the findings from the resilience analysis. Over the next several months, the project team will share project results in relevant conservation meetings. The project team is also preparing a manuscript on the resilience analysis for a conservation journal. This manuscript will address a critical science gap for conservation managers by providing much needed case studies of the development and implementation of resilience assessments based on the latest recommendations from global experts. The project results will also be presented at an upcoming MPA workshop planned for October in Saipan to explore the current structure of MPAs. A presentation on the project results is also planned in November at the annual symposium of the Asia-Pacific Academy of Science, Education, and Environmental Management (APASEEM).

In mid-2013 (May and June), the project team is planning further fieldwork in CNMI. A research proposal has been submitted to NOAA's Coral Reef Conservation Program to increase the geographic extent of the fieldwork and resilience analysis described here. The current project plan includes surveying 40 sites around the islands of Tinian and Rota (FY13) and potentially Guam (FY14). The same field and desktop methodologies will be applied as presented in this report, and the same approach will be used to analyze the data. Following the fieldwork, the project team will be able to re-assess the maxima for each variable used to anchor scores in the present analysis, thus increasing our understanding of the effects of anthropogenic stressors on relative resilience potential. For example, a site currently thought to have high herbivore biomass (when the Saipan biomass maxima is used) may have low biomass relative to that found on reefs around Tinian and/or Rota, which are largely unexplored. Expected outcomes of the proposed 2013 fieldwork and analysis include: 1) a revised analysis of the relative resilience potential of sites throughout CNMI that is inclusive of sites near populated and unpopulated areas; 2) a report containing management recommendations to all local government agencies regarding actions to reduce stress on reefs and support recovery processes; 3) a publication on resilience analysis methodologies focusing on ways to maximize distinguishing sites at the local-scale while also being able to compare results between geographically disparate areas; and 4) user-friendly tools for practitioners based on (3).

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**Appendix 1. Methods and materials.**

**Methods**

Methods descriptions below are divided between two major project phases: remote sensing and climate modeling, and field-based assessments of resilience potential.

**Remote sensing and climate modeling**

*Remote sensing*

*Data source and analysis* – Observed sea surface temperature (SST) data for the period 1982-2010 was obtained from NOAA AVHRR Pathfinder Version 5.2, which has a resolution of 4 km (http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/). The data was quality screened; only data with a quality flag of 4 or greater was used. For each pixel the maximum monthly mean (MMM) was calculated – this is the month of the year with the highest average temperatures during the 28-yr period. The month with the MMM and one month either side was considered the 12 week summer period. Daily temperatures above the MMM are positive anomalies. With a unit of deg. C these positive anomalies are degree heating days (see Maynard et al. 2008). The sum total number of degree heating days during the 12-week summer period was divided by 7 to calculate degree heating weeks (DHWs). The threshold above which bleaching is projected to occur was set at 6 DHWs (van Hooidonk and Huber 2009a). Here, 6 DHWs occurring during a year is called a 'thermal stress event', meaning an event likely to induce a bleaching response though bleaching was not necessarily directly observed.

*Outputs* – The SST data compiled were used to produce two outputs for the Micronesia region.

1) Map of the average frequency of thermal stress events likely to induce a bleaching response (>6 DHWs) per decade between 1982 and 2010.

Thermal stress event frequency is only shown on the map graphic for pixels where reefs occur. Reef locations are derived from the merged ReefBase/UNEP-WCMC and Millennium Coral Reef Mapping Project reefs database (http://imars.usf.edu/MC/index.html). Bleaching is likely to have been a more important driver of habitat condition and ecosystem dynamics on reefs where thermal stress event frequency is high relative to other sites in the region. This and all other maps have been made available to project partners as images and ArcGIS shape files.

2) Map of 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. During similarly stressful events, reefs with high variability in temperatures during the summer period have been observed to bleach less severely than reefs with low temperature variability (Guest et al. 2010). It is unknown, however, how variable temperatures need to be for an increase in temperature tolerance to be noted. Whether there is a thermal threshold beyond which there is no benefit from past temperature variability is also unknown but is likely.

## Climate modeling

*Data source and analysis* - Modeled SST data was retrieved for the relative concentration pathway experiments (RCP 2.6 and 8.5) for each available General Circulation Model (GCM) from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 5 (CMIP5) data set at http://pcmdi3.llnl.gov. The RCP experiments describe future forcing conditions, and the experiment name indicates the total forcing in watts/$m^2$ at the year 2100. RCP8.5 can be characterized by business-as-usual aggressive emissions growth with reductions anywhere heavily outweighed by increases in other locations; emissions do not stabilize in this experiment. In contrast, RCP2.6 presents an alternate future with 40% emissions reductions by 2040 and 80% by 2080.

Correcting model means ensures projections of the timing and severity of future thermal stress events are not severe underestimates (van Hooidonk and Huber 2011). To match the start of each model with the observed climatology, the models' mean temperature were corrected using observational data from the NOAA Optimal Interpolated SST V2 (Reynolds 2002) obtained from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, (http://www.esrl.noaa.gov/psd/ ). This dataset is computed weekly at 1°x1° resolution, and combines in situ and satellite data. Model means were corrected at each location by subtracting the 2006-2011 mean of each model and adding the mean of the OISST 1982-2005 climatology to the entire time series. To further prevent underestimation of thermal stress, the annual cycles in the models were also replaced with those from the observed climatology (van Hooidonk and Huber 2011).

Reef locations were selected based on the same map used to produce the remote sensing outputs (see above). A model cell was noted as having a reef if there was at least one reef within that 1° X 1° cell. To ensure data was available at all reef locations, missing values like near-coast pixels were filled in using a nearest-neighbor algorithm. Available GCMs for each of the two RCP experiments used were grouped as ensembles and DHWs were projected from 2010-2100 using the corrected modeled SST data. GCM-based SST data is made available at a temporal resolution of a month. The three-month period when bleaching is most likely has the month with the highest average temperatures, the 'MMM', as the middle month. For each RCP experiment, the anomalies for these three months were summed to get Degree Heating Months. These are converted to DHWs by multiplying them by the mean number of weeks in a month (4.3). This does not create true DHWs, as it does not include weekly variability. This is a necessary compromise in order to be able to compare the model DHWs with previously established bleaching thresholds.

*Outputs*

The modeled SST data and associated projections of thermal stress events were used to produce four outputs for each of the two RCP experiments used. All outputs are maps of the Micronesia region.

1) Projected temperature trends this century – the projected change in temperature between 2010 and 2100.

2) Frequency of thermal stress events per decade – the number of thermal stress events likely to induce a bleaching response (>6 DHWs) projected for the following periods: 2015-2024, 2025-2034, 2035-2044, and 2045-2054.

3) Projected year 2x per decade bleaching begins – the year in which a decade begins that is projected to have at least 2 thermal stress events likely to induce a bleaching response. This amounts to an average return time between events of 5 years or less.

4) Projected year 10x per decade (annual) bleaching begins – the year in which, from that point forward, a thermal stress event likely to induce a bleaching response is projected to occur every single year.

**Field-based resilience assessments**

*Data collection*

Eleven variables are included in the resilience analysis, based on the site selection framework described in McClanahan et al. (2012). Data were collected and compiled on all 11 in Saipan from March to May of 2012 at a total of 35 sites. Appendix 2 contains the survey site coordinates and Figure 8 shows the site locations. Survey and assessment methodologies used for each variable are described below with variables categorized as having been assessed in the field or via a desktop analysis.

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 5cm 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 (Green and Bellwood 2009) 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 access. The methodologies used to assess each are described below.

Temperature variability: See number 2 under 'Outputs' in the Remote Sensing section of the Methods on page 25.

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 (www7.ncdc.noaa.gov/), and used as inputs to calculate wave height as following Ekebom et al. (2003). Specifically, mean height was calculated by:

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

$H_m$ 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.

## Data analysis

### *Resilience potential*

Nine variables were used to calculate resilience potential - coral diversity, recruitment, herbivore biomass, bleaching resistance, temperature variability, macroalgae cover, nutrient input, sedimentation and fishing access. To calculate resilience potential (the final output) values for each variable were first anchored to the maximum value for the variable among the pool of sites and then normalized to a 0 to 1 scale. For each variable, the site with the maximum value 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 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 the same - 0 to 1 – and be uni-directional; i.e., here, a high score is always a good score. This requires producing the inverse of the anchored score for macroalgae cover, nutrient input, sedimentation and fishing access since high levels of these are a negative rather than a positive for reef resilience.1 minus the anchored score results in the inverse such that the site with the highest values for these is 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 - is also produced by using the anchoring and normalizing procedure again whereby the site with the highest resilience score receives a 1 and so on. Both values are shown in summary tables. Sites are ranked from highest to lowest anchored resilience score. Rankings, from 1 to 35 – are the numbers used to identify the sites throughout all of the other tables and on the mapping outputs. Sites with an anchored resilience score of 0.8 to 1 are considered to have high (relative) resilience potential, 0.6-0.79 medium, and <0.6 is low; these are green, yellow and red, respectively, in the relevant mapping outputs.

A principal components analysis (PCA) was undertaken to test whether differences between sites in final resilience scores are consistently driven by a few rather than all of the variables examined.

*Anthropogenic stress*

A composite score was produced for anthropogenic stress by averaging the anchored scores for fishing access, nutrient input and sedimentation. 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 the figure caption help with interpretation of the maps that describe the anthropogenic stressors and the colors used remain intuitive in that red denotes the sites with high stress.

*Mapping outputs*

Maps have been produced using ArcGIS for resilience potential (more below), anthropogenic stress, and for each of the nine variables. Anchored scores are presented on the maps as 0 to 100 (to reflect percentage of max value) for ease of interpretation, but are from 0 to 1 in the tables (Tables 1 and 2).

## Appendix 2: Waypoints for survey sites.

| Resilience rank | Site name | Latitude (N) | Longitude (E) |
|---|---|---|---|
| 1 | Forbidden Island | 15.15 | 145.783 |
| 2 | Bird Island | 15.259 | 145.816 |
| 3 | Lanyas | 15.242 | 145.702 |
| 4 | Nanasu Reef | 15.249 | 145.81 |
| 5 | MMT - Managaha MPA | 15.242 | 145.707 |
| 6 | Obyan Beach | 15.104 | 145.738 |
| 7 | South Laolao | 15.127 | 145.749 |
| 8 | Laolao Bay East | 15.159 | 145.767 |
| 9 | Agingan Point | 15.117 | 145.693 |
| 10 | Oleai Rocks | 15.175 | 145.697 |
| 11 | Laolao Bay Mids | 15.16 | 145.76 |
| 12 | North Dakota | 15.149 | 145.747 |
| 13 | Old Man By the Sea | 15.21 | 145.779 |
| 14 | Point Break Reef | 15.129 | 145.685 |
| 15 | Pau Pau | 15.253 | 145.761 |
| 16 | Achu Dangkulu | 15.255 | 145.746 |
| 17 | Boy Scout | 15.099 | 145.743 |
| 18 | South Dakota | 15.14 | 145.744 |
| 19 | Wing Beach | 15.273 | 145.791 |
| 20 | Lighthouse Reef | 15.184 | 145.7 |
| 21 | Ladder Beach | 15.107 | 145.719 |
| 22 | MMT - Outside Grand Hotel | 15.16 | 145.692 |
| 23 | Elbow Reef | 15.251 | 145.715 |
| 24 | Oleai Staghorn | 15.175 | 145.701 |
| 25 | Coral Ocean Point | 15.108 | 145.706 |
| 26 | Achugao | 15.248 | 145.754 |
| 27 | Tanapag Staghorn | 15.247 | 145.753 |
| 28 | MMT - Managaha Patch Reef | 15.235 | 145.715 |
| 29 | Pak Pak Beach | 15.133 | 145.69 |
| 30 | Tuturam | 15.152 | 145.75 |
| 31 | Tank Beach | 15.176 | 145.788 |
| 32 | Peysonnelia Reef | 15.212 | 145.702 |
| 33 | Marianas Resort | 15.264 | 145.783 |
| 34 | Quartermaster Staghorn | 15.189 | 145.706 |
| 35 | Fishing Base Staghorn | 15.203 | 145.71 |

**Appendix 3. Table of raw data for all resilience variables.**

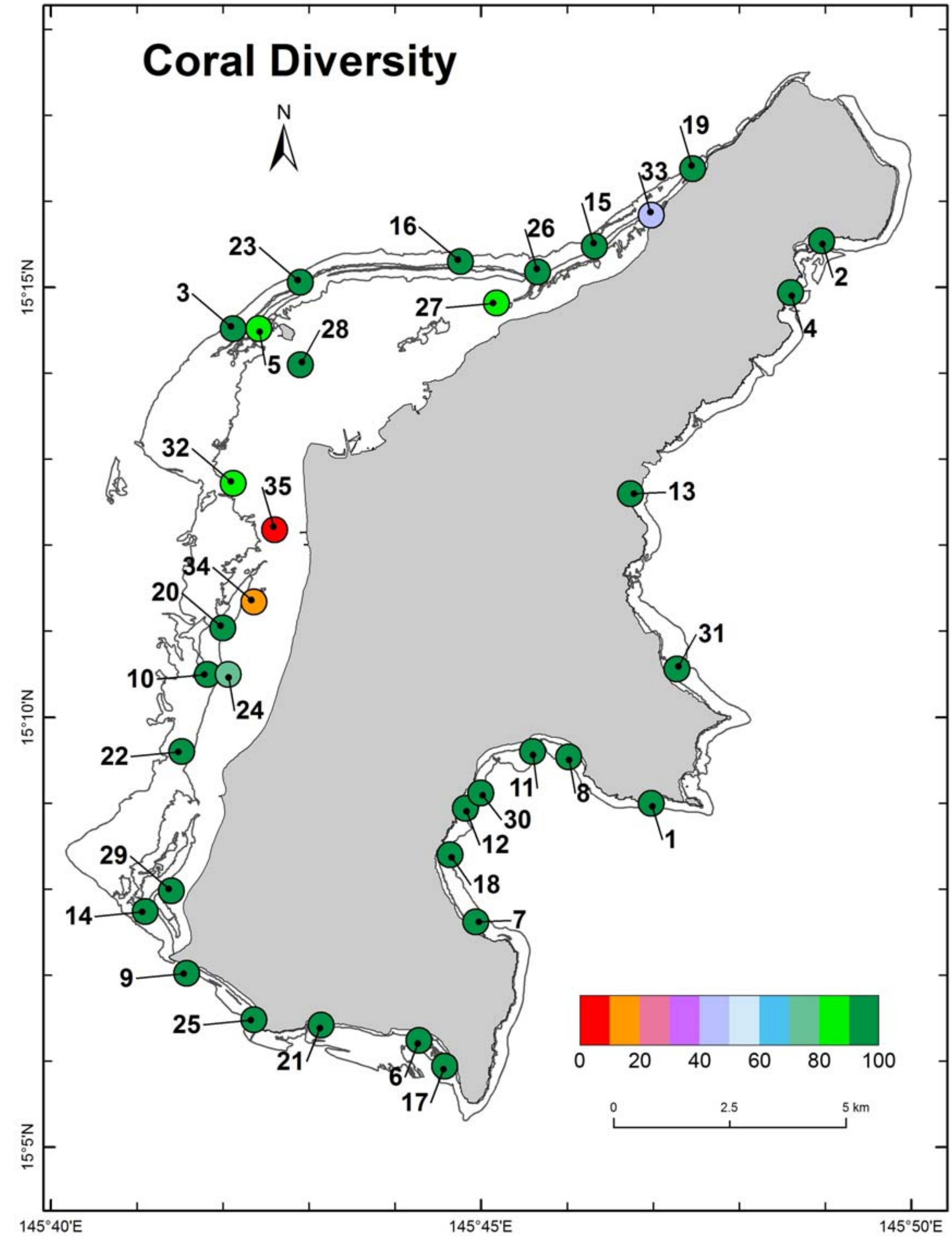
Resilience Score:
- (green) = High
- (yellow) = Medium
- (red) = Low

| Site Names | Rank | Coral Diversity | Recruitment | Bleaching Resistance | Temperature variability | Herbivore biomass | Macroalgae cover* | Nutrient input* | Sedimentation* | Fishing access* |
|---|---|---|---|---|---|---|---|---|---|---|
| Forbidden Island | 1 | 0.93 | 9.75 | 64.99 | 0.96 | 1.95 | 0.00 | 2.46 | 1.57 | 1440 |
| Bird Island | 2 | 0.95 | 5.81 | 59.91 | 0.98 | 3.33 | 0.00 | 5.18 | 2.28 | 550 |
| Lanyas | 3 | 0.94 | 11.00 | 59.66 | 0.96 | 1.18 | 0.00 | 2.04 | 1.43 | 142 |
| Nanasu Reef | 4 | 0.92 | 7.44 | 53.85 | 0.99 | 3.01 | 6.00 | 3.97 | 1.99 | 1429 |
| MMT - Managaha MPA | 5 | 0.79 | 7.58 | 71.23 | 0.96 | 1.48 | 9.33 | 2.04 | 1.43 | 12 |
| Obyan Beach | 6 | 0.95 | 13.50 | 59.27 | 0.95 | 2.65 | 0.00 | 4.41 | 2.10 | 54 |
| South Laolao | 7 | 0.95 | 10.46 | 73.95 | 0.95 | 0.47 | 24.61 | 3.22 | 1.80 | 1671 |
| Laolao Bay East | 8 | 0.93 | 14.31 | 81.79 | 0.96 | 1.25 | 1.00 | 3.67 | 1.92 | 20 |
| Agingan Point | 9 | 0.91 | 13.50 | 66.80 | 0.97 | 0.67 | 0.00 | 2.28 | 1.51 | 130 |
| Oleai Rocks | 10 | 0.92 | 10.69 | 58.52 | 0.94 | 1.47 | 0.00 | 2.04 | 1.43 | 100 |
| Laolao Bay Mids | 11 | 0.91 | 8.44 | 63.76 | 0.96 | 1.98 | 0.50 | 2.83 | 1.68 | 85 |
| North Dakota | 12 | 0.94 | 10.31 | 64.53 | 0.96 | 0.65 | 0.00 | 3.97 | 1.99 | 616 |
| Old Man By the Sea | 13 | 0.94 | 4.75 | 69.79 | 0.94 | 1.27 | 6.00 | 7.16 | 2.68 | 1397 |
| Point Break Reef | 14 | 0.92 | 10.92 | 61.98 | 0.95 | 0.90 | 0.00 | 2.04 | 1.43 | 119 |
| Pau Pau | 15 | 0.94 | 11.06 | 54.07 | 0.96 | 1.07 | 0.00 | 2.04 | 1.43 | 107 |
| Achu Dangkulu | 16 | 0.94 | 8.94 | 67.74 | 0.96 | 0.30 | 0.00 | 2.04 | 1.43 | 443 |
| Boy Scout | 17 | 0.94 | 10.06 | 70.68 | 0.95 | 1.19 | 0.00 | 4.20 | 2.05 | 57 |
| South Dakota | 18 | 0.95 | 4.81 | 80.95 | 0.95 | 0.51 | 33.67 | 3.25 | 1.80 | 1405 |
| Wing Beach | 19 | 0.94 | 10.88 | 50.59 | 0.98 | 0.57 | 0.00 | 2.04 | 1.43 | 139 |
| Lighthouse Reef | 20 | 0.95 | 6.42 | 71.85 | 0.94 | 1.02 | 0.00 | 2.04 | 1.43 | 38 |
| Ladder Beach | 21 | 0.96 | 10.19 | 54.15 | 0.95 | 0.48 | 0.00 | 2.34 | 1.53 | 223 |
| MMT - Outside Grand Hotel | 22 | 0.95 | 6.93 | 69.66 | 0.95 | 0.77 | 0.00 | 2.04 | 1.43 | 113 |
| Elbow Reef | 23 | 0.96 | 6.69 | 62.98 | 0.96 | 0.36 | 0.00 | 2.04 | 1.43 | 448 |
| Oleai Staghorn | 24 | 0.69 | 2.50 | 88.46 | 0.94 | 2.06 | 11.33 | 2.04 | 1.43 | 7 |
| Coral Ocean Point | 25 | 0.96 | 9.50 | 51.36 | 0.95 | 0.65 | 0.00 | 5.30 | 2.30 | 103 |
| Achugao | 26 | 0.94 | 9.06 | 40.07 | 0.95 | 0.26 | 0.00 | 2.04 | 1.43 | 107 |
| Tanapag Staghorn | 27 | 0.78 | 4.88 | 82.67 | 0.96 | 0.78 | 10.67 | 6.59 | 2.57 | 7 |
| MMT - Managaha Patch Reef | 28 | 0.92 | 5.08 | 64.71 | 0.95 | 1.34 | 4.00 | 27.45 | 5.24 | 30 |
| Pak Pak Beach | 29 | 0.90 | 3.38 | 45.45 | 0.95 | 0.13 | 3.00 | 2.04 | 1.43 | 16 |
| Tuturam | 30 | 0.95 | 8.38 | 72.17 | 0.95 | 0.45 | 72.44 | 4.57 | 2.14 | 614 |
| Tank Beach | 31 | 0.96 | 6.13 | 68.75 | 0.95 | 0.26 | 0.35 | 27.72 | 5.26 | 1771 |
| Peysonnelia Reef | 32 | 0.79 | 8.56 | 85.95 | 0.94 | 0.48 | 0.33 | 19.95 | 4.47 | 137 |
| Marianas Resort | 33 | 0.43 | 0.94 | 20.00 | 0.96 | 0.88 | 22.33 | 2.34 | 1.53 | 7 |
| Quartermaster Staghorn | 34 | 0.10 | 1.06 | 20.00 | 0.94 | 1.42 | 32.33 | 2.04 | 1.43 | 10 |
| Fishing Base Staghorn | 35 | 0.00 | 0.00 | 0.00 | 0.95 | 0.42 | 0.00 | 2.62 | 1.62 | 13 |

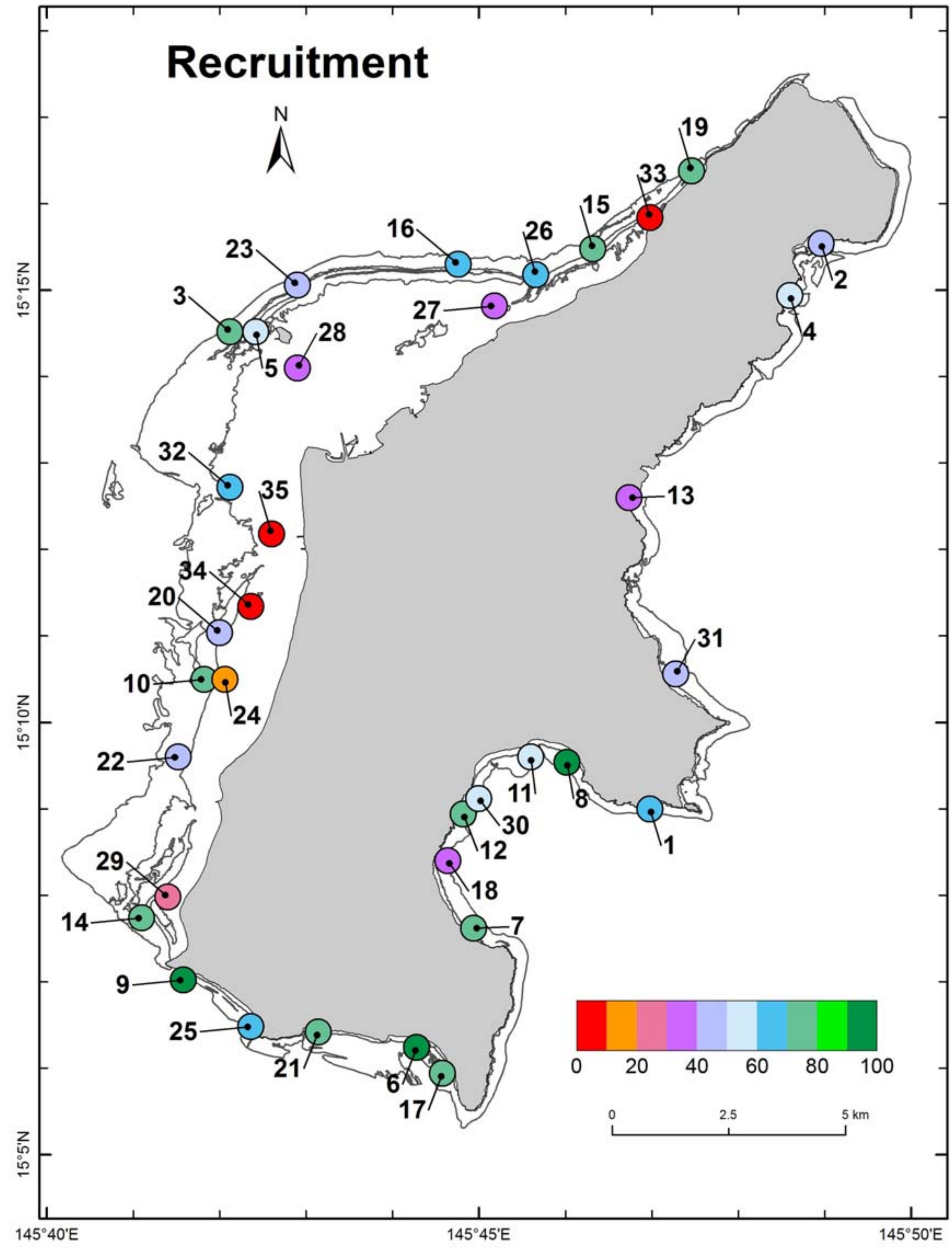
**Appendix 4. Maps showing the anchored scores for each of the resilience variables.**

Data used to produce these maps can be found in Table 1 of the Results section of the report. Coral disease and Anthropogenic physical impacts are shown here but are not included in the body of the main report or in the resilience analysis. Values for all sites for these two variables are the same; i.e., no coral disease or anthropogenic physical impacts were observed.

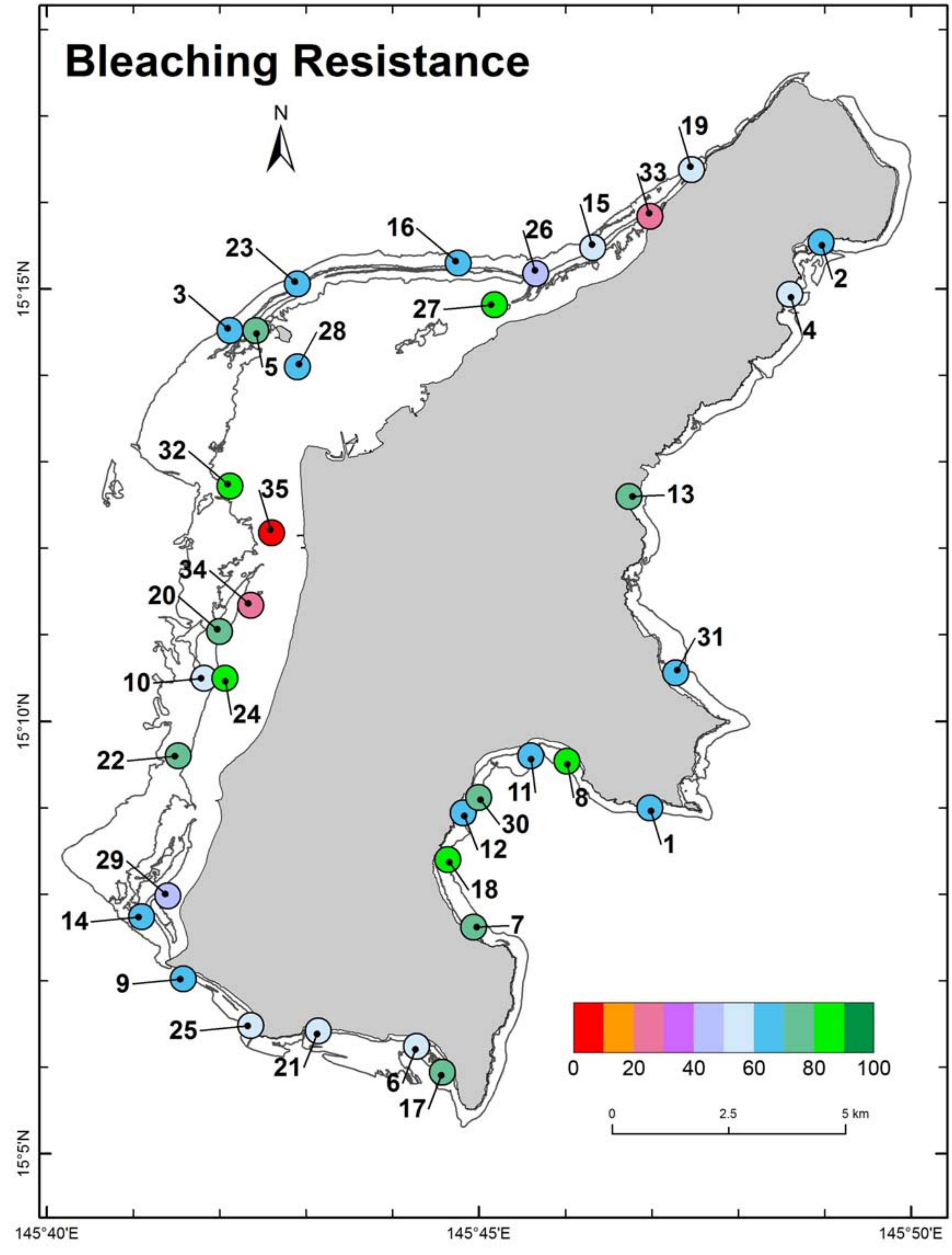
1 – Coral diversity
2 – Recruitment
3 – Bleaching resistance
4 – Temperature variability
5 – Herbivore biomass
6 – Macroalgae cover
7 – Nutrient input
8 – Sedimentation
9 – Fishing access based on wave exposure
10 – Coral disease
11 – Anthropogenic physical impacts



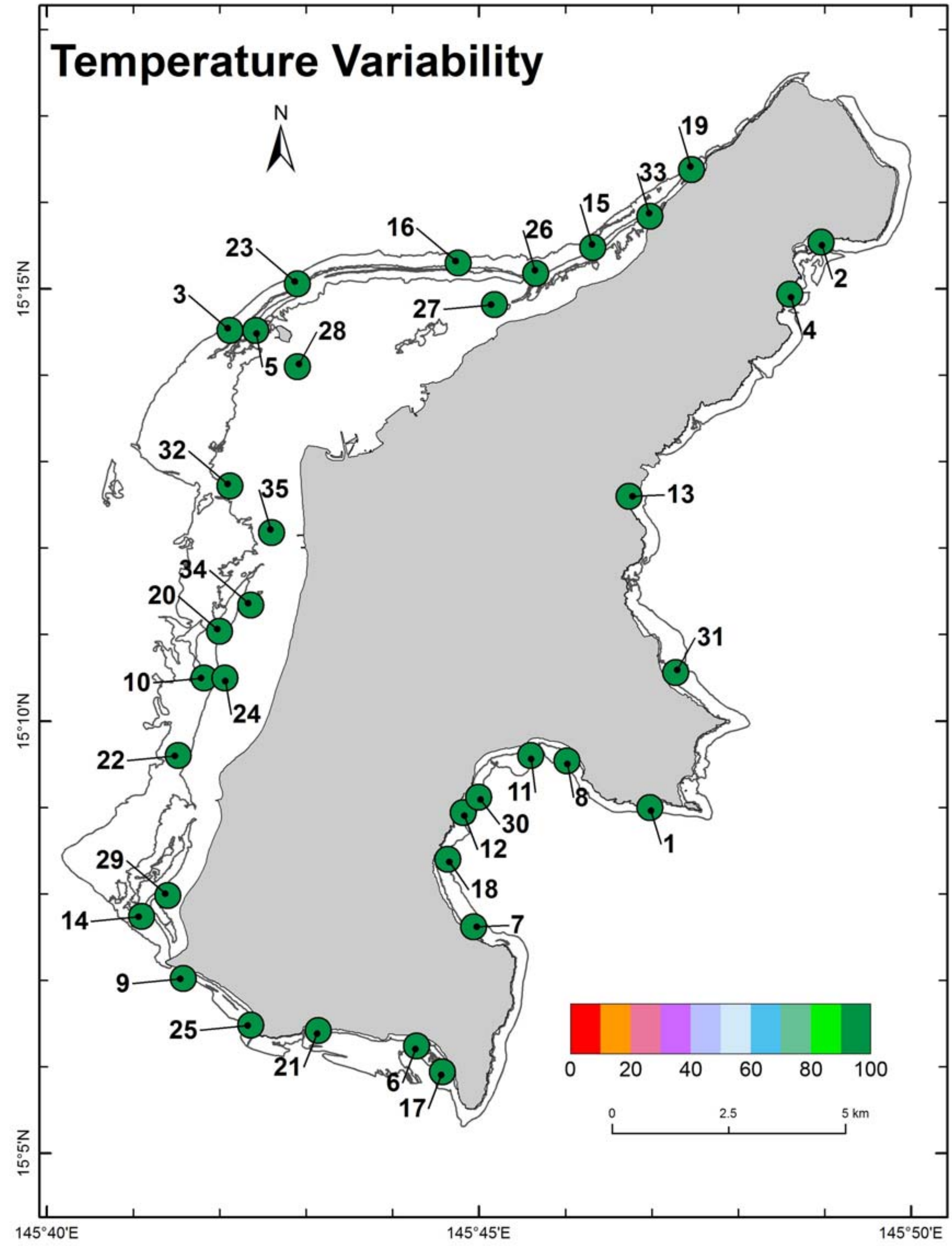

1 – Coral diversity (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for coral diversity across surveyed sites.



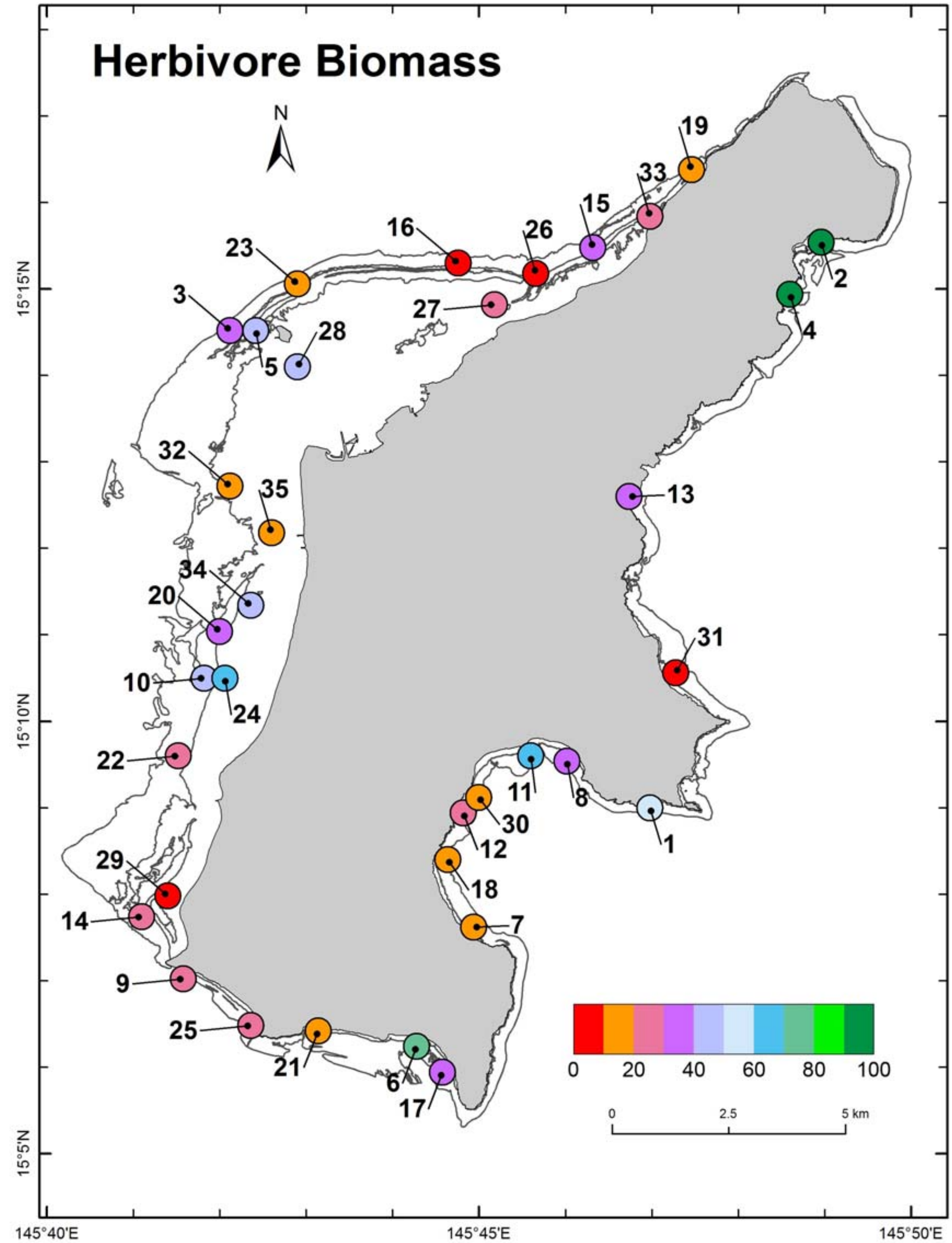

2 – Recruitment (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for recruitment across surveyed sites.



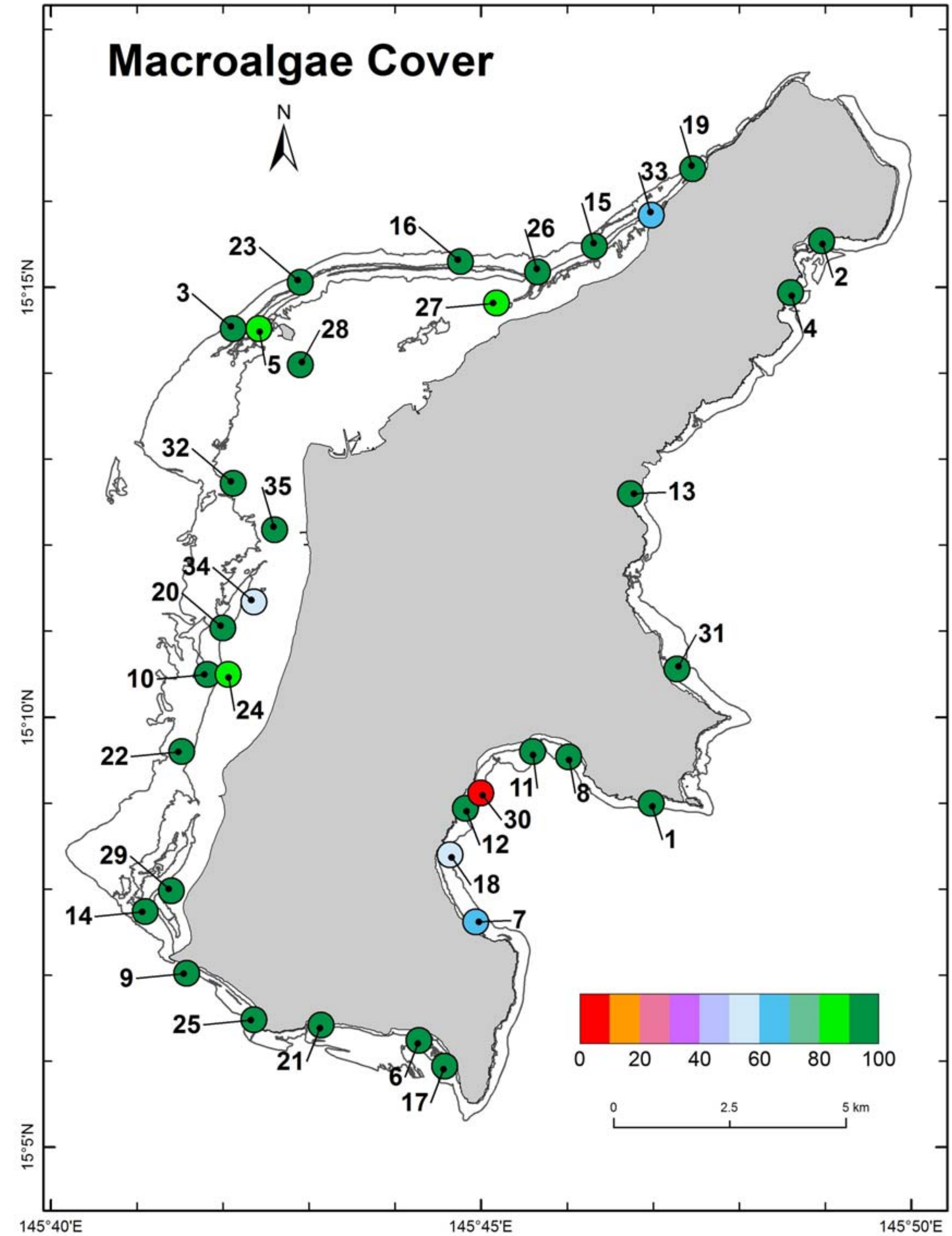

3 – Bleaching resistance (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for bleaching resistance across surveyed sites.



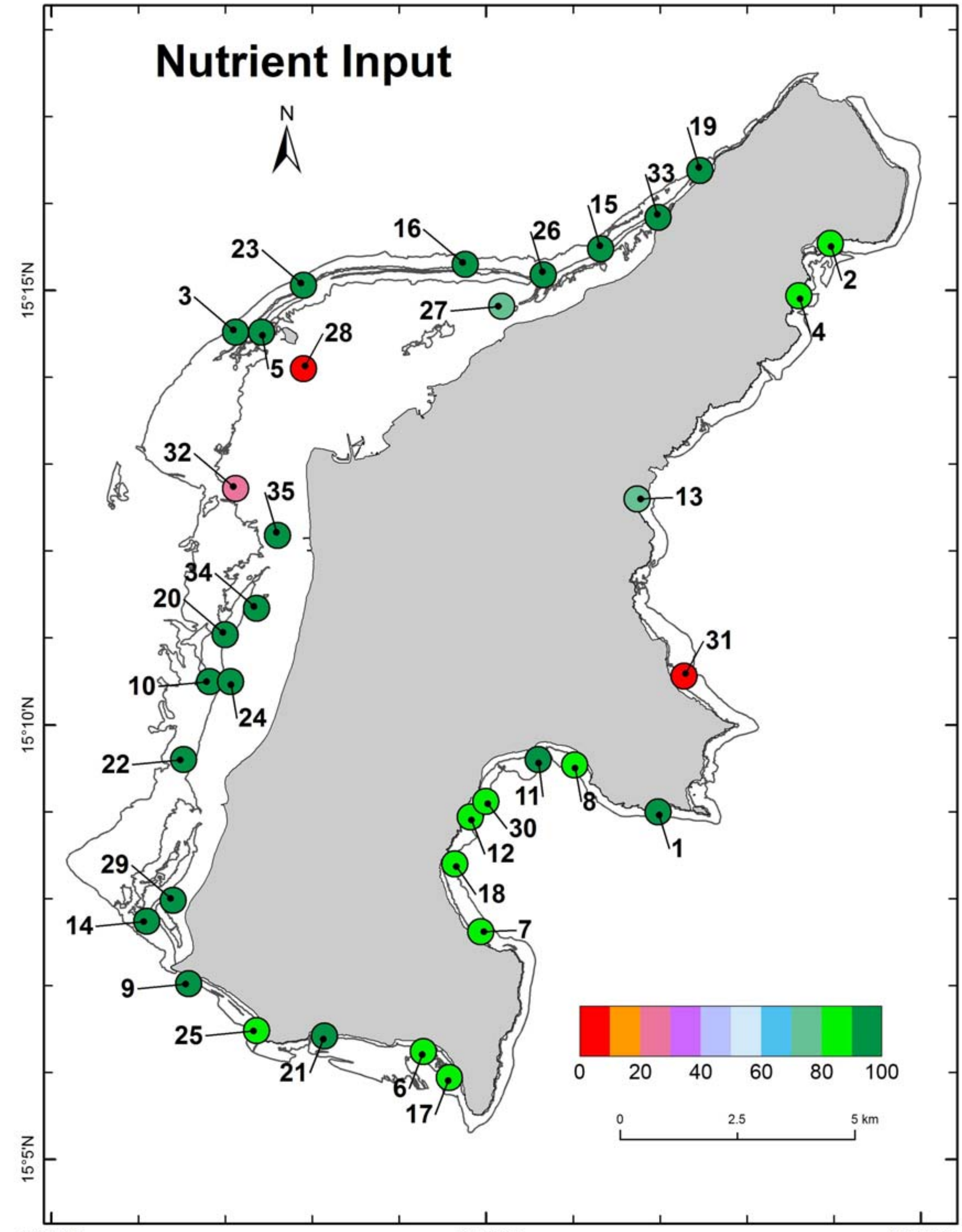

4 – Temperature variability (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for temperature variability across surveyed sites.



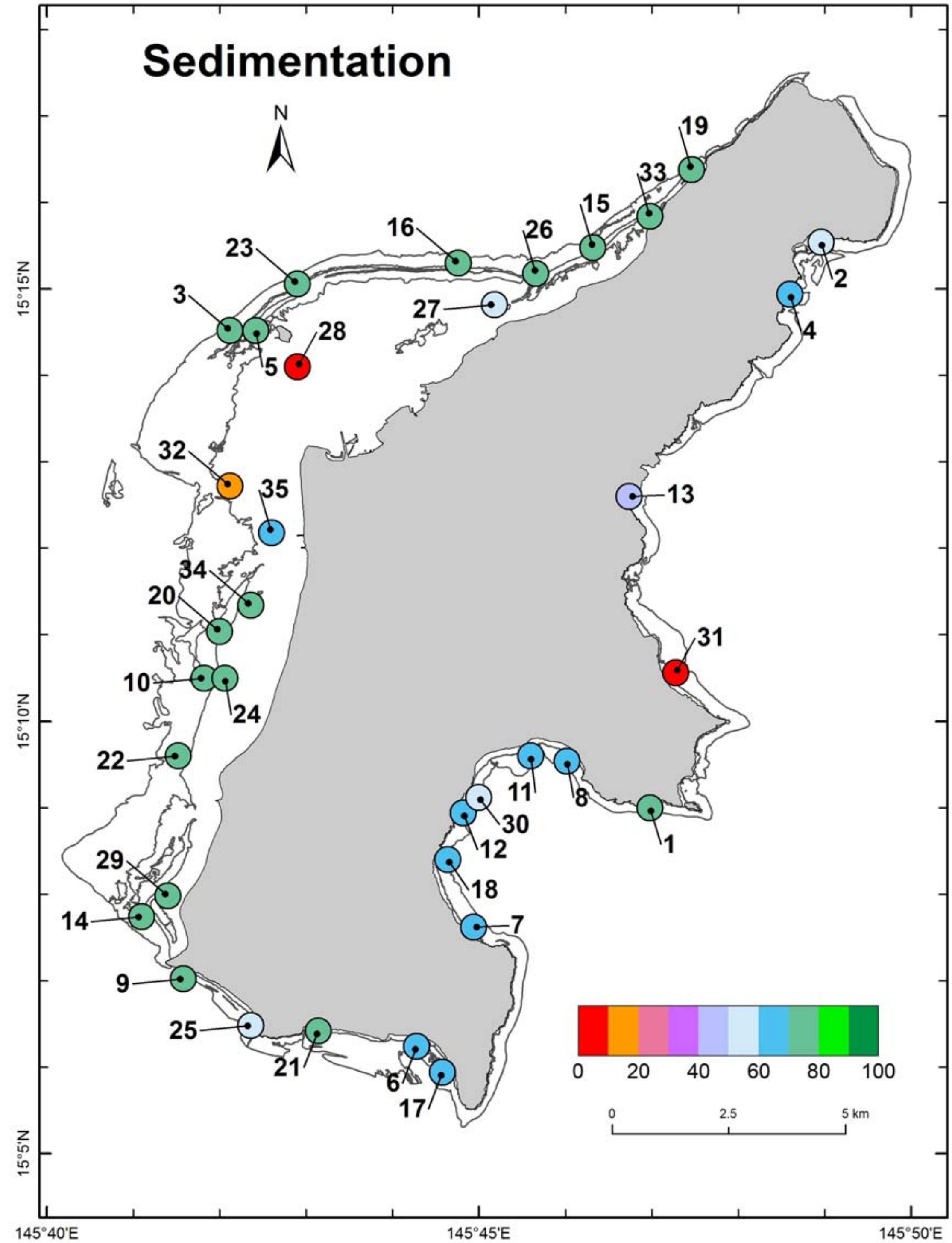

5 – Herbivore biomass (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for herbivore biomass across surveyed sites.



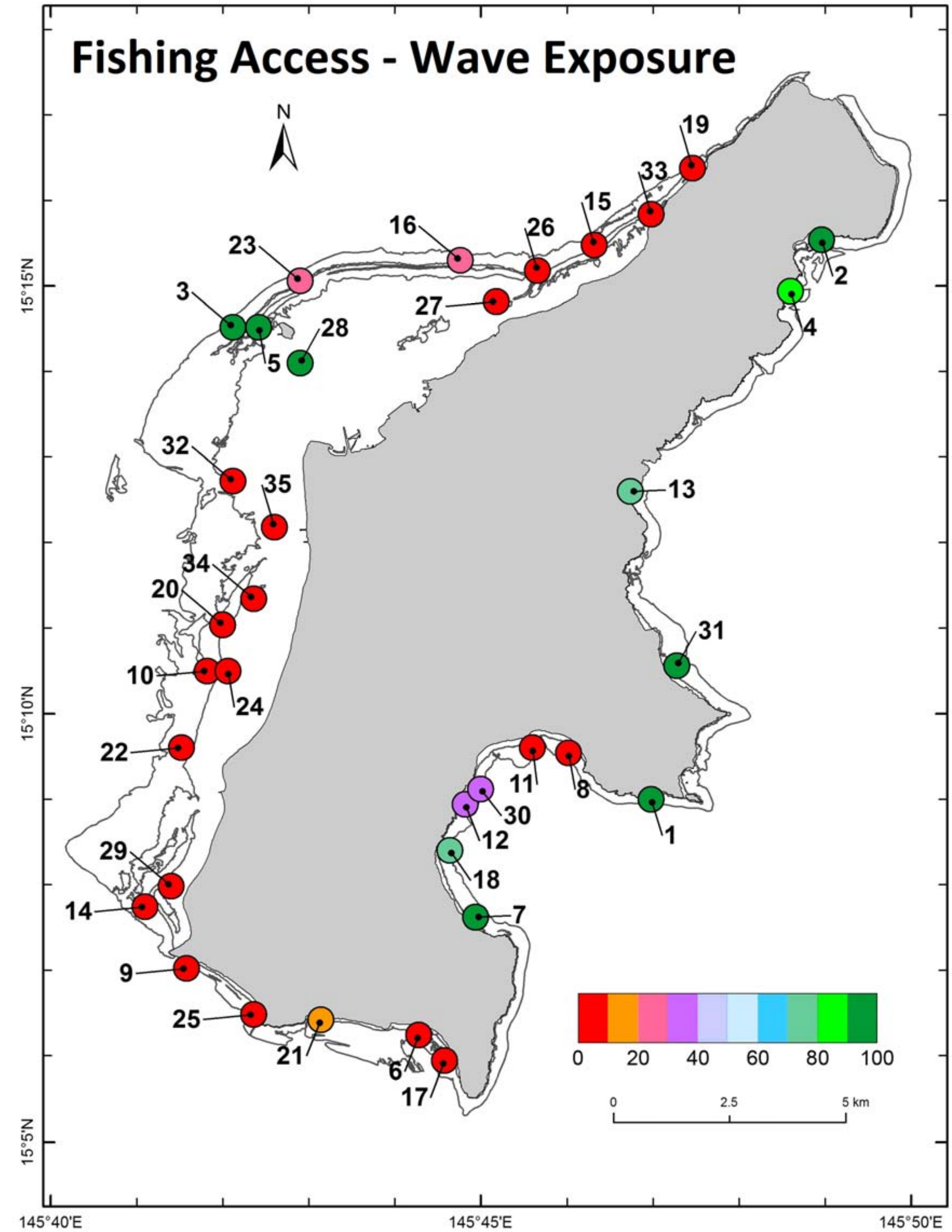

6 – Macroalgae cover (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for macroalgae cover across surveyed sites.



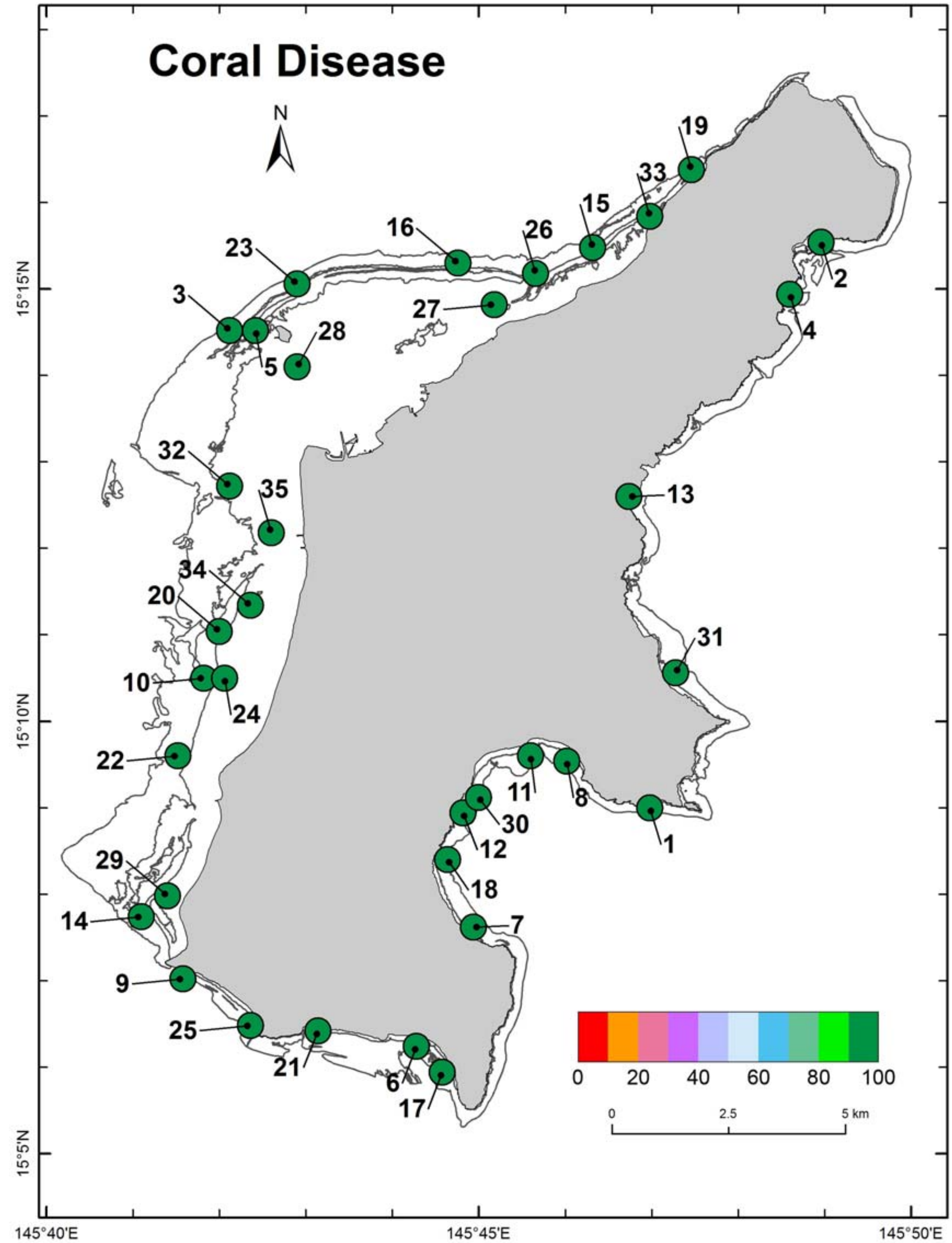

7 – Nutrient input (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for nutrient input across surveyed sites.



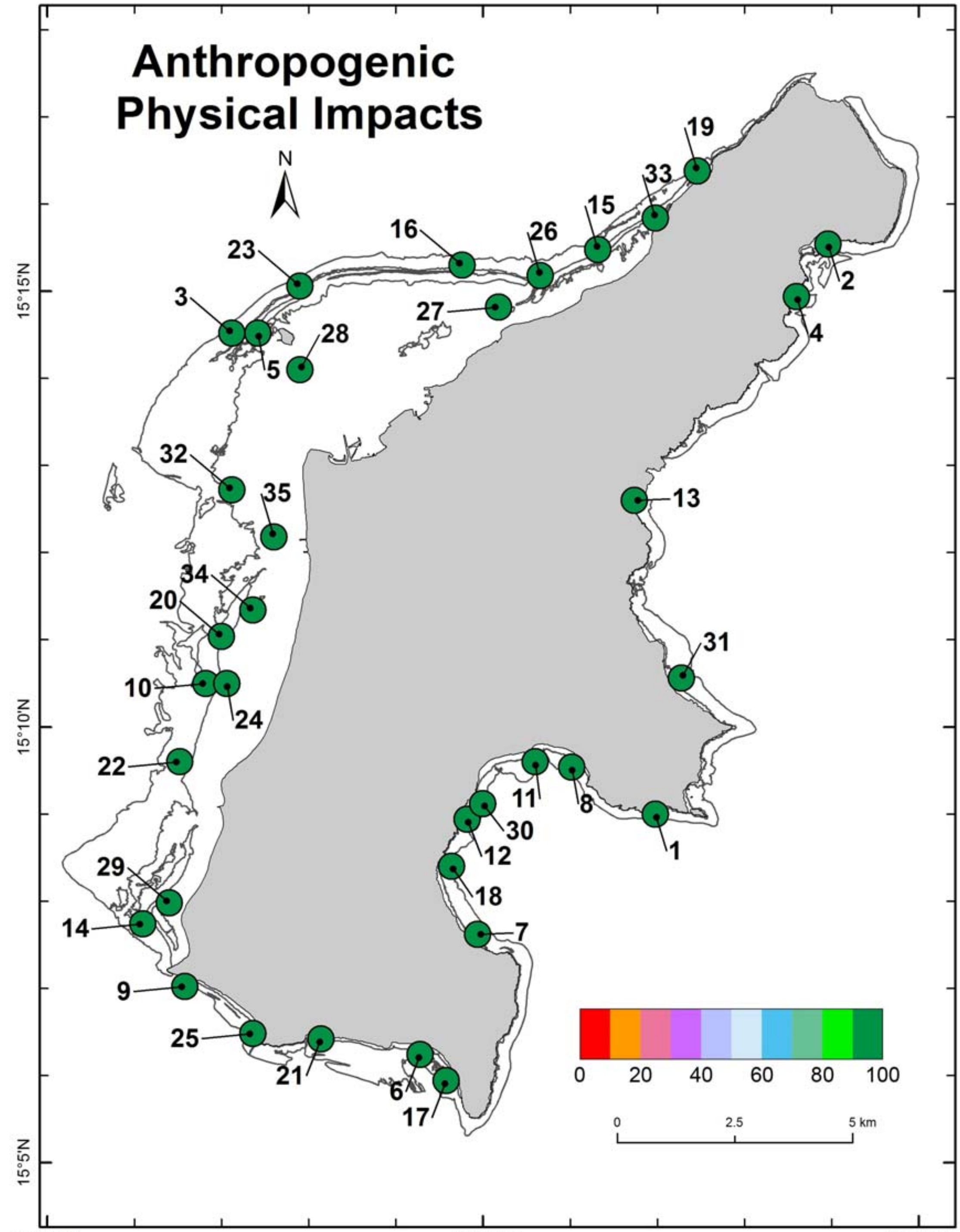

8 – Sedimentation (see also Appendix 3).
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for sedimentation across surveyed sites.




9 – Fishing access.
The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for fishing access across surveyed sites.




10 – Coral disease; note – no coral disease was observed at any of the sites barring a pigment change immune response on some *Porites* colonies at some sites. The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for coral disease across surveyed sites.

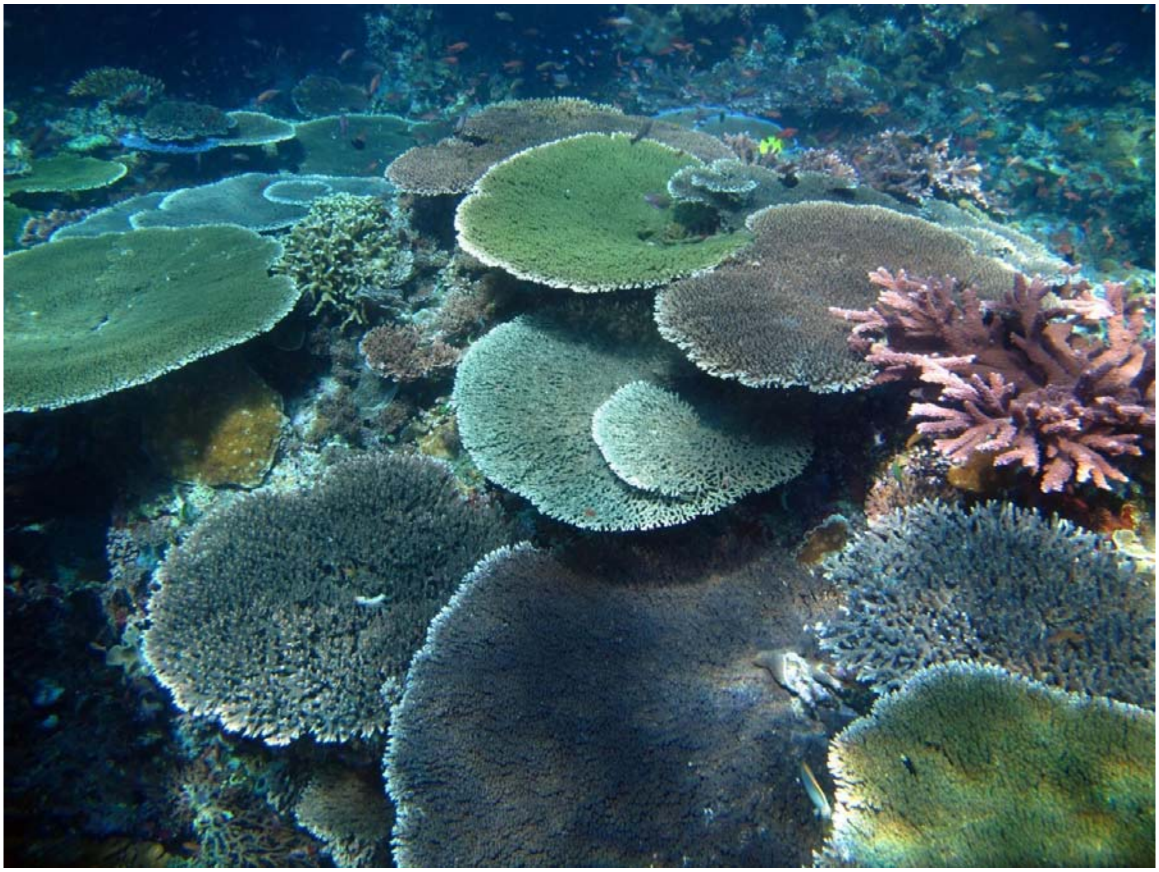



11 – Anthropogenic physical impacts; note – no physical impacts were observed at the survey sites. The color bar in the legend represents the anchored score as 0 to 100, to reflect the percentage of the max value for anthropogenic physical impacts across surveyed sites.

## Appendix 5. How-to-guide for conducting resilience assessments

**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.

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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).

| | Perceived importance (0 to 10) | | | Scientific evidence (−5 to +5) | | | Feasibility (0 to 10) |
|---|---|---|---|---|---|---|---|
| **Ecological factor** | **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.

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**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<br>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<br>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:
- (green) = High
- (yellow) = Medium
- (red) = 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.

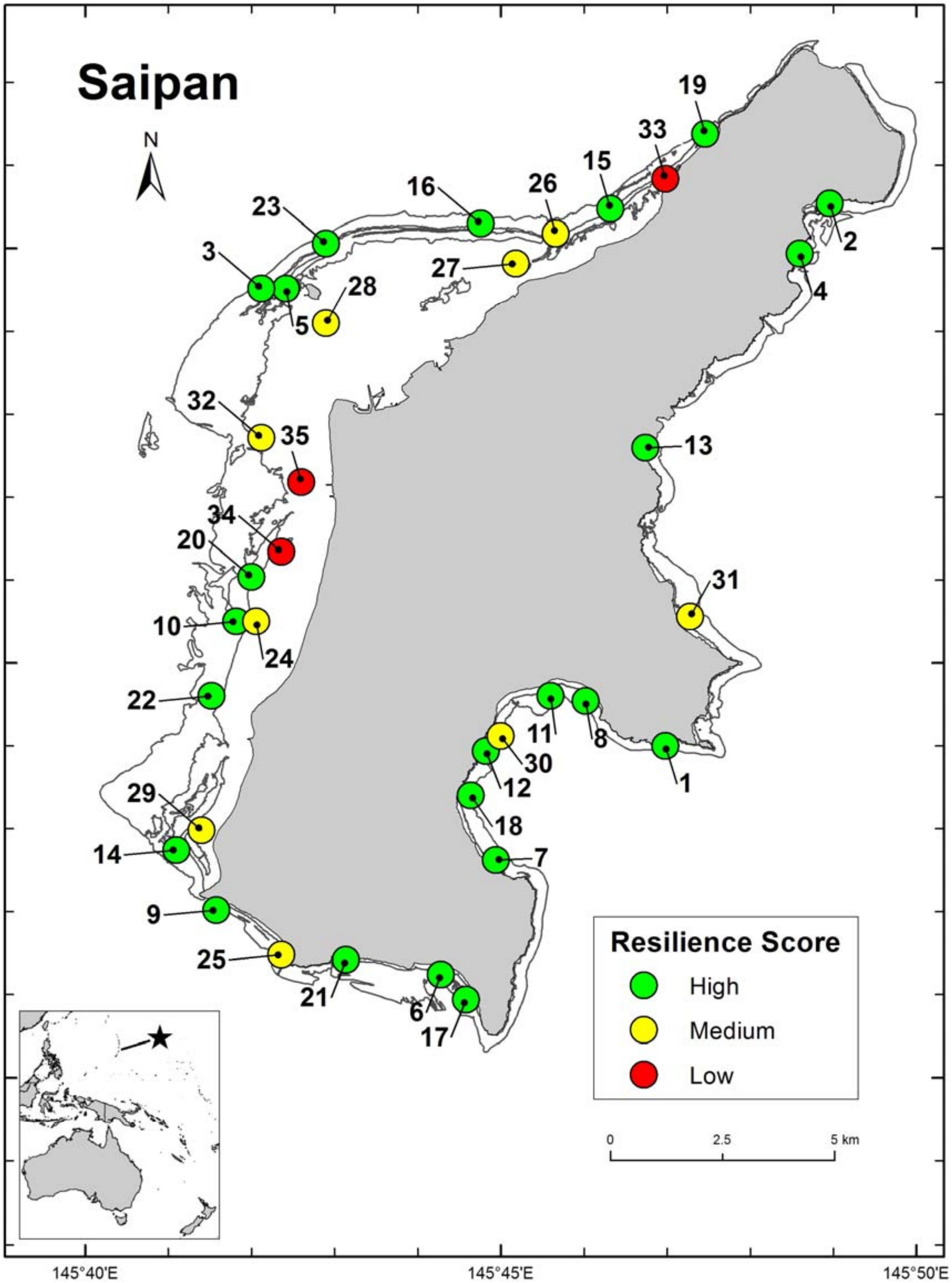

Table C. Combined anthropogenic stress scores and low, medium and high classifications for anthropogenic stress for all sites.

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 |