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ABSTRACT

Ecological resilience assessments are an important part of resilience-based management (RBM) and can help prioritize and target management actions. Use of such assessments has been limited due to a lack of clear guidance on the assessment process. This study builds on the latest scientific advances in RBM to provide that guidance from a resilience assessment undertaken in the Commonwealth of the Northern Mariana Islands (CNMI). We assessed spatial variation in ecological resilience potential at 78 forereef sites near the populated islands of the CNMI: Saipan, Tinian/Aguijan, and Rota. The assessments are based on measuring indicators of resilience processes and are combined with information on anthropogenic stress and larval connectivity. We find great spatial variation in relative resilience potential with many high resilience sites near Saipan (5 of 7) and low resilience sites near Rota (7 of 9). Criteria were developed to identify priority sites for six types of management actions (e.g., conservation, land-based sources of pollution reduction, and fishery management and enforcement) and 51 of the 78 sites met at least one of the sets of criteria. The connectivity simulations developed indicate that Tinian and Aguijan are each roughly 10× the larvae source that Rota is and twice as frequent a destination. These results may explain the lower relative resilience potential of Rota reefs and indicates that actions in Saipan and Tinian/Aguijan will be important to maintaining supply of larvae. The process we describe for undertaking resilience assessments can be tailored for use in coral reef areas globally and applied to other ecosystems.

1. Introduction

Coral reef managers face the challenge of supporting the resilience of reef systems to climate change by reducing other sources of stress (Anthony et al., 2015). Coral reef resilience is the capacity of a reef to resist or recover from degradation and maintain provision of ecosystem goods and services (Mumby et al., 2007). Resilience-based management (RBM) has been developed to overcome the challenges of supporting ecosystem resilience in this era of rapid change (Bestelmeyer and Briske, 2012). RBM involves the application of resilience theory and tools to deliver ecosystem-based management outcomes into the future (Chapin et al., 2009). RBM of coral reefs can include assessing spatial variation in resilience potential and then targeting and tailoring appropriate actions. Such assessments have been strongly recommended by coral reef ecology experts and leading conservation organizations (McClanahan et al., 2012; Graham et al., 2013; Anthony et al., 2015). However, there are few examples of assessments of resilience potential that explicitly guide managers in making targeted decisions (Maynard et al., 2010; Weeks and Jupiter, 2013).

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The simplest method of incorporating resilience into coral reef conservation planning is the use of representation and replication during the spatial planning of marine protected areas (MPAs) and networks (Fernandes et al., 2005; Grimsditch and Salm, 2006; Mcleod et al., 2008). Ensuring that a range of habitat types are represented and replicated within protected areas spreads risk and increases the likelihood that at least a few resilient areas will be protected and connected to support recovery (McLeod et al., 2008; Maynard et al., 2015a). Assessments of resilience potential are more resource-intensive, but can provide important planning and management guidance to supplement a representation and replication approach. Resilience assessments can help to target a wide range of management initiatives to support reef resilience, many of which may be more tractable in many jurisdictions than MPAs (e.g., quotas, gear restrictions, community management; MacNeil et al., 2015).

Assessing the resilience potential of coral reefs was first conceptually developed in Salm et al. (2001) and later in West and Salm (2003) in the wake of the 1998 coral bleaching event. These authors made the case that there are physical and ecological characteristics of coral reefs that provide some reefs with a greater likelihood of resisting and/or recovering from disturbances such as coral bleaching. These characteristics, which we have come to refer to as 'resilience indicators' (McClanahan et al., 2012), are variables that can be assessed or measured. Obura and Grimsditch (2009) were the first to develop an approach to assess the ecological resilience of coral reefs, which included recommending 61 resilience indicators. This report identified a wide range of potentially important indicators but contained limited guidance on implementation and consequently has been challenging to apply. Maynard et al. (2010) then applied a resilience assessment framework in the southern Great Barrier Reef using a sub-set (30) of the indicators recommended within the Obura and Grimsditch (2009) report. That case study was the first to scale resilience indicators based on perceived relative importance and the first coral reef resilience assessment to inform a management decision; the designation of no-anchoring areas (Maynard et al., 2010; Beeden et al., 2014).

To prioritize resilience indicators to help make resilience assessments more feasible, McClanahan et al. (2012) surveyed reef scientists and managers to assess the perceived importance, strength of scientific evidence and feasibility of assessment/measurement of 31 resilience indicators. Within the McClanahan et al. (2012) review, eleven resilience indicators were prioritized for use in resilience assessments. The study results added to the body of evidence that while ecosystems are complex, they are "frequently controlled by just a few strong variables operating at a given scale" (McClanahan et al., 2012). This is supported by Graham et al. (2015), who identified a range of factors affecting recovery patterns in the western Indian Ocean. These authors found that structural complexity and water depth alone accurately predicted broad-scale ecosystem responses following coral bleaching.

Then, in 2014, two workshops were held on resilience-based coral reef management; one included coral reef ecologists and managers from the Coral Triangle, and the other included ecologists and managers from the western Indian Ocean, Pacific and Caribbean. Both groups generated reports explaining the challenges managers face in conducting resilience assessments (UNEP, 2014; Maynard et al., 2015b) and identified the same gaps: attendees felt that assessing fewer indicators makes resilience assessments less resource-intensive and therefore more feasible. Despite the advancements in identifying which resilience indicators to assess, guidance is still lacking on how to analyze the data to produce the assessment results.

Guidance is also lacking on how to interpret the results and ensure assessment results inform management actions that are effective. Connectivity information can be a key input to both of these parts of the process (i.e., interpretation and implementation). Four of the 11 indicators recommended within McClanahan et al. (2012) have direct or indirect links to connectivity. Connectivity is a major driver of spatial variation in coral and fish recruitment, which will affect coral diversity and herbivore biomass and, in turn, macroalgae cover. Consequently, understanding spatial variation in connectivity can help interpret spatial variation in scores for those indicators and the final scores for relative resilience potential. Resilience assessment results can then be considered in the context of connectivity to inform management decisions. Specifically, connectivity data can be used to determine where management actions are most needed to maintain larvae supply and least likely to be effective due to low larvae supply.

We present the results of the first field-based implementation of the resilience assessment framework recommended within McClanahan et al. (2012) and the first combination of an ecological resilience assessment with connectivity information. The overarching goal of this paper is to describe a detailed and adaptable process that can guide the implementation of ecological resilience assessments in coral reef areas and combination of resilience assessments with connectivity information (if available). The fieldwork took place in the Commonwealth of the Northern Mariana Islands (CNMI), which is in the west Pacific just north of the island of Guam. CNMI is an ideal setting for the study because the reefs there are diverse, set within a large range of oceanographic conditions, and human population density varies greatly among the surveyed islands so stress on reefs related to human activities also varies greatly. Further, reefs and adjacent watersheds are under ongoing management meaning the results could inform ongoing management efforts in the CNMI region. Ongoing management efforts include: fishery management, maintenance of no-take marine protected areas, reef and coast stewardship and citizen science programs, water treatment facilities and managing land-use to limit runoff.

The three primary study objectives were to: 1) assess the relative resilience potential of forereef sites within and among the surveyed islands, 2) better understand the primary drivers of resilience potential at the island and CNMI-wide scale, and 3) identify priority areas to target management actions that can support reef resilience.

2. Materials and methods

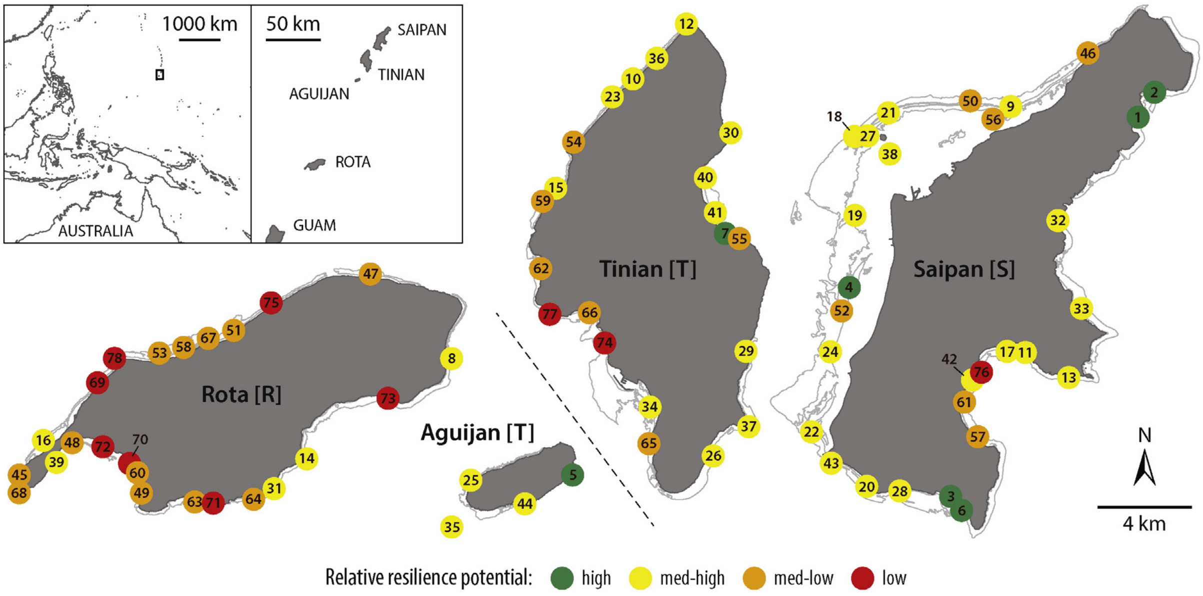
The resilience assessment process undertaken in the CNMI involved 5 major steps that others can follow and adapt: 1) select indicators, 2) collect and compile data, 3) analyze data, 4) identify targets for management actions, and 5) present and communicate the results. Methods for the first four of these are described below and the 5th is reviewed in the Results and Discussion sections, with the figures here and in the online appendices serving as examples.

2.1. Select indicators

All 11 'resilience indicators' recommended in the site selection framework described in McClanahan et al. (2012) were considered for inclusion in the assessment: bleaching resistance, temperature variability, coral diversity, coral recruitment, macroalgae cover, herbivore biomass, physical human impacts, coral disease, nutrients (pollution), sedimentation, and fishing pressure, which we call fishing access. Herbivore diversity was added (and combined with biomass, see below) due to the growing body of evidence that herbivore diversity is as important to coral reef and herbivorous fish community resilience as biomass (Green et al., 2009; Heenan and Williams, 2013).

2.2. Collect and compile data

Data were collected at forereef sites (8–12 m) of the fringing reefs of the three main populated islands of the CNMI: Saipan (May 2012, $n = 29$), Tinian and Aguijan, (May–June 2014, $n = 25$), and Rota (May–June 2014, $n = 24$, see Table A1 for coordinates and Fig. 1 for locations). The sites surveyed represent the full range of ecological settings and physical conditions present in the CNMI as well as roughly even spatial coverage of the forereef around each of the islands (i.e., a



1 (1) [S] - Nanasu Reef
2 (2) [S] - Bird Island
3 (4) [S] - Obyan Beach
4 (3) [S] - Lighthouse Reef
5 (4) [T] - East Aguijan Falls
6 (5) [S] - Boy Scout
7 (1) [T] - Unai Masilok
8 (3) [R] - As Dudo_MMT
9 (7) [S] - Pau Pau
10 (6) [T] - Unai Babui_MMT
11 (6) [S] - Laolao Bay East
12 (10) [T] - Tahgong Point
13 (8) [S] - Forbidden Island
14 (1) [R] - Haina Point
15 (3) [T] - Lamanibot
16 (2) [R] - West Harbor_MMT
17 (10) [S] - Laolao Bay Mids
18 (11) [S] - Lanyas
19 (9) [S] - Peysonnelia Reef
20 (14) [S] - Coral Ocean Point
21 (12) [S] - Elbow Reef
22 (13) [S] - Point Break Reef
23 (5) [T] - Unai Chulu
24 (15) [S] - Outside Grand Hotel_MMT
25 (12) [T] - Aguijan Island_MMT
26 (8) [T] - Suicide Cliff
27 (16) [S] - Managaha MPA_MMT
28 (18) [S] - Ladder Beach
29 (9) [T] - Barangka
30 (2) [T] - Asiga Point
31 (4) [R] - Agatasi
32 (17) [S] - Old Man By the Sea
33 (19) [S] - Tank Beach
34 (16) [T] - Dynasty_MMT
35 (13) [T] - Naftan Rock
36 (17) [T] - Unai Lamlam
37 (11) [T] - Puntan Kastiyu
38 (20) [S] - Managaha Patch Reef_MMT
39 (7) [R] - East Wedding Cake
40 (14) [T] - Unai Asiga
41 (7) [T] - Long Beach_MMT
42 (22) [S] - North Dakota
43 (21) [S] - Agingan Point
44 (18) [T] - Happy Days
45 (5) [R] - Senhanom Wall
46 (24) [S] - Wing Beach
47 (9) [R] - Mochong
48 (12) [R] - Sasanhaya_MMT
49 (6) [R] - Coral Gardens_MMT
50 (23) [S] - Achu Dangkulu
51 (10) [R] - Coconut Village
52 (25) [S] - Oleai Rocks
53 (8) [R] - Sunset Villa_MMT
54 (19) [T] - Puntan Lamanibot Sanhilo
55 (15) [T] - Masilok Beach Wall
56 (28) [S] - Achugao
57 (26) [S] - South Laolao
58 (16) [R] - Iota Salvage_MMT
59 (22) [T] - Puntan Lamanibot Sampapa
60 (15) [R] - Honey Gardens
61 (27) [S] - South Dakota
62 (21) [T] - Atgidon
63 (14) [R] - Okgok_MMT
64 (11) [R] - Malilok Point
65 (20) [T] - South Point_MMT
66 (23) [T] - Barcinas Bay_MMT
67 (13) [R] - Teteto
68 (17) [R] - Harnom Point
69 (18) [R] - Cave Museum_MMT
70 (20) [R] - Takta Sagua
71 (19) [R] - Talakhaya_MMT
72 (22) [R] - Joanne's Reef
73 (21) [R] - South I Chenchon Park
74 (24) [T] - Leprosarium
75 (23) [R] - Rota Resort_MMT
76 (29) [S] - Tuturam
77 (25) [T] - Puntan Diapblo
78 (24) [R] - Sailigai Point

Fig. 1. Inter-island relative resilience potential of the 78 forereef survey sites in CNMI. Resilience rankings are from highest to lowest resilience score; the average score for the 6 resilience indicators after normalizing and scaling scores among islands (see also Table A3a,b). Relative classifications for resilience scores are as follows: high (>avg. + 1 sd), medium-high (<avg. + 1 sd and >avg), medium-low (<avg. and >avg. − 1 sd), and low (<avg. − 1 sd, see Fig. 3). Intra-island rankings are shown in square brackets '[]' to the right of the inter-island rankings used as site numbers on the maps. Sites with 'MMT' in the name refer to sites surveyed by the marine monitoring team of the Bureau of Environmental and Coastal Quality in CNMI. The results for the intra-island analysis are shown in Fig. 2.

survey site every 1–2 miles along the island coastlines). Variables assessed in the field were macroalgae cover, bleaching resistance, coral recruitment, coral diversity, and herbivore biomass and diversity (combined into herbivore average functional group (AFG) biomass). Variables assessed using remote sensing and GIS software were temperature variability, land-based sources of pollution (LBSP — nutrients, and sedimentation considered together), and accessibility due to wave exposure (fishing access). Methods for assessment or measurement of each of the variables are described in Table 1 as are explanations for the use of any proxies.

2.3. Analyze data

2.3.1. Relative resilience potential

The following indicators are included in the assessment of relative resilience potential: macroalgae cover, bleaching resistance, coral recruitment, coral diversity, temperature variability, and herbivore AFG biomass. Coral disease and physical human impacts (e.g., anchoring and fin damage) were excluded due to having extremely low prevalence among the survey sites and because diseases could only be identified for a portion of the sites. McClanahan et al. (2012) include the anthropogenic stressors assessed here as 'resilience indicators' (LBSP and accessibility due to wave exposure are the proxies used here for the indicators 'Nutrient input', 'Sedimentation' and 'Fishing pressure'). However, these are variables that challenge resilience while all the others we include are indicators of resilience processes. For this reason, the proxies for anthropogenic stress are excluded from the assessment of relative resilience potential. The anthropogenic stressors are included later within the decision-support framework that targets management actions (described below). Both inter-island and intra-island analyses of relative resilience potential were completed (i.e., two resilience scores are calculated for each site).

Values for each variable are first normalized to a uni-directional scale of 0–1 by: dividing by the maximum value for the variable among all 78 sites (inter-island analysis), and dividing by the maximum value for the variable among sites surveyed at each island (intra-island

Table 1
Field-survey and desktop-based methods for resilience indicators (bold) used and for two anthropogenic stressors (denoted by **).

Indicator name (unit)	Methods
Macroalgae cover (%)	Average percent of points classified as fleshy macroalgae (>5 cm in height) on three 50-m point-intercept transects where points were classified at 50-cm intervals.
Coral community	*12–16 0.25 m^2 quadrats thrown in a stratified random manner ~10 m on left and right sides of the three 50-m transects used to assess macroalgae cover (Starmer and Houk, 2008). All stony corals were identified to species and the longest diameter and perpendicular diameter measured for all colonies that fell within the quadrat. Species were classified from 1 to 5 from low to high bleaching susceptibility. Susceptibility ratings were produced using an expert focus group that reviewed the literature, as well as data from the only well documented bleaching event in Saipan (in 2001, see Table A2 for* susceptibility ratings).
Bleaching resistance (%)	Percent of the community made up of species considered to be resistant (rating ≤ 3 in Table A2)
Coral recruitment (#/m^2)	Average density of corals with a geometric mean < 5 cm (two longest diameters multiplied and then take the square root of the product) within the assessed quadrats. We assess new recruits so exclude massive and encrusting colonies that commonly have parts of larger colonies that are <5 cm (e.g., *P. rus*).
Coral diversity (unitless)	The inverse of Simpson's index of diversity, which is based on the frequency each species was observed and the species richness. The resultant value ranges from 0 to 1 and assesses the probability two species selected at random from the sampled community will be different, so higher percentages equate to higher diversity.
Herbivorous fish community	*The fish community was assessed using three 3-min 5 m radius stationary point counts (SPCs) performed along each of the 50 m transect lines described above for macroalgae cover (9 SPCs in total), which is in keeping with recommendations from a power analysis previously undertaken in the region (Houk and Starmer, 2010). All herbivorous fish and all other fish larger than 8 cm in body length were identified to species, and their length was estimated to the nearest cm. The weight of each fish in grams was then calculated using standard weight-length relationships. The coefficients used were sourced from NOAA's Coral Reef Ecosystem Division (Weijerman et al., 2013). Species were classified as herbivores using IUCN classifications and were grouped as: 1) browsers, 2) grazers/detritivores, and 3) scrapers/excavators (Green et al., 2009).*
Herbivore AFG biomass (kg/ha)	The average biomass was calculated in kg/ha for each of the 3 major groups (see just above) and then these values were averaged to produce the final Herbivore average functional group (AFG) biomass (kg/ha) value. The herbivore AFG biomass is thus inclusive of herbivore diversity. This ensures the herbivorous fish community is accounted for within only one (rather than 2) indicator, which avoids doubling the importance of the herbivorous fish community relative to the other indicators.
Temperature variability (unitless)	Observed sea surface temperature (SST) data for the period 1982–2012 was obtained from NOAA Pathfinder Version 5.2 (4-km resolution, Casey et al., 2010). The final value used is the standard deviation of warm season temperatures with warm season defined as the three months that center on the month with the maximum monthly mean temperature for the 1982–2012 period.
Land-based sources of pollution (unitless)**	Geographic information system (GIS) layers were developed pertaining to watershed size, topography, land use and human population (land use data from United States Forest Service, www.fs.usda.gov/r5). The proxy represented a measure of land-based influence to coastal water quality based on the coverage of barren land, urbanized areas, and human populations. Digital elevation models (i.e., topographic data) were used to define watershed boundaries and flow patterns for surface discharge, and then each of our forereef survey sites was attributed to an adjacent watershed. The proxy was calculated by multiplying standardized values for altered land use and human populations (i.e., land use × human population interactions). The proxy is not inclusive of any ongoing management actions since information on spatial variation in their efficacy was not available for this study. Future studies may include action efficacy in calculating proxy scores and/or greater in situ water quality data once available.
Accessibility due to wave exposure (fishing access, unitless)**	A primary driver of fishing pressure in CNMI is access, which is influenced by wave height and distance to boat launches (Houk et al., 2012). Site-based wave exposures were calculated based on 10-year wind-speed records, fetch distances to the nearest reef or land feature, and angles of exposure (Quikscat wind datasets from 1999 to 2009; https://winds.jpl.nasa.gov/, wave energy in J/m^3, full description found in Ekebom et al., 2003, Chollett and Mumby, 2012). The final value used was calculated by multiplying standardized wave energies and distances to the nearest points of fishing access (i.e., wave and distance interactions). Values for wave exposure and accessibility were considered to be '0' for all no-take marine protected areas irrespective of wave energy at the site (see MPA locations in Fig. 5).

Methods descriptions for the coral community (applies to bleaching resistance, coral recruitment, and coral diversity) and herbivorous fish community (applies to herbivore AFG biomass) are in italics.

analysis). To ensure that high scores always infer higher relative resilience potential, normalized scores were inverted for macroalgae cover. The normalized scores were then scaled based on differences in the perceived importance of each variable to resistance and recovery from Table 2 in McClanahan et al. (2012). Bleaching resistance had the highest perceived importance score in that study of 15.57, which is 1.37× the value of the lowest perceived importance score for our variables of 11.43 for coral recruitment (i.e., perceived importance scores were divided by the lowest score of 11.43 to produce a scaling multiplier of 1 (11.43/11.43) or larger). Scaling multipliers are as follows: macroalgae cover — 1, bleaching resistance — 1.37, coral recruitment — 1, coral diversity — 1.08, temperature variability — 1.22, and herbivore AFG biomass — 1.02. The scaled scores are then averaged (in this paper, 'average' is always the mean average), to produce the raw resilience scores. Raw resilience scores are then normalized by dividing by the maximum value, which results in resilience potential scores ranging from 0 to 1 that are expressed as a percentage of the site with the greatest score. We determined the effect of scaling on the final rankings by counting relative classification changes (e.g., from low to medium-low or vice versa) when comparing classifications produced using raw versus scaled indicators. The analysis results presented in the results text and figures include scaled indicators per the methods described above. Relative classifications for resilience scores are as follows: high (final scores that are >1 sd above average (avg.)), medium-high (<avg. + 1 sd and >avg.), medium-low (<avg. and >avg. − 1 sd), and low (<avg. − 1 sd). These relative classifications are also used to describe and compare scores for the individual resilience indicators (i.e., the classifications for indicators have no bearing on the analysis). The range in scores meant that there are all four classifications among our sites for 5 of 7 indicators. For macroalgae cover and coral diversity the value of the average + 1 sd exceeds the maximum possible value of 1 so no sites are given the 'high' classification.

2.3.2. Examining indicator variability

We used a canonical analysis of principal coordinates (CAP, Anderson and Willis, 2003) to examine which indicators were driving differences in resilience potential across the four relative classifications for the inter- and intra-island analyses. The CAP was based on Bray–Curtis similarity matrices where variables that might be responsible for group differences are investigated by calculating the Spearman-

Table 2
Criteria for queries used to suggest targets for different types of management actions in CNMI.

Query name	Criteria (*n* of 78)	Relevant management actions
Conservation	High or low resilience potential and are currently outside established no-take MPAs (14)	Any of the actions described below (as appropriate)
Land-based sources of pollution reduction	Above average scores for resilience potential and land-based sources of pollution (13)	Afforestation, stream bank stabilization, riparian restoration, road and storm drain improvement, other erosion control practices, wetland enhancement and sewage treatment upgrades
Fishery management and enforcement	Above average resilience potential and accessibility due to wave exposure (10) *OR* Below average herbivore AFG biomass and above average accessibility due to wave exposure (15) *OR* both (6)	Increased enforcement, marine protected areas*, temporary closures*, LMMAs, size regulations and bag and catch limits, moorings and no-anchoring areas, fish stocking, marine debris removal
Bleaching monitoring and supporting recovery	Low bleaching resistance and low herbivore AFG biomass (20)	Increased monitoring during warm seasons, shading or other cooling measures, supporting recovery processes using any of the other actions described in this table
Reef restoration/coral translocation	Above average resilience potential and low coral diversity or coral cover (10)	Priority coral nursery and transplantation area, artificial reef installation
Tourism outreach and stewardship	Above average coral diversity and above average fish species richness and biomass and above average accessibility due to wave exposure (2)	Establish moorings, undertake targeted outreach, develop stewardship and/or citizen science programs, marine debris removal

The lists of relevant management actions are examples only and the lists and this set of queries are not meant to be exhaustive. Other queries and actions will be relevant for other jurisdictions. The location of targets for different management actions are shown in Fig. 5, and are summarized in Table A10 and Figs. A8–A13.

* Not an anticipated action in CNMI at this time.

rank correlations of canonical ordination axes with the original indicator variables (Anderson, 2008).

2.3.3. Connectivity simulations

Larval connectivity among the surveyed islands and with other islands in and outside of the 15-island Marianas archipelago was examined using computer simulations that tracked cohorts of virtual fish and coral larvae transported according to an ocean circulation model (Kendall and Poti, 2015). Daily current vectors for the 0–10 m depth layer were sourced from the Hybrid Coordinate Ocean Model's (HYCOM) Global Hindcast. Virtual larvae were spawned seasonally from 2004 to 2012 at islands in and around the Marianas. Larval production was scaled to each island's area of potential reef ecosystem as calculated from GEBCO/NOAA bathymetry. Maximum Pelagic Larval Durations (PLD) of 10, 20, 50, and 100 days were simulated where larvae were competent to settle once 60% of their maximum PLD elapsed. In one set of simulations, representing larvae with minimal and no swimming ability (corals), larvae could only settle at a destination with potential reef habitat.

In another set of simulations, representing larvae with strong sensory and swimming abilities (reef fish), larvae could settle within 18 km of potential reef habitat. A constant mortality rate was applied following competency, which resulted in 100% mortality by the end of each maximum PLD. Matrices were produced for each PLD that state the number of larvae transported from and to each of 6 locations (Saipan/Marpi Bank, Tinian/Aguijan, Rota, Other Mariana Islands, Guam and Other archipelagos). For each PLD, total larval contributions to and from each of our survey islands were converted to percentages of the maximum value, expressing the extent to which each surveyed island is a source or destination relative to the maximum source/destination. These values were then averaged across all four PLDs for each of the two simulations (i.e., with and without the 18-km buffer). Connectivity simulations were used to: 1) interpret spatial variation found in relative resilience potential, and 2) determine where management actions are most needed to maintain larvae supply and least likely to be effective due to low larvae supply. The connectivity simulations help to interpret spatial variation in relative resilience potential because 4 of the 6 resilience indicators are directly (d) or indirectly (i) linked to connectivity (coral recruitment (d) and coral diversity (i), and herbivore biomass (d) and macroalgae cover (i)).

2.4. Identify targets for management actions

The scores for relative resilience potential, individual resilience indicators, and the proxies for anthropogenic stress were queried using 6 criteria to identify sites that are targets for different types of management actions. High resilience sites are more likely to persist as disturbance frequencies increase under climate change so are considered priority targets for several of the queries (justified further in the discussion). The queries include identifying targets for: Conservation, LBSP reduction, Fishery management and enforcement, Bleaching monitoring and supporting recovery, Reef restoration/coral translocation and Tourism outreach and stewardship. Table 2 presents the criteria for each of these queries, the number of sites for which each set of criteria applies, and specific options for relevant management actions. Sites identified using these queries were then considered in the context of the connectivity results. Implementing actions at sites near islands that are relatively great sources will help maintain larvae supply and implementing actions at sites near islands that are relatively poor destinations may be ineffective.

3. Results

3.1. Relative resilience potential

The average final score for resilience potential for the inter-island analysis was 0.81 (±0.06 sd), which results in values of ≤0.75 considered to be low and values ≥0.87 considered to be high (Fig. 3). There were 7 sites with high relative resilience potential. The highest-scoring site, Nanasu Reef, is on the exposed side of Saipan (see 1 in Fig. 1) and had high or medium-high scores for four of six variables (had low bleaching resistance and temperature variability, Table A3b). There were 37 sites with medium-high and 24 sites with medium-low resilience potential; these are found on all sides of all islands (Table A3a,b). There were 10 sites with low relative resilience potential. The lowest scoring site was Sailigai Point in northern Rota on the leeward side; the score of 0.62 means the lowest score for relative resilience potential was 38% lower than the highest score. Sailigai Point had low or medium-low scores for all variables excepting temperature variability. 11 of the survey sites are within no-take marine protected areas; 2 had high resilience (1 and 2 in Fig. 1), 6 had medium-high

(13, 18, 21, 27, 33, 38), 2 had medium-low (49,60) and 1 had low resilience (70 in Fig. 1, see Fig. 5 for MPA locations).

There were key differences between the islands. Five of the 7 high resilience sites are reef sites of Saipan and two are reef sites of Tinian. 7 of the 10 lowest-scoring sites are reef sites of Rota where many sites had medium-low or low scores for nearly all indicators and consistently had low coral recruit densities and high macroalgae cover. In Rota, 5 of the 24 surveyed sites were medium-high; the rest were medium-low or low. In contrast, 16 of 25 surveyed sites of Tinian/Aguijan were medium-high or high, with a similar proportion (21 of 28 sites) on Saipan (Fig. 1, Table A3a,b).

The average final score for relative resilience potential for the intra-island analysis was ~0.85 for all three islands (Tables A4a, 5a, and 6a). There were ≥2 sites at each island with resilience scores above or below the distribution defined by the average ± 1 standard deviation (i.e., high or low resilience sites (Fig. 2)). There are higher proportions of relatively high and low resilience sites at Rota. The general pattern is that the sites with high intra-island resilience potential are on the exposed sides of the islands, which applies to 7 of the 9 total high resilience sites. 6 of the 9 total low resilience sites in the intra-island analysis are directly offshore of human communities (i.e., within 2 km, Fig. 2), implying that human activities are acting on the resilience indicators.

3.2. Indicator variability.

Only 5 sites changed relative classification when comparing scaled versus un-scaled results for the inter-island analysis (the range in scaling factors used is small; 1–1.37). Therefore, indicators with the greatest variability had greater influence than indicators with low variability on the distribution of resilience scores and resultant rankings. Differences between the maximum value of 1 and the average (the data spread) were comparable for macroalgae cover, bleaching resistance, coral diversity and temperature variability (average values all within 0.40 of 1, Fig. 3; see Figs. A1–A6 for maps of indicator results). Differences between the maximum value of 1 and the average were far greater for coral recruitment (0.6+) and herbivore AFG biomass (0.7+). There was great consistency among the islands in the difference between the maximum and average values (Fig. 3) for the indicators. This is the first of two indications (see CAP results below) that herbivore AFG biomass and coral recruitment have the greatest influence on rankings in the inter-island analysis and intra-island analyses.

For the inter-island analysis, the CAP results indicate that high resilience sites generally had high values for herbivore AFG biomass, coral recruitment and coral diversity and low macroalgae cover (Fig. 4); the opposite is true for sites with medium-low or low resilience potential (Fig. 4). For the intra-island analyses, medium-high and high resilience sites for all three islands were associated with high herbivore AFG biomass and coral recruitment and low macroalgae cover.

3.3. Connectivity

Saipan was the biggest source of coral and fish larvae for all four of the PLDs used (10, 20, 50 and 100 days) and for both simulations (with and without larvae swimming capability, Tables A8 and A9). For both simulations, Tinian/Aguijan contributed ~50% as much larvae back to the reefs of the CNMI as Saipan. Depending on the PLD, Rota, a much smaller source based on potential habitat area, only contributed 10–30% as much larvae to reefs of the CNMI as Saipan (Table A6). The results vary more when comparing the extent to which each island was a destination for larvae. For the 0-km buffer simulation: Tinian was the biggest larvae destination for all PLDs; Saipan was 53–98% the destination than Tinian was; and, Rota was a far greater destination for larvae as PLD increases (5% for 10-day PLD and 90% for 100-day, Table A8). For the 18-km buffer simulation, Saipan and Tinian were comparable destinations for the 10 and 20-day PLDs. Tinian was the greatest destination for the 50-day PLD and Rota is the greatest destination for the 100-day PLD (Table A9). Considering both simulations together and all PLDs combined, Saipan was roughly twice as great a source as Tinian and 10× that of Rota. Tinian and Saipan were comparable destinations and each was roughly twice as great a destination as Rota (Table A7).

3.4. Identifying targets for management actions.

A total of 51 of the 78 sites met at least one of the 6 criteria set to identify targets for management actions (Fig. 5, Table A9). For example, there are targets for LBSP reduction (i.e., above average scores for LBSP

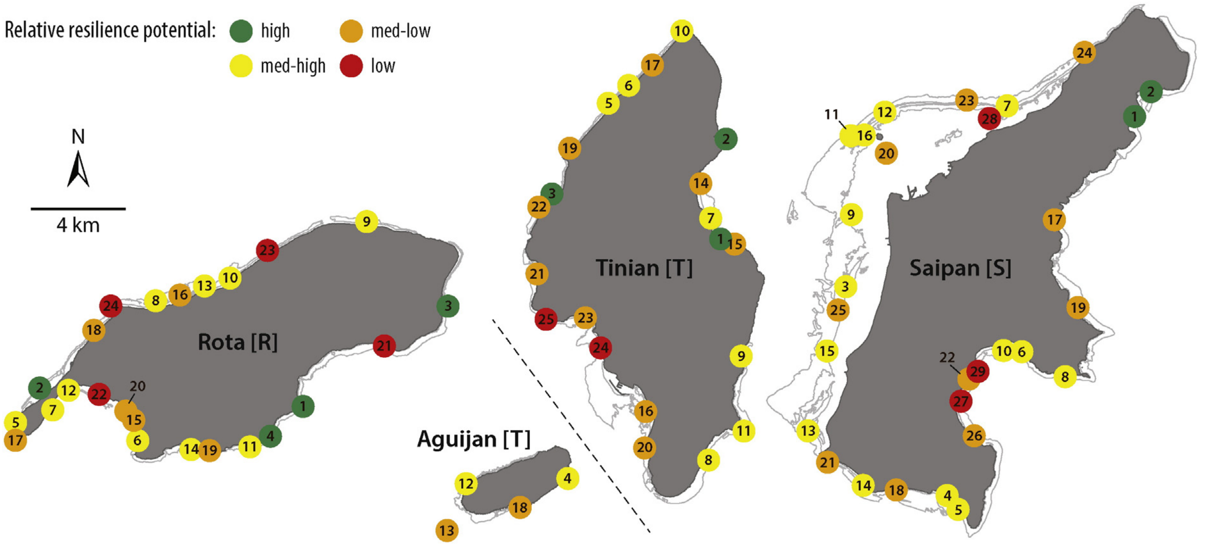


Fig. 2. Intra-island relative resilience potential of the 78 forereef survey sites in the Mariana Islands. Resilience rankings are from highest to lowest resilience score; the average score for the 6 resilience indicators after normalizing and scaling scores within islands (Tinian and Aguijan are grouped) (see Tables A4a,b–A6a,b). Relative classifications for resilience scores and site names are per Fig. 1, which can be referred to for inter-island rankings.

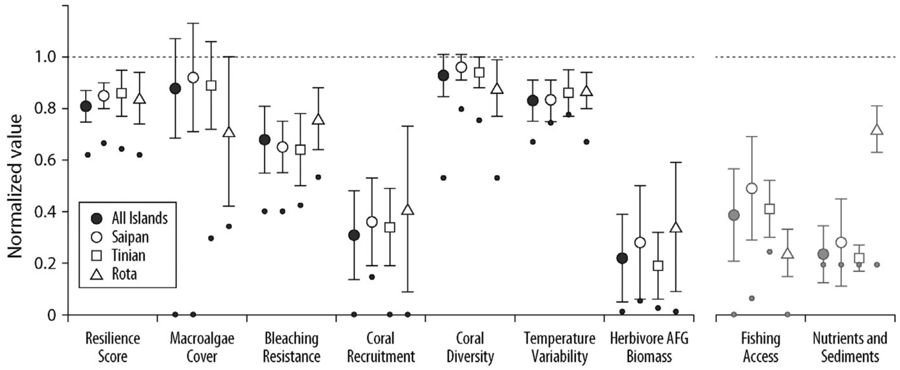


Fig. 3. Distribution of normalized values for the resilience scores, indicators and anthropogenic stressors for the inter-island and intra-island analyses (see also Figs. 1 and 2). Shapes represent average values, the tails equal 1 sd, and the dots are the minimum values; maximum values are all 1.0 (dashed line). Relative classifications for resilience scores and resilience indicator scores are as follows: high (final scores that are >1 sd above average (avg.) *as long as ≤ 1*), medium-high (<avg. + 1 sd and >avg.), medium-low (<avg. and >avg. − 1 sd), and low (<avg. − 1 sd). The range in scores meant that there are all four classifications among our sites for 5 of 7 indicators. For macroalgae cover and coral diversity the value of the average + 1 sd exceeds the maximum possible value of 1 so no sites are described as being relatively 'high'.

and resilience potential) at all islands and on both the leeward and windward sides of the islands (Fig. A9). These sites are generally in close proximity (within ~5 km) to human communities where the percentage of the watersheds made up by urban and cleared areas is greatest (see 19, 38, 76 for Saipan and 34 for Tinian/Aguijan, Fig. 5). Sites that are targets for fishery management and enforcement ($n = 25$, Fig. 5, Fig. A10) are all on the leeward side of Saipan and southern end and leeward side of Tinian/Aguijan (Fig. A9). Results from the 6 criteria set for identifying targets for management actions are summarized within Table 2 and Fig. 5, and for the individual queries in Figs. A8–A13.

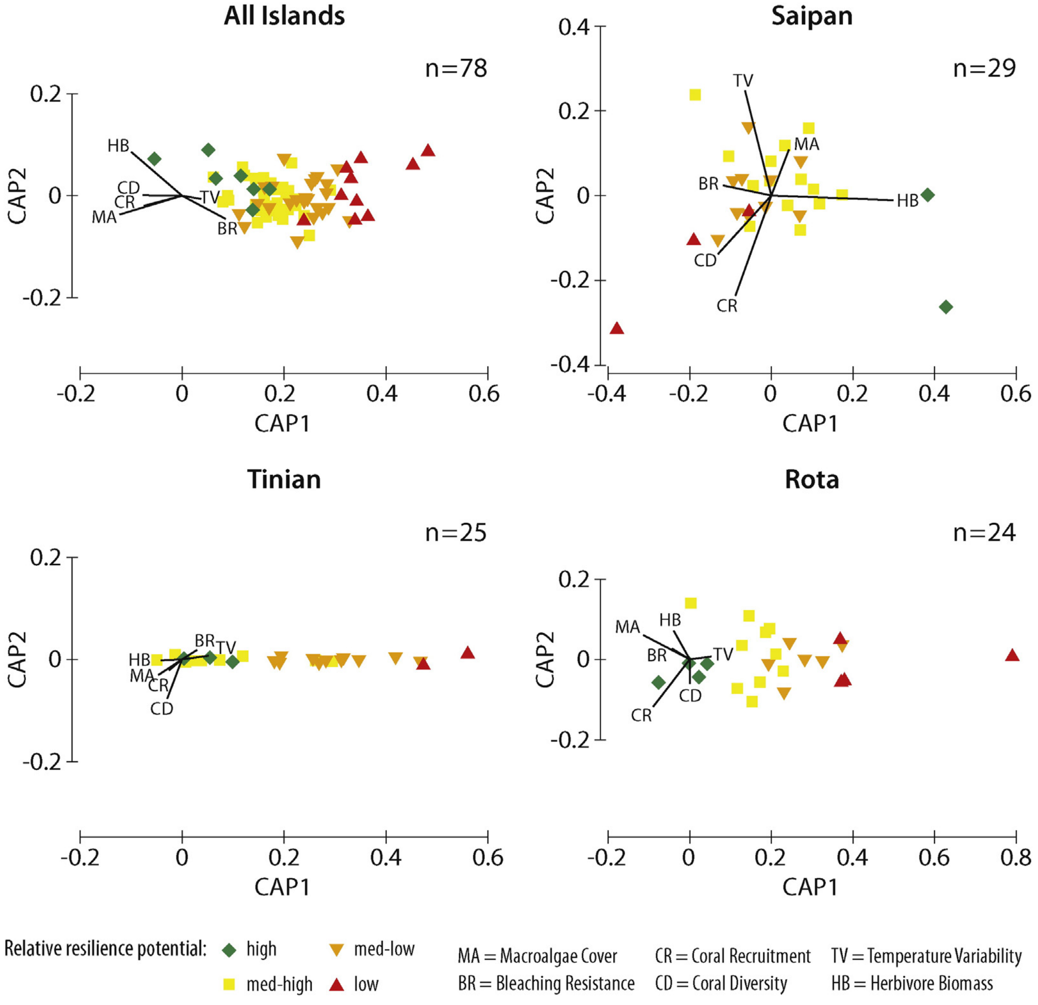


Fig. 4. Canonical analysis of principal coordinates showing the relative contribution of six resilience indicators (overlaid as vectors) to the overall resilience of reef sites for the inter-island analysis (A) and intra-island analyses (B-D). Squared canonical correlation values (δ^2) of the first and second ordination axes are 0.603 and 0.112 for all islands, 0.690 and 0.364 for Saipan, 0.697 and 0.001 for Tinian, 0.727 and 0.088 for Rota.

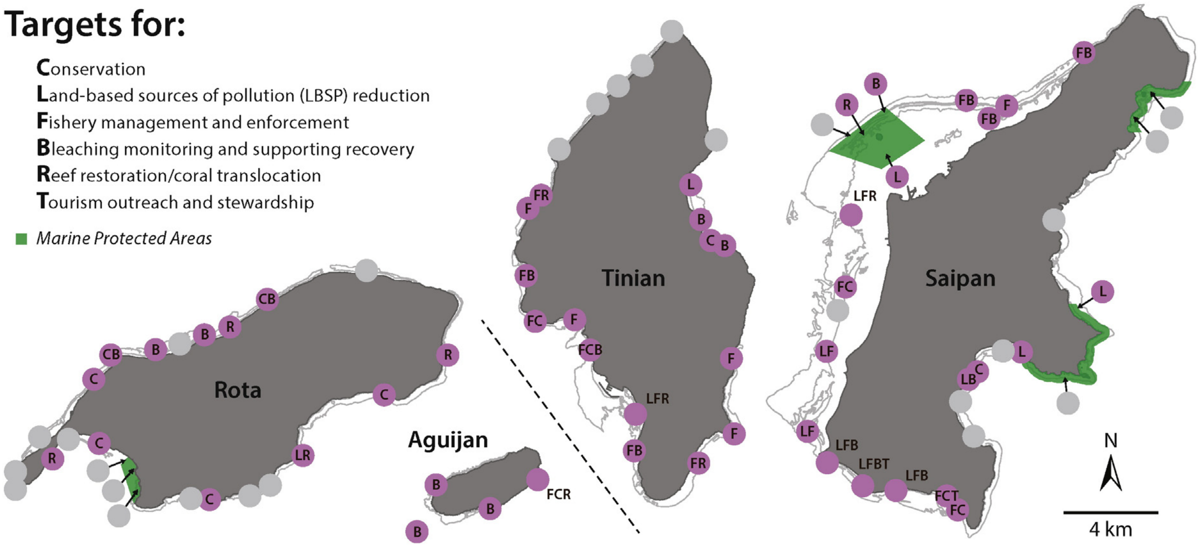


Fig. 5. Results of the 6 queries used to identify targets for different types of management actions that can support site or system resilience. Criteria for the queries and relevant suggested management actions are described within Table 2. Sites in gray meet none of the 6 set criteria but may warrant some of these same kinds of management actions for reasons distinct from the resilience assessment results. Query results are also shown in Table A10 and for each of the individual queries in Figs. A8–A13.

4. Discussion

4.1. Relative resilience potential in CNMI.

We found spatial variation in relative resilience potential among and within the surveyed islands, with ~20% of the sites for the inter- and intra-island analyses classified as having high or low relative resilience. These sites have higher or lower resilience potential than is typical of the sites in the area; i.e., are outside the bounds of one standard deviation of the average. A key finding from examining the locations of the low and high resilience sites is that these are not evenly distributed either among or within the islands. This is an unsurprising result in a sense and would be the case in most other locations if similar assessments are undertaken. However, scientists or managers had never visited more than half of the sites in CNMI surveyed in this study. We had no preconceived notions as to where exactly the sites with highest and lowest relative resilience potential would be, but suspected the sites most remote and least exposed to anthropogenic stressors would be among those with the highest resilience scores. We found this to be the case when comparing inter-island and intra-island scores within each of the islands.

When only comparing resilience scores within island, sites remote from the human population centers have the highest resilience scores and sites with the lowest resilience scores are within a few km of the population centers. The anthropogenic stress proxies used for LBSP and fishing access are not included in the resilience potential scores. Rather, these stressors are likely acting on several of the resilience indicators. For example, sites with lower relative resilience tended to have lower herbivore AFG biomass, lower recruitment and higher macroalgae cover, and above-average fishing access and LBSP. This local (within island) pattern seen for all islands does not translate to the region-wide inter-island analysis. If it did, we would expect sites classified as having high resilience in the inter-island analysis to be furthest from the most populated islands. However, the majority of the locations classified as having high relative resilience in the inter-island analysis are in Saipan, where >90% of the 50,000 people residing in CNMI live. There are no sites classified as having high relative resilience in Rota in the inter-island analysis, which is ~50 km south of Tinian/Aguijan and north of Guam and has only ~2000 residents.

There are three potential explanations for differences between Saipan and Rota in relative resilience potential, all of which likely play a role. (1) There are 3 no-take MPAs in Saipan and only 1 in Rota. 6 of the 8 sites within no-take MPAs in Saipan were classified as having medium-high resilience and the other 2 have high resilience. (2) Coral growth capacity is inherently lower on Rota than Saipan due to varying geological settings (i.e., only Rota has low relief framework with limited Holocene deposition, Houk et al., 2014). (3) Rota has poor connectivity to the large larvae sources of Saipan, Tinian/Aguijan, and Guam.

There are two lines of evidence that support connectivity as a major driver of differences among the islands in resilience potential. Firstly, the results of our connectivity simulations indicate that Rota is a destination for roughly half as many larvae as is the case for either Saipan or Tinian/Aguijan. Further, Rota produces only 10% as much larvae as the larger islands of Saipan and Tinian/Aguijan and is the poorest self-recruiter. Lesser amounts and percentages of the 20, 50 and 100-PLD larvae from Rota arrive at Rota reefs for both our simulations than was the case for Saipan or Tinian/Aguijan. The second line of evidence supports the first. Average scores in Rota are lower for all four of the resilience indicators that relate to connectivity than average scores for these indicators for the other islands. Herbivore AFG biomass and coral recruitment are both lower on average in Rota. Perhaps consequently, macroalgae cover is higher (i.e., lower scores on our uni-directional scale) and coral diversity is also lower in Rota. The resilience assessment results suggest that inter-island connectivity differences, especially in the extent to which each island is a destination, are potentially a major driver of differences among the islands in relative resilience potential. Being able to make this interpretation demonstrates the value of connectivity information for helping understand resilience assessment results.

The contrasting drivers of the inter- and intra-island variation in resilience potential highlight the value of our having undertaken the analyses at both spatial scales. Among island variation in resilience potential in CNMI is likely driven by differences in MPA investment, geomorphology and connectivity. However, the relative classifications in the inter-island analysis (red, orange, yellow and green in Fig. 1) make it difficult to interpret within-island differences, which is why the data are represented as an intra-island analysis in our Fig. 2. The within-island comparisons indicate that resilience potential at each island is driven at least in part by spatial variation in exposure to anthropogenic stress. This effect is exemplified in Saipan by two medium-low resilience sites (orange) in the inter-island analysis becoming low resilience sites (red) in the intra-island analysis. Assessments undertaken in many other reef locations would likely find this same result in that differences in the (regional) drivers of inter-island differences in resilience potential will vary from (local) drivers of intra-island differences.

Understanding which variables most influence differences in resilience potential is another valuable product of resilience assessments. This is because the indicators most influencing rankings 1) are the most important to include in monitoring programs, and 2) may reveal the types of management actions that would benefit the greatest number of sites. Since the scaling factors used to weight the indicators based on differences in perceived importance were small (1–1.37), the indicators with the greatest variability have the greatest influence on the resilience rankings. Herbivore AFG biomass, macroalgae cover and coral recruitment were the indicators with the greatest variability in CNMI. It was possible that high and low resilience sites could have these classifications as a result of having high scores for different indicators, which we examined using a CAP analysis. For the intra- and inter-island analysis, the CAP analysis indicated that herbivore AFG biomass and coral recruitment were most strongly associated with high and medium-high resilience sites. Without exception, high resilience sites have high scores for herbivore AFG biomass and coral recruitment and all low resilience sites have below average scores for herbivore AFG biomass and usually below average scores for coral recruitment (2 of 10 have medium-high scores). In this study, herbivore AFG biomass is clearly one of the primary drivers of differences in resilience potential, which has important management implications. For all sites surveyed, management actions to maintain herbivore AFG biomass are likely to be among the most important management actions to support resilience.

4.2. Resilience assessment results inform management.

For many reef managers, identifying sites with the highest and lowest relative resilience potential will be an important motivation for undertaking an ecological resilience assessment (Weeks and Jupiter, 2013). Among our queries to identify targets for various types of management actions, these are the 'Conservation' priorities; the sites with high or low resilience that are currently outside established no-take MPAs. Once these sites are identified, managers are faced with the challenge of deciding how to allocate resources; should managers prioritize the high resilience sites or spread capacity across high/low resilience sites?

Some researchers have explored whether we should protect the 'strong' (high resilience sites) or the 'weak' (low resilience sites), and have suggested the following. We should protect weak sites if we expect sites to spend most of their time in a healthy state and strong sites if we expect sites to spend most of their time in a degraded state (Game et al., 2008). With climate change and increasing disturbance frequencies, sites will likely spend most time in a recovering state. The global decline of coral reefs is well established (Hoegh-Guldberg et al., 2007) and this trend is likely to continue into the future (van Hooidonk et al., 2013, 2014, 2015; Maynard et al., 2015c). Further, it may take a decade or longer for the benefits of place-based management initiatives to manifest (Babcock et al., 2010; MacNeil et al., 2015). For these reasons, strong (high resilience) sites should be a higher priority than weak (low resilience) sites under climate change. Accordingly, two of our queries used to identify targets for management actions are combinations of above average values for resilience potential and the anthropogenic stressors.

In total, we developed six examples of how the resilience assessment results and assessments of anthropogenic stress could be queried to identify targets for different types of management actions (summarized in Fig. 5). We used the inter-island analysis results for the management queries as this enabled a synoptic view of threats and opportunities in CNMI and ensured management query results could be considered at the scale at which the connectivity simulation data was available. We identified high (and low) resilience sites that are conservation priorities (McLeod et al., 2008) and identified priority locations for improving water quality by limiting deforestation, stabilizing stream banks, enhancing wetlands or upgrading sewage treatment (Wolanski et al., 2003). We also identified priorities for fishery management and enforcement, which may further protect herbivorous fish populations and high resilience sites. Sites where bleaching monitoring and supporting recovery may be needed were identified, which can help target management responses during future bleaching events (Maynard et al., 2009). The target sites identified for reef restoration may be among those where reef restoration is most likely to succeed, so restoration practices could be trialed at these locations prior to broader implementation in the region. Lastly, we identified priority sites for establishing moorings and undertaking outreach and stewardship programs for tourism operators. These actions can help reduce impacts and help with awareness raising both of resilience as a concept and the need for resilience-based management actions.

The results for MPAs highlight the need for managers to use a range of approaches to reduce stress to reefs caused by human activities. Only two of the 11 sites within no-take MPAs were high resilience sites (Nanasu Reef and Bird Island in Saipan). 4 of the 9 other sites are targets for actions that would support resilience beyond the effects of the current fishing regulations within the MPAs. The list of queries developed for CNMI is not exhaustive of all of the possible options; other queries will be relevant for other coral reef jurisdictions. The suggested actions associated with the queries are also not new (reviewed in Table 2); marine managers have been implementing these kinds of actions all over the world during recent decades. The innovation in the decision-support framework presented is in explicitly using resilience information to determine where these actions should be targeted to support site and system resilience.

Once targets for management actions were identified, we considered the results of the management queries in the context of the connectivity simulation results. The connectivity results only inform the targeting of management actions at the island-scale because there is a scale mis-match between our resilience assessment results and connectivity simulations. This is due to limitations of the ocean transport models used and is likely to be a common challenge in reef areas given that available connectivity information is often at a far coarser, regional resolution than field surveys (Kendall and Poti, 2015). Even so, understanding connectivity at the whole-of-island scale can help decide where to target management actions to help maintain larvae supply and determine where actions may be ineffective due to having low connectivity to larvae sources. In CNMI, management actions implemented in Saipan and Tinian/Aguijan will be more helpful in maintaining larvae supply than in Rota since Saipan and Tinian/Aguian are each roughly 10× as great a larvae source as Rota (Table A7). Secondly, management actions may be ineffective in supporting resilience potential in Rota due to the limited availability there of larvae for settlement.

4.3. Future directions.

For future resilience assessments, indicator selection can start with a recommended core set of indicators and then indicators can be excluded or added as is appropriate for local contexts. For this to be possible, indicators need to be recommended for each region. As one example in support of this, recent research highlights differences in resilience in the Caribbean vs. the Pacific due to differences in drivers of resilience processes (Roff and Mumby, 2012). Additionally, suggestions for scaling resilience indicators and the identification of tipping points for resilience indicators can ensure resilience assessments are tailored to local contexts. Potential indicators can be prioritized and scaled via a combination of the following approaches: 1) surveying scientists on the perceived importance, empirical evidence and feasibility of assessment/measurement for a list of indicators (as in McClanahan et al., 2012); and 2) examining the relative importance of a range of indicators following a major disturbance event for an aspect of resilience (e.g., recovery rates; as in Graham et al., 2015); and empirically deriving tipping points (as in Jouffray et al., 2015; Levin and Mollmann, 2015). Understanding tipping points is an especially promising research area relevant to undertaking resilience assessments. However, research in this area can be time-consuming and costly and requires access to time-series monitoring datasets not available everywhere. Where available, information on tipping points could be used as an additional layer to complement the use of aggregate scores, such as those presented here. Where tipping points can be integrated into a resilience assessment, comparisons of resilience potential can include assessing whether any indicators are likely to be prohibitively low or high for the site to be resilient.

Another key future direction for the type of applied research presented here is the development of a dynamic understanding of spatial variation in vulnerability. This requires undertaking resilience assessments semi-regularly (every 3–5 years) and mapping exposure to disturbances (see Maynard et al., 2015d). For example, researchers are rapidly advancing methods and technologies to map historic and projected future exposure to thermal stress severe enough to cause bleaching. Spatial data on historic exposure to bleaching conditions became available very recently at 4-km resolution (http://coralreefwatch.noaa.gov/satellite/thermal_history/index.php). Downscaled climate model projections (~11-km resolution) are already available for the Caribbean (van Hooidonk et al., 2015) and are expected to be available at 4-km resolution in 2015. In the future, assessments like ours can be combined with data on impacts and recovery (from reef monitoring programs) and projections of future exposure to disturbances. Such an approach will expand the realm of possibilities for using resilience assessment results to target management actions. For example, actions can be targeted to sites with high resilience potential and high anthropogenic stress that have a lower or later projected future exposure to conditions conducive to bleaching and disease (van Hooidonk et al., 2014; Maynard et al., 2015c).

Ecological resilience assessments can be undertaken everywhere coral reefs occur by following the general steps outlined in our methods and then adapting each step to fit local resource constraints and contexts. Similar processes to that described here, whereby resilience potential is produced as an aggregate of a range of indicators of resilience processes, are also starting to be applied in other ecosystems (e.g., Conway-Cranos, 2012). Coral reef managers everywhere have limited resources so resource-constraints will be a determinant of whether and how an assessment is conducted. However, field surveys are by far the most resource-intensive aspect of the process we describe. Costs can be reduced in some locations by undertaking resilience assessments by collating and analyzing existing monitoring data, assuming the data have adequate spatial coverage within a set timeframe. The resource investment associated with resilience assessments may be more easily justified if the data collected during the resilience assessment can be used to support other conservation priorities (e.g., through generating complete species lists for fish and coral at each site, as was done for CNMI during our fieldwork, see Online Appendix B). Our experience in CNMI indicates that involving managers and reef stakeholders in every step of the process maximizes support for the process and the results. In many areas, the scientist-manager and local stakeholder collaborations we recommend can ensure that managers have access to the types of expertise required for the assessment and may reduce costs or add outreach and education value that further justifies undertaking the assessment (as in Maynard et al., 2010).

The resilience assessment and process presented here represents a major step forward in explicitly considering spatial variation in resilience potential in management planning, which helps to operationalize resilience concepts and theory. This is a rapidly advancing and popular research area. Disagreements among researchers about which resilience indicators are most important are expected, as are differing views on methods for measuring/assessing indicators and analyzing resultant data. However, this study describes much of the current thinking with respect to undertaking ecological resilience assessments in coral reef areas by measuring and assessing resilience indicators. The scientific and management community can now expand and refine these ideas and approaches through application in other locations and then sharing experiences and lessons learned. Consequently, we can increase our understanding of resilience drivers and the extent to which resilience is an explicit consideration in coral reef management decision-making.

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Appendix A and B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2015.09.001.

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