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SCUBA divers above the waterline: Using participatory mapping of coral reef conditions to inform reef management

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ABSTRACT

Coral reefs provide important ecological services such as biodiversity, climate regulation, and cultural benefits through recreation and tourism. However, many of the world's reefs are declining, with Caribbean reefs suffering a significant decline in living corals over the past half century. This situation emphasizes the need to assess and monitor reef conditions using a variety of methods. In this study, a new method for assessing reef conditions to inform management using participatory mapping by coral reef “experts” in the U.S. Virgin Islands (USVI) is described. Occupational SCUBA divers were recruited (n=87) to map coral reef conditions, uses, and threats (stressors) using an internet-based mapping website. The data reveal an uneven geographic distribution of reef conditions in the USVI with the most frequently mapped perceived healthy reef characteristics being: large amount of physical reef structure (n=872 markers); endangered or threatened species present (n=721); and large amount of live coral cover (n=615). The greatest perceived threats were: invasive species (n=606); water pollution (n=234); and unsustainable fishing (n=200). Areas of important reef characteristics, perceived threats to reefs, and perceived recovery potential were plotted to identify areas requiring critical management attention. The authors found that perceptions of healthy reef conditions outnumbered perceptions of reef threats for nine of the ten most familiar coral reefs; the most frequent activity type within the coral reefs was tourism diving; and for the most familiar coral reefs, the divers perceived a high recovery potential. Given the novelty of participatory mapping methods to assess coral reefs, the strengths and weaknesses of the method is evaluated. The authors further propose a management typology for categorizing reef areas to inform their future management. In the absence of primary data, or, as a supplement to underwater surveys and remotely-sensed data on reef condition, participatory mapping can provide a cost-effective means for assessing coral reef conditions while identifying place-specific reef locations requiring management attention.

1. Introduction

Coral reef ecosystems in the Caribbean provide a range of valuable services to people, including reef-related tourism and recreation (e.g., SCUBA, snorkeling, and recreational fishing), commercial fishing, coastal amenities related to real estate, and protection of the shoreline from storms [2,15]. However, long-term monitoring data indicate that Caribbean reefs are in decline, as evidenced by substantial reductions in live coral cover and key herbivorous species (i.e., sea urchins and parrot fish), coupled with concomitant increases in the number of reefs dominated by macroalgae [27]. In the U.S. Virgin Islands (USVI), scientific assessments have confirmed declining trends in overall coral reef health [12,28] both inside and outside marine protected areas [36]. This decline has resulted from a number of enduring, cumulative, and interacting factors, including inadequate land use planning, non-sustainable exploitation of marine resources, and significant natural events such as hurricanes and mass coral bleaching [38]. According to [27], without intervention, coral reefs in the USVI could become

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"ecologically extinct" within the next decade given current trends. The term "ecologically extinct" means that coral reefs would "no longer play any significant ecological role in determining the distribution and abundance of surviving species" ([27], 76) Impediments to improving the management of coral ecosystems include both a lack of actionable information about the status of reefs as well as their relative importance to the local community [42]. Without this type of information, resource managers are challenged to effectively prioritize competing management objectives in a fiscally limited environment.

Coral reef ecosystems have historically been monitored via the collection of data characterizing habitat features and the physical environment, as well as the presence and absence, abundance, composition, and distribution of key plant and animal species. Commonly, marine habitat and biological data are gathered using in-water surveys by research divers who systematically record data on coral reef features and species ([26,31,35]). Data on the status of commercially-important species, such as finfish, are also collected through fishery-dependent monitoring programs. Data on physical features and processes, such as water chemistry, water temperature, and currents are gathered manually with sampling or through the use of in-water automated or remote sensing technologies, such as buoys, remotely operated underwater vehicles, aerial photography, or satellite imagery [19,32]. Monitoring data are generally collected over time, enabling longitudinal analysis of coral reef communities and processes. However, scientific monitoring programs can be expensive or impractical for jurisdictions having significant reef areas spanning vast geographies [27].

In general, scientists are recognizing the value of connecting local ecological knowledge (LEK) of systems with data collected through the western scientific tradition, particularly in marine ecosystems [3,10,14,25,41,43]. To this end, scientists and resource managers have increasingly recruited SCUBA divers to collect data to improve understanding about the status of marine resources. Lorenzo et al., [30] collected information from recreational divers related to habitat quality, along with the distribution, status, and threats to endangered red coral. They concluded that information provided by divers was valuable for monitoring the status of the species over a broad geographic range. Goffredo et al., [22] relied on data collected by recreational SCUBA divers to aid in the assessment of seahorse (*Hippocampus* spp.) populations. Taylor et al. [41] and Forrester et al. [20] each surveyed divers to document trends in species presence and abundance, as well as habitat status over time, finding local expert knowledge useful for identifying some trends. Finally, Goffredo et al. [21] recruited recreational divers to gather data on marine species, as well as marine debris, finding that data reported was comparable in accuracy and consistency to that gathered by research divers. Increased reliance on SCUBA divers has enabled researchers to expand data collection efforts, while minimizing research costs.

Using participatory mapping methods, described below, local ecological knowledge can be used to provide an assessment of the relative quality and threat levels of coral reefs, as well as to understand which reefs are of most importance for human use activities. With this information, natural resource managers can more effectively direct management investments of value to the user community. By looking at the co-occurrence of reef quality characteristics and stress levels in coral reef areas used by people, resource managers can better decide whether to monitor reef quality, work to mitigate or reduce threats, initiate restoration activities, or simply divert management effort to other areas. In ideal cases, expert assessment would supplement biophysical data collected through regular coral reef monitoring activities. In other cases, where rich biophysical data does not exist, expert assessment may be the sole source of data to inform reef management.

1.1. Participatory mapping nomenclature

Participatory mapping is a general term that refers to a wide range of participatory and social research methods where spatial information is a core component. The terms public participation GIS (PPGIS), *participatory GIS* (PGIS), and *volunteered geographic information* (VGI) are common labels applied to spatial mapping processes involving different sampling groups. In the academic literature, there is continuing ambiguity over the use of the terms PPGIS/PGIS/VGI with PPGIS being the original term developed in 1996 at meetings of the National Center for Geographic Information and Analysis (NCGIA) to describe how GIS technology could support public participation for a variety of applications [33,34]. The term "participatory GIS" emerged from participatory approaches in rural areas of developing countries from the merging of Participatory Learning and Action (PLA) methods with geographic information technologies [37]. The term volunteered geographic information (VGI) was introduced by Goodchild [23] to describe the harnessing of tools to create, assemble, and disseminate geographic data provided voluntarily by individuals.

The concepts of "crowdsourcing" and "crowd wisdom" have become associated with VGI [40] and PPGIS [5] in recognition of the potential for a "crowd of people" to identity useful spatial information for a wide range of planning and management applications. The term "citizen science" has also become associated with VGI systems that involve research or monitoring activities conducted by amateur or non-professional scientists [24].

In this study, the recruitment of occupational SCUBA divers to map spatial information about reef conditions cannot be unambiguously situated within existing nomenclature. Is the mapping process best described as PPGIS, PGIS, VGI, crowd-sourcing, or citizen science? Are study participants volunteers, experts, or citizen scientists? The sampling and recruitment of study participants was purposive and not "volunteer" in the purest sense, the data collected was explicitly spatial, participants appear closer to "experts" than members of a "crowd"; and although some occupational SCUBA divers lack formal ecological training, they were requested to map reef conditions as a type of citizen scientist. For comparison, Goffredo et al. [21] and Lorenzo et al. [30] described recreational SCUBA divers in their studies as citizen "volunteers", Taylor et al. [41] described study participants as simply "long-term divers", while Forrester et al. [20] described divers engaged in reef monitoring activities as "volunteers" engaged in citizen science.

For convenience, the group of occupational SCUBA divers sampled and recruited for this study will be referred to as "experts" who engaged in *participatory mapping*; there is no compelling need to classify the mapping process as either PPGIS or VGI as it contains features common to both as described by Brown and Kyttä [7].

1.2. Reef assessment using expert participatory mapping

With coral reef ecosystems in decline globally, there is a pressing need to increase efforts geared toward their protection, restoration, and recovery [27]. Concurrently, there is a need to monitor the outcomes of such intervention by tracking and evaluating progress. However, because fiscal resources are increasingly limited, even basic scientific monitoring programs are unrealistic for some jurisdictions. For this reason, exploration of relatively low-cost monitoring options that can provide useful information on the current status as well as the long-term change of coral reef systems is needed. In this paper, the use of participatory mapping is demonstrated as one option for meeting this objective. Through mapping, social science researchers can harness the observational and experiential knowledge of SCUBA divers who are experts on the coral reefs where they dive.

In this study, an online mapping and survey tool to collect information on the status of coral reefs in the USVI from occupational SCUBA divers was developed. Our research was guided by the following research questions:

(1) Is participatory mapping of reef conditions by occupational divers an effective method to describe the geographic distribution of coral reef qualities and threats across a large study area consisting of multiple reefs?
(2) How are different perceived reef qualities and threats related, and can reef areas be analyzed and classified based on these relationships?
(3) At what spatial scale(s) does participatory mapping appear valid and useful for reef management?
(4) Can mapped data be used to develop a topology of reef conditions to inform future reef management?

Following analyses and a discussion of findings, the strengths and limitations of participatory mapping methods to assess and inform future reef management are addressed.

2. Methods

2.1. Study location and context

The study location was the U.S. Virgin Islands (USVI), a territory of the United States, located in the Caribbean east of Puerto Rico (see Fig. 1). The USVI is composed of three large islands, St. Croix, St. Thomas, and St. John, and several smaller islands. An extensive coral reef ecosystem surrounds the islands of the USVI. This broader ecosystem is composed of many types of habitat including coral, sea grass, and mangrove. These habitats together support a variety of organisms that are of importance to people.

The USVI resident population is approximately 106,500 with a majority of these residents concentrated on St. Thomas. St. Croix, the largest of the three islands, has a population only slightly smaller than St. Thomas, but with a much lower population density. St. Croix has experienced severe economic decline in the last five years with the closure of an oil refinery [13]. St. John Island, the smallest of the main islands, has a population that is, on average, the most wealthy of the USVI. Three quarters of St. John falls within a national park boundary under the purview of the U.S. National Park Service and is largely undeveloped [18].

Tourism, trade, and other services are the primary economic activities for the USVI. These sectors account for half of total civilian employment and more than half of total GDP [13]. The islands host nearly three million tourists per year, mostly from visiting cruise ships. One of the primary attractions of the tourism economy is the territory's coral reefs. These reefs provide a range of important services including recreation and culture, amenities, storm protection, and commercial fishing. In 2011, the total economic value of coral reef ecosystems in the USVI was estimated to be approximately $187 million per year [45]. Due to the importance of coral reefs and marine activities, a variety of occupations in the USVI are associated with SCUBA diving. These occupations include tourism diving, SCUBA instruction, research diving, and commercial and technical diving.

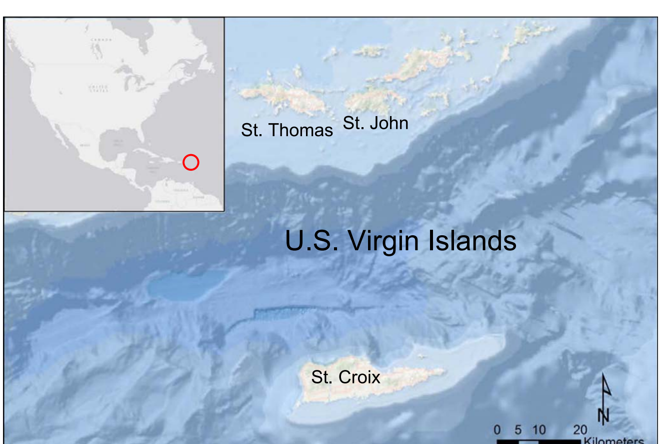

Fig. 1. Map of study area covering the island groups of St. Thomas and St. John (North) and St. Croix (South).

2.2. Data collection and sampling

The target population for this study was occupational SCUBA divers living and working in the USVI during the period from August to November 2014. An "occupational SCUBA diver" was defined as any person who engages in SCUBA diving activity for their profession, occupation, or business. Excluded from this definition were commercial fishermen whose fishing practices involve taking fish while SCUBA diving (e.g., spearfishing or traps) and people whose volunteer work includes SCUBA. During the recruitment process, all potential respondents were screened by an interviewer to determine if they met the project definition of an occupational SCUBA diver.

A relatively small population of occupational SCUBA divers was anticipated in the USVI, thus a census of divers was attempted. A "seed list" of potential respondents was developed through consultation with local partners and by accessing business directories specific to the USVI. To further identify and recruit respondents, a "chain referral" strategy was implemented where all participants who completed the survey were asked to provide referrals to other occupational SCUBA divers. The referrals were tracked, and new names were compared to the list of participants. Data collection occurred from August to November 2014 to increase the likelihood of participation during the low tourism season and concluded once no new referrals were identified.

The research team designed, pre-tested and implemented an internet-based mapping application for data collection. The application used a Google® maps interface where participants could drag and drop digital markers onto a map of the USVI (see Fig. 2). The process consisted of participants entering the website, providing informed consent, mapping the reef attributes with digital markers, and answering text-based survey questions following the mapping activity. Participants were instructed to place the markers in locations based on their own personal observations and experience diving in the study area. To assist participants with spatial orientation, a variety of informational features were added to the website including boundaries of marine protected areas, a predicted reef layer to identify where coral reef areas were located, and 10 m depth contours. Geographic coordinates were also provided as an option for participants to locate reef locations by latitude and longitude using GPS coordinates. Respondents were able to place markers on the map at three different Google map zoom levels that approximate the following scales: 17=1:9028; 18=1:4514; and 19=1:2257. Most participants mapped at the default zoom level (1:9028).

The list of 25 mapping attributes was developed by the research team in consultation with the natural scientists having expertise in coral reef ecology and associated marine resources in the Caribbean. The attributes were divided into categories that describe reef features (n=11), best diving locations for tourism, research, or personal leisure purposes (n=3), potential reef threats (n=8), and areas with various levels of recovery potential (n=3). The attributes and their operational definitions appear in Table 1.

The post-mapping survey questions included basic sociodemographic variables, diving experience, the participants' value-orientation toward coral reef ecosystems, and self-identified knowledge of the study area.

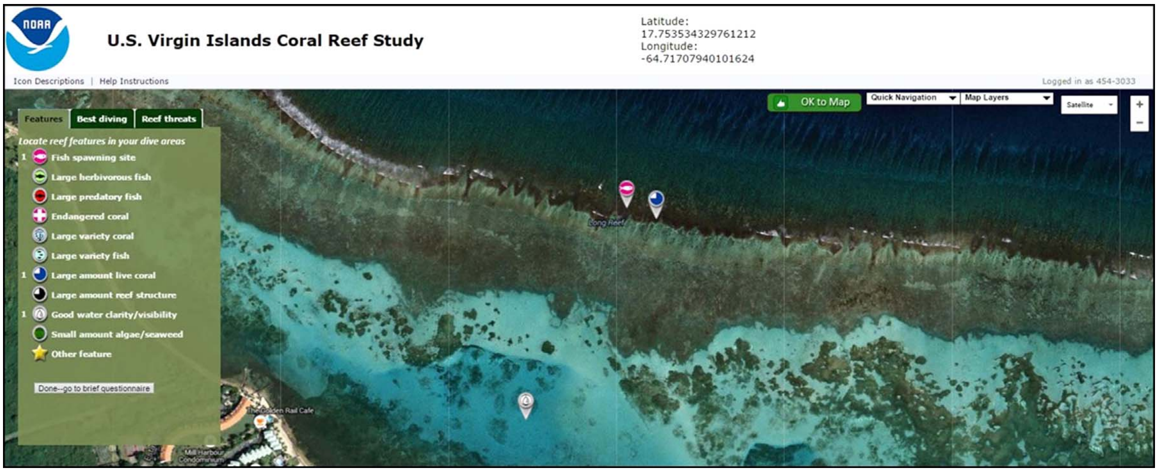

Fig. 2. Computer interface for mapping coral reef attributes. Markers from "tab panels" on left are dragged and dropped onto reef locations.

2.3. Analyses

2.3.1. Data preparation

All data was collected in a web server database and downloaded for analysis. The spatial data identifying reef locations and attributes were imported into ArcGIS 10.3.1 for spatial analysis and joined with text responses to post-mapping survey questions. A conservative approach by the researchers to ensure data quality by limiting our analysis to "full completions" where a study participant mapped at least one marker as well as answered the post-mapping survey questions (n=87). Individuals that mapped locations but failed to complete the post-mapping survey questions (n=9) and individuals that accessed the website but did not mark any locations (n=23) were excluded from analysis.

In the ArcGIS environment, a point shapefile was created from the spatial data by plotting the *x-* and *y-coordinates* of the markers. Using the ModelBuilder interface, individual point shapefiles were created for each of the 25 marker categories and the four groups of related markers

Table 1
Participatory mapping markers and operational definitions.

TAB 1	REEF CHARACTERISTICS & FEATURES	OPERATIONAL DEFINITION
	Fish spawning aggregation site	Place where one can see fish aggregating to spawn.
	Large herbivorous fish (e.g., parrotfish or surgeonfish)	Place where one can see large herbivorous fish such as parrotfish or surgeonfish.
	Large predatory fish (e.g., sharks or barracuda)	Place where one can see large predatory fish such as sharks or barracuda.
	Endangered or threatened species present (e.g., elkhorn and staghorn coral)	Place where one can see endangered or threatened coral species such as elkhorn and staghorn coral.
	Large variety of coral species	Place where one can see a large variety of coral species.
	Large variety of fish species	Place where one can see a large variety of fish species.
	Large amount of live coral cover	Place where one can see a large amount of live coral cover.
	Large amount of physical reef structure	Place where one can see a large amount of physical reef structure.
	Good water clarity/visibility	Place where one can find good water clarity and visibility.
	Small amount of macro algae/seaweed	Place where there is a small amount of macro algae/seaweed.
	Other features	Other coral reef feature (Please describe).
TAB 2	**REEF ACTIVITY AREAS**	
	Tourism Diving	Best place(s) for tourism diving activities.
	Personal Leisure Diving	Best place(s) for personal/recreational diving activities
	Research Diving	Best place(s) for research diving activities.
TAB 3A	**STRESSORS**	
	Storms	These places are threatened or stressed by storms.
	Coral Bleaching	These places are threatened or stressed by coral bleaching.
	Water Pollution	These places are threatened or stressed by water pollution.
	Shipping and Other Boats	These places are threatened or stressed by shipping or other boats.
	Unsustainable Fishing	These places are threatened by too much fishing or unsustainable fishing practices.
	Recreational Overuse	These places are threatened or stressed from too much recreational use.
	Invasive Species	These places are threatened or stressed by invasive species.
	No Stressors	This place is not currently experiencing stress.
TAB 3B	**RECOVERY POTENTIAL**	
	High Recovery Potential	*These coral reef areas have high potential for recovery from reef stressors.*
	Low Recovery Potential	*These coral reef areas have low potential for recovery from reef stressors.*
	No Recovery Potential	*These coral reef areas have no potential for recovery from reef stressors.*

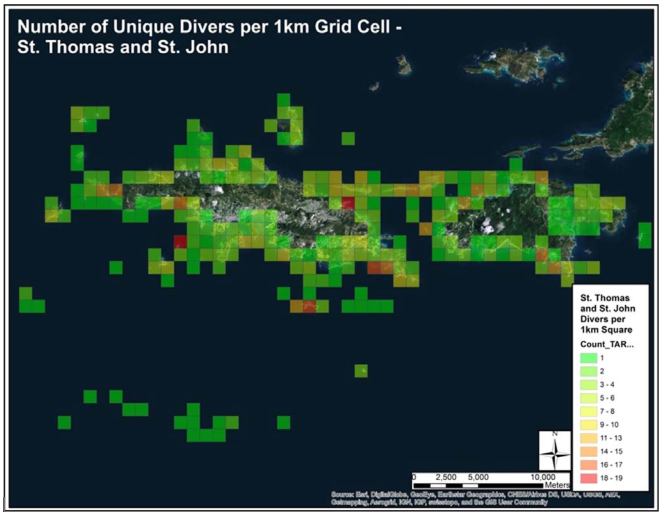

Fig. 3. Distribution of number of unique divers mapping one or more reef markers in 1 km grid cells near St. Thomas and St. John (USVI).

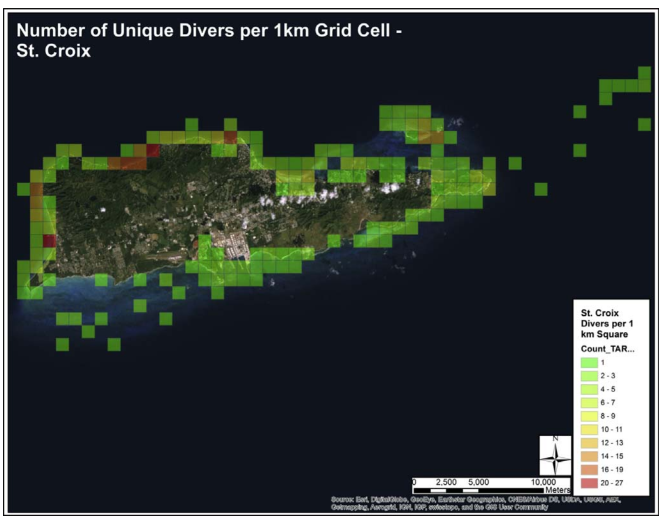

Fig. 4. Distribution of number of unique divers mapping one or more reef markers in 1 km grid cells near St. Croix (USVI).

(reef qualities, threats, activity locations, and recovery potential). Individual point shapefiles were also created for each diver using a similar method. After examining the spatial coverage of the diver point data, the divers were divided into two distinct groups to facilitate analyses: St. Croix divers (n=53) and St. Thomas/St. John divers (n=45). The combined diver counts for islands (n=98) exceed the number of unique divers (n=87) because 11 divers marked reef locations in both island areas.

To finalize the spatial data preparation, a 1 km by 1 km fishnet grid was created for each of the island sets. Although the spatial precision of individual markers placed by study participants was likely finer than 1 km, the grid size was selected for spatial analysis to provide sufficient aggregation of markers for quantitative comparison given the number of markers placed and the size of the study area.

2.3.2. Frequency and location of mapped attributes by individual reef

Using the ModelBuilder interface, a model was created to spatially join individual diver points to the 1 km grid and to summarize the count of unique divers per grid cell for each island group. To achieve the highest confidence in inferences based on the spatial data, 10 reef areas were selected (5 for each island group) with the largest number of unique divers that mapped in the location. These 10 reef locations thus represent the greatest collective familiarity of divers with reef conditions using a "one diver, one vote" rule in assessing familiarity.

Once the top ten cells (i.e., reef locations) were determined, all marker types that fell within each of the cells were collected. From all marker categories, the following categories were selected and aggregated: seven perceived threat types (*storms, coral bleaching, water pollution, shipping and other boats, unsustainable fishing, recreational overuse, and invasive species*); seven perceived reef quality types (*large herbivorous fish, large predatory fish, endangered or threatened species present, large variety of coral species, large variety of fish species, large amount of live coral cover, and large amount of physical reef structure*); three observed activity types (*diving tourism, personal diving, and research diving*); and three levels of perceived recovery potential (*high recovery potential, low recovery potential, or no recovery potential*). In all but one case (Frederiksted Pier, St. Croix) the indicators of healthy reef conditions outnumbered the indicators of perceived threats to coral reefs.

For each of the 10 reef locations, the frequency distribution of markers by category to describe and characterize the reefs on the dimensions of qualities, threats, activity types, and recovery potential was analyzed. The marker counts of qualities and threats were aggregated into indices and normalized scores that provide for comparison across reef locations and cross-tabulation with dominant reef activity and the perceived potential for recovery. A Simpson's diversity index was also calculated that quantifies the distribution of reef qualities and threats by the number and abundance of threats and qualities present in the reef location. Higher diversity of positive reef characteristics would suggest the reef is perceived to support multiple species and ecological functions while a high diversity of threats would indicate the reef is at risk from multiple stressors that may be difficult to manage.

2.3.3. Identifying and plotting reef conditions by qualities and threats by study area (management matrix)

The final step in the analysis was to develop a management classification matrix to provide insight into the range of reef conditions found in the USVI. The management matrix consisted of two dimensions—reef qualities by reef threats. Each reef location, based on quality and threat indices, was plotted to identify which of the four matrix quadrants a reef location would fall into—high quality, high threat; high quality, low threat; low quality, high threat; and low quality, low threat. In the final step, each of the 10 reef locations was classified into one of three dominant activity categories (i.e., tourism, personal, research) and dominant recovery potential categories (high, medium, and no recovery) based on the largest number of activity and recovery markers. The position of the reefs within the management matrix, in combination with the dominant use types and recovery potential, suggest potential management strategies.

3. Results

3.1. Participation rates and response profile

A total of 87 out of 135 identified occupational divers participated in the study for a response rate of 64%. Study participants were predominately male (69.0%). The average age of the typical respondent was 41, with a majority (51.7%) of respondents falling between 18 and 39 years of age. Respondents were well educated with 64.3% of participants holding a Bachelor's degree or higher. Respondents possessed an average of eight years of both occupational and recreational diving experience. However, 25.3% of the respondents reported ten or more years of occupational diving experience. The occupational categories most frequently reported by participants, in rank order, were SCUBA guide, teaching SCUBA, and scientific research/monitoring. The majority of divers lived on St. Croix (48.3%) and St. Thomas (41.4%) with only a few divers residing on St. John (10.3%). Finally,

Table 2
Metrics for 10 reef areas included number of unique divers, marker counts for reef conditions, activities, and recovery potential. Largest counts for threats, qualities, activities, and recovery potential categories are indicated by shaded cells.

	# Divers	Reef threats/stressors: storm	bleach	pollution	ships	fishmuch	recmuch	invasive	Threat Total	Normalized Total[c]	Threat Diversity[a]	Reef qualities: herbfish	predfish	ets	varcoral	varfish	livecoral	structure	Qualities Total	Normalized Total[c]	Quality Diversity[a]	Ratio of Qualities/Threats[b]	Activities: tourism	personal	research	Recovery Potential: low	high	none
REEF 1	18	7	8	15	6	9	5	12	62	0.56	0.85	11	8	32	19	19	19	21	129	0.82	0.84	2.08	22	11	6	2	4	0
REEF 2	19	5	7	5	4	2	2	3	28	0.16	0.86	6	2	60	18	15	22	19	142	0.93	0.76	5.07	13	5	5	0	6	0
REEF 3	17	4	4	1	2	0	1	11	23	0.11	0.73	8	11	14	13	14	10	15	85	0.44	0.86	3.70	29	9	3	0	3	0
REEF 4	15	3	2	0	1	1	0	7	14	0.00	0.73	4	5	6	5	6	4	7	37	0.03	0.88	2.64	19	7	2	0	2	0
REEF 5	17	3	3	2	1	2	3	9	23	0.11	0.81	4	2	0	7	4	8	9	34	0.00	0.83	1.48	24	4	0	0	3	0
REEF 6	19	4	1	6	4	8	2	6	31	0.20	0.85	7	14	7	11	14	12	20	85	0.44	0.85	2.74	20	11	10	1	6	0
REEF 7	27	4	7	6	8	5	9	15	54	0.47	0.85	9	20	27	31	16	17	30	150	1.00	0.84	2.78	29	29	22	1	11	0
REEF 8	19	1	1	1	0	11	1	2	17	0.04	0.59	9	7	11	6	8	12	12	65	0.27	0.86	3.82	20	7	7	0	1	0
REEF 9	19	7	6	1	0	14	0	19	47	0.39	0.72	9	12	16	18	16	24	12	107	0.63	0.85	2.28	18	10	17	0	3	0
REEF 10	26	6	1	12	19	25	3	33	99	1.00	0.78	10	7	3	11	21	11	7	70	0.31	0.83	0.71	31	4	36	4	5	1
Total		44	40	49	45	77	26	117	398			77	88	176	139	133	139	152	904			2.3	225	97	108	8	44	1

[a] Diversity calculated using Simpson's diversity index. Indices range from 0 to 1 with higher indices indicated greater diversity of threats or qualities.
[b] Ratio calculated by dividing the total number of qualities by the total number of threats.
[c] Normalized total = $\frac{(X-Xmin)}{(Xmax-Xmin)}$

approximately 60% of respondents indicated that they mapped 49% or less of their known coral reef areas for this study. Ten percent of respondents reported mapping 90–100% of their known coral reef areas.

3.2. General frequency distribution of mapped reef attributes

The 10 top reef locations representing the greatest collective familiarity of divers with reef conditions were identified by counting the number of unique divers that mapped one or more attributes in the reef location (see reef location in Figs. 3 and 4). The number of unique divers mapping a single reef location ranged from 15 to 27 (Table 2) with divers somewhat more familiar with the five reef locations in the St. Croix island group (Mann-Whitney U=23.5, $p < 0.05$). This difference is likely the consequence of the St. Croix island group being used more for research activities than reefs in the St. Thomas/St. John island group (Mann-Whitney U=25.0, $p < 0.05$). There were no other significant differences between the island groups based on the number of mapped perceived reef qualities and stressors with the exception of the *unsustainable fishing* threat which was mapped more frequently in the St. Croix group (Mann-Whitney U=23.0, $p < 0.05$). With the exception of Reef 10, the dominant activity type in all 10 reef locations was tourism.

There were more mapped reef qualities (n=907) than reef threats (n=398) across the 10 reef locations. The most frequently mapped reef threat across all reef locations was *invasive species* followed by *unsustainable fishing*. The least mapped perceived threat was *recreation overuse*. The most frequently mapped reef quality was the presence of *endangered and threatened species,* followed by a *large amount of reef structure*. The least frequently mapped qualities were the presence of *herbaceous fish* and *predatory fish*. The diversity of reef threats mapped (Simpson's index) ranged from 0.72 to 0.86 indicating relatively high diversity in the types of threat markers, while the diversity of reef qualities ranged from 0.76 to 0.88, also indicating high diversity in the type of reef qualities mapped.

The ratio of mapped reef qualities to threats provides an overall indicator of whether a given reef location is perceived to have more positive qualities than associated threats. Healthier reefs should have ratios that exceed 1.0, i.e., more positive qualities than perceived threats. The quality-threat ratio ranged from a high of 5.1 (Reef 2) to a low of 0.7 (Reef 10). Given the propensity for divers to map reef qualities more than threats by a factor greater than 2 to 1, the highest risk reefs would have ratios less than two, indicating that Reef 5 (ratio=1.5) could also be classified as a high risk reef location.

The *recovery potential* markers were the least frequently mapped by divers and thus the least reliable in terms of inferential confidence. However, the correlation coefficient between the combined categories of low or no potential for recovery and the number of mapped threats across the 10 reef areas was r=0.92 suggesting internal consistency in diver perceptions of reef conditions. In other words, there was a logical correlation between the quantity of mapped threats and recovery potential markers as one would expect if the divers were consistent in mapping behavior.

3.3. Distribution of mapped reef conditions by specific reef location

3.3.1. Coral Reef #1 (Coki Bay to the north and Water Bay to the south)

Water Bay was perceived as threatened with 11 divers placing 30 markers spanning seven categories with *pollution* as the greatest threat (see Fig. 5). Only two divers placed quality markers spanning four categories, the largest number being the presence of *endangered/threatened species*. Tourism diving was the most recorded activity type with all tourism markers located in Coki Bay. Water Bay to the south had two markers for *low recovery potential*, while Coki Bay had four *high recovery potential markers*.

3.3.2. Coral Reef #2 (Flat Cay and Little Flat Cay)

The largest number of markers was placed to the east of Flat Cay (94 quality and 22 threat). The east side of the Flat Cays is most threatened by *coral bleaching* according to divers, while the presence of *endangered/threatened species* was the highest mapped reef quality. To the west of the Cays, 54 total markers (6 threat and 48 quality) were mapped spanning 12 different categories with *large reef structure* and *endangered /threatened species* having the highest mapped qualities, and *unsustainable fishing* the greatest threat. The six *high recovery potential* markers were split equally among both sides of the Cays. *Tourism* activity dominated with nine divers placing markers on the east side of the Cays.

3.3.3. Coral Reef #3 (Cow and Calf Rocks)

The largest number of markers were placed near Calf Rock (eastern outcrop), with *endangered/threatened species* the most frequently

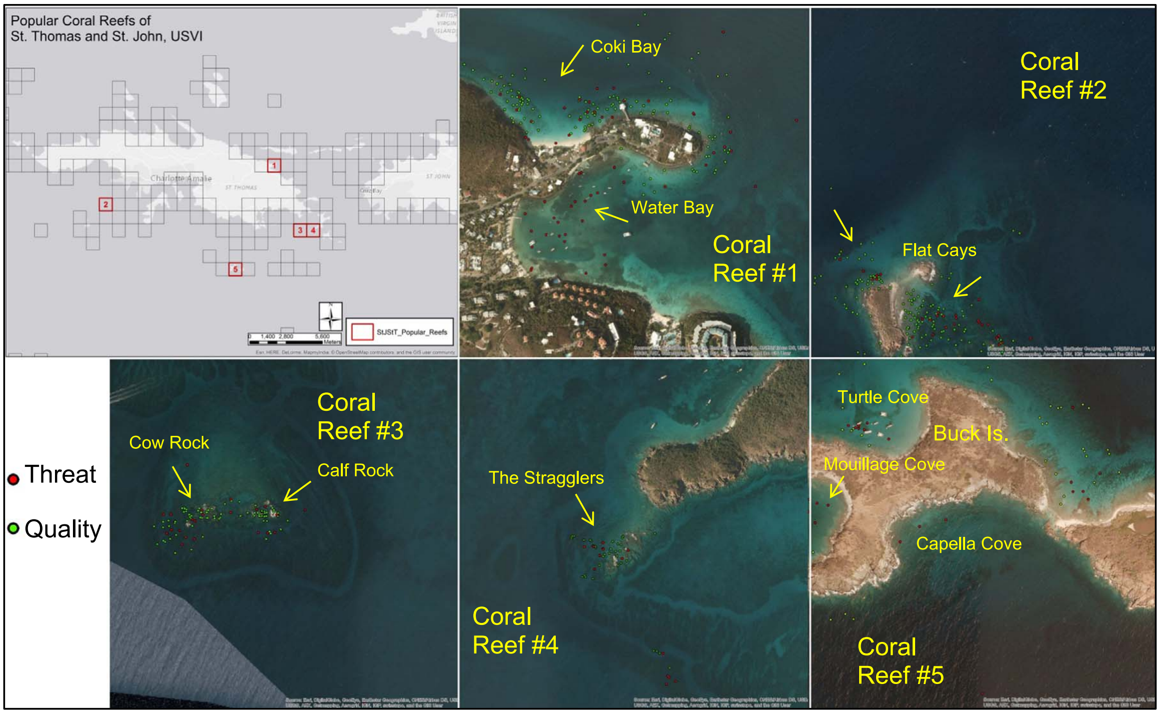

Fig. 5. Distribution of mapped coral reef threats and indicators of quality for selected reefs near St. Thomas and St. John (USVI).

mapped quality and *invasive species* the most frequently mapped threat. *Invasive species* was also the most frequently mapped threat for Cow Rock (western outcrop) and *large reef structure* was the most frequently mapped quality. The 29 *tourism* activity markers were evenly divided between the two locations.

3.3.4. Coral Reef #4 (The Stragglers)

The majority of markers from all categories were concentrated around the rocky outcrops known as The Stragglers. The most frequently mapped reef quality was *large reef structure* and the most frequently mapped threat was *invasive species*. Tourism activity was most frequently mapped and was concentrated around The Stragglers. The reef had two markers placed for *high recovery potential*–one near the Stragglers outcrop and the other to the south east.

3.3.5. Coral Reef #5 (Buck Island – St. Thomas)

The majority of reef quality markers (21 of 34) were placed on the western side of Buck Island. The two highest quality categories were *large live coral cover* and *large reef structure*. Turtle Cove had seven threat markers, while Mouillage Cove had more threat markers than quality markers. Capella Bay only had threat markers mapped. Tourism was the most frequently mapped activity with the majority of markers located in the western waters off Buck Island.

3.3.6. Coral Reef #6 (The Mouth of Salt River Bay)

Markers in this reef area were evenly distributed to the east and west of the channel formed by Salt River's outfall. The east side is dominated by *invasive species* and *unsustainable fishing* reef threats, while *large reef structure* was the most frequently marked quality. The western side of the channel was dominated by *unsustainable fishing* and *pollution* for threats and *large reef structure* for quality. Tourism was the most mapped activity type and was evenly split to the east and west of the channel. *High recovery potential* markers were also mapped evenly between east and west (Fig. 6).

3.3.7. Coral Reef #7 (The Pavilions)

The majority of markers (95 out of 150) were mapped in the southwest of the reef area. The most frequent reef quality was *large reef structure* and the most frequent mapped threat was *invasive species*. The northeast reach of the reef area was dominated by *endangered/threatened species* quality and *invasive species* threat. Tourism and personal diving shared the majority of activity type markers 29 each, mostly in the southwest sector. The reef was mapped with *high recovery potential* (n=11) by divers, the highest of all 10 reefs analyzed.

3.3.8. Coral Reef #8 (Cane Bay–East)

The markers within this reef area were fairly evenly distributed with the center section containing the highest marker density. The most frequently mapped quality was *large reef structure* and the most frequently mapped threat was *unsustainable fishing*. Tourism activity dominates reef area.

3.3.9. Coral Reef #9 (Cane Bay–West)

Mapping in this reef area was concentrated along the western side (121 of 154 total markers) with *large live coral* dominating reef qualities and *invasive species* dominating among threats. Although less frequently mapped, the same qualities and threats were mapped in the eastern reach of the reef. Tourism was the most mapped activity type and was concentrated in the west. However, research diving was mapped almost as frequently (17 and 18 markers respectively).

3.3.10. Coral Reef #10 (Frederiksted Pier)

This was the only reef area where threats outnumbered the indicators of reef quality. The area can be divided between north and south with the pier located in the north. In the north around Frederiksted Pier, the most frequently mapped reef quality was *large variety fish species* while the most frequently mapped threat was *unsustainable fishing*. In the south, *large variety fish species* and *large herbivorous fish* were the most frequently mapped qualities while *invasive species* was the most frequently mapped threat. Research

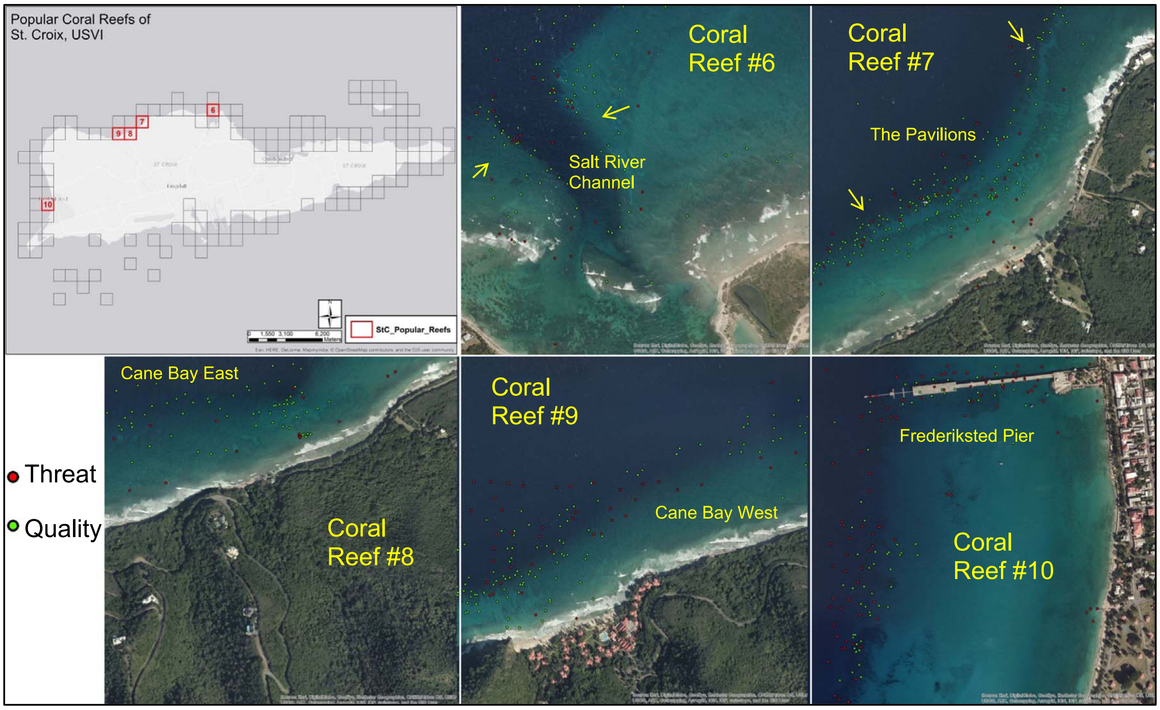

Fig. 6. Distribution of mapped coral reef threats and indicators of quality for selected reefs near St. Croix (USVI).

diving was the most frequently mapped activity, the only reef area where research activity was dominant among divers. Of the 10 reef areas, this reef area had the highest number of *low* or *no recovery potential* markers (n=5). However, this reef area also had 5 *high recovery potential* markers.

3.4. Reef qualities by reef threats (management matrix)

The 10 reef locations were plotted in two dimensions by total normalized counts of mapped reef qualities by reef threats. The resulting plot creates individual reef profiles that provide for easy visual comparison with other reefs in the study area. Reef areas that are located proximate to each other in the plot share similar distributions of qualities and threats. The two dimensions of qualities and threats were simplified into categories of high and low on each axis. Visually, one can see that Reef 1 and Reef 10 appear differentiated from the other reef areas based on conditions of high quality, high threat (Reef 1) and low quality, high threat (Reef 10). The other eight reef locations fall into quadrants described as high quality, low threat or low quality, low threat.

The dominant mapped reef activity type for all reefs was tourism diving with one exception, Reef 10. The dominant activity for this reef was research diving. When the most frequently mapped recovery potential markers were overlaid on reefs in the matrix, Reefs 2, 6,

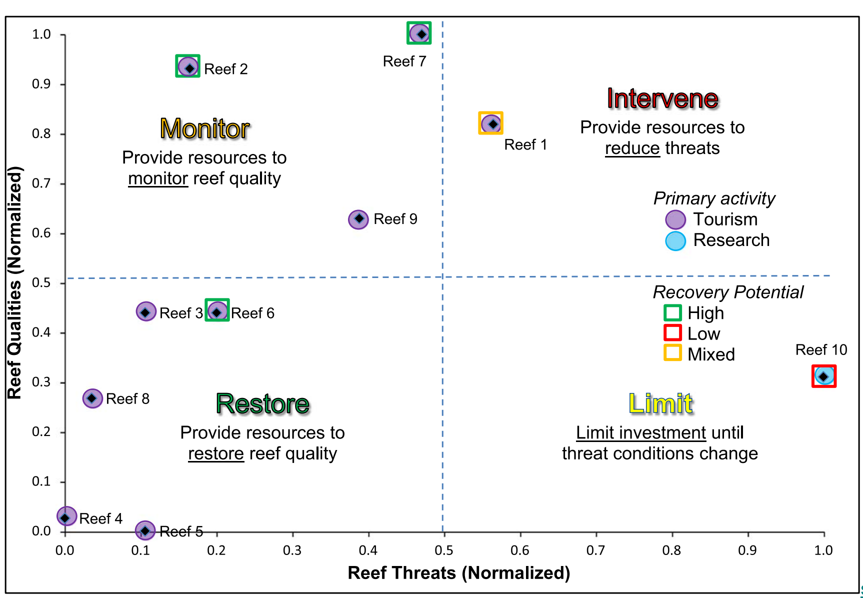

Fig. 7. Management matrix showing 10 reef locations plotted in two dimensions by normalized number of mapped reef qualities (y axis) and reef threats (x axis). Primary diving activity types are indicated for each reef location. Recovery potential is indicated for selected reefs based on mapped recovery potential markers.

and 7 indicated relatively high potential for recovery, Reef 10 showed relatively low potential for recovery, and Reef 1 indicated a mixed prospect for recovery with both high and low recovery markers mapped in the area.

Management strategy labels were applied to each of the four quadrants and forms the basis for our discussion on how the spatial information collected might be used to inform future reef management.

4. Discussion

The assessment and monitoring of coral reef ecosystems can be expensive or impractical for jurisdictions with limited fiscal resources or those with significant spans of reef covering vast geographic areas. Thus, there is a need to identify monitoring strategies that can be employed in these contexts. The purpose of this study was to evaluate the use of participatory mapping with occupational divers in the USVI to identify the distribution of coral reef qualities and threats, dominant human usage activities on the reefs, and the recovery potential for reefs under stress. The authors also sought to describe how this information could be used to inform future reef management.

Findings suggest that mapped indicators of healthy reef conditions (n=904) exceeded mapped reef threats (n=398) by a factor of 2.3 to 1. The magnitude of this difference may be partially attributed to the order in which the markers were presented to divers as it is well-established in web-based mapping interfaces that study participants will map more marker categories that appear first in order. Nevertheless, it is important to note that occupational divers in the USVI more often identified features associated with healthy reefs. This finding is noteworthy given the general belief amongst scientists that reefs in the USVI are in poor condition overall and in continuing a state of decline. However, this difference could be related to “shifting baselines,” a concept discussed in more detail below. Another explanation for the difference in marker placement may be related to the extent of reef threats. Several threats including water pollution, storms, and coral bleaching are believed to be geographically widespread. As a result, divers may not have marked these separately on all reef areas. For example, despite the guidance of the research team, some respondents were observed placing a single threat marker and verbally indicating that the marker applied to the entire USVI.

The mapping method provided sufficient data for analysis of reef conditions at multiple spatial scales. At a macro-scale, reefs in the USVI can be viewed as a system subject to larger regional and global processes that are likely to share common qualities and stressors. For example, the most frequently mapped reef threat indicator was *invasive species*, the likely culprit being the lionfish (*Pterois volitans*). First sighted in the USVI off the island of St. John in 2008, the lionfish was largely unseen until 2010 [11]. However, the lionfish has increased in geographic distribution such that there are now websites to collect presence/absence data about the fish, programs to eradicate the species, lionfish siting telephone hotlines, and an “Eat Lionfish” campaign [11,29].

At a micro-scale, USVI reefs can be viewed as a locally distinctive combination of natural and anthropogenic conditions that contribute to the ecological status of local reef areas. Within the larger reef system, occupational divers were able to identify distinctive areas or reef “hotspots” of ecological conditions and human activity types. Ten reef areas with a sufficiently large numbers of divers were analyzed to have relatively high confidence in the spatial results. Occupational divers were able to identify important differences in reef conditions at a spatial resolution smaller than 1 km. For example, there were significant differences in mapped reef conditions between physically proximate and adjacent bays and coves located in Reefs 1 and 5.

The observations and perceptions of occupational divers will naturally differ based on experience and familiarity. Variability in the mapped data is to be expected and requires aggregation and synthesis to reveal dominant patterns by spatial location. A number of metrics were calculated (aggregate counts, normalized counts, diversity indices, and ratios) to compare different reef areas within the study area. The metrics indicated a wide range of reef conditions across the 10 local areas from areas under high stress (Reef 10) to reefs in relatively good ecological health (Reef 2). A visual plot of aggregated reef qualities and threats provided a useful heuristic for identifying reef areas that are similar or different in profile. Two reef areas (Reef 1 and 10) in particular, emerged as having a significantly different profile from the other reefs, with relatively low quality-to-threat ratios of markers. These low ratios were consistent with diver markers indicating lower recovery potential for these areas.

4.1. Coral reef management implications

Given the above findings, how can the data be used to inform future reef management and should it be used for this purpose? From our perspective, the answer to the latter question is, yes. Participatory mapping appears well-suited as a reef *assessment* or *monitoring* tool, but the quality of information depends on who does the mapping and the sampling effort [4]. Other studies have found that participatory mapping with non-experts can yield relatively high quality spatial data for identifying environmental features [6,9,16,17]. In the present study, an additional strength is gained by focusing on occupational divers (local “experts”) in contrast with previous SCUBA studies that targeted recreational or tourism divers. Arguably, the collective experience of occupational divers should be given greater weight than more casual recreational or tourism divers in assessing reef conditions. This is because occupational divers spend many hours and days underwater diving on reefs as a part of their profession. Thus, aside from any training or education they receive on marine ecosystems, these divers gain significant experiential knowledge about local reefs, and importantly, are present to observe important reef characteristics and changes over time. For example, nearly 40% of the divers included in this study dive more than 200 times per year and have completed more than 1200 career dives. Of course, crowd-sourcing efforts such as the USVI lionfish campaign, mentioned previously, could potentially augment and triangulate data provided by the occupational divers.

A second strength of the present study is that it is spatially explicit and larger in geographic coverage compared with previous studies employing SCUBA divers to collect information on marine resources. An important question is whether the type of spatial data collected in this study has the potential to go beyond reef *assessment* to suggest *management* strategies for different reef areas. Again, the authors believe there is some value to using this information in a management context. The management matrix in Fig. 7 is intended to inform the allocation of management resources across a system. Potential management strategies for each of the four quadrants in the matrix were identified and labeled *restore*, *monitor*, *intervene*, and *limit*. Under a *restoration* strategy, management activities would focus on restoring reef physical qualities (e.g., structure, habitat) that have become degraded. In this quadrant, reefs threats are considered low so fiscal investments can be focused on the reef itself. This might include management actions like repopulating a reef with coral grown in a nursery setting, for example. Similarly, the *intervention* strategy also requires investment of resources, but these resources would be more appropriately directed toward reducing the threat conditions that are high, such as by stepping up efforts to remove invasive species or altering unsustainable fishing practices. This strategy may require investment of resources off-reef (e.g., fishing regulations, pollution abatement) to address the sources of threat.

The *monitor* strategy would apply to reefs that have relatively high quality conditions, but current low levels of threat. Threshold conditions or “limits of acceptable change” should be established for key quality indicators for reefs in this quadrant. The management strategy is to prevent reefs in this quadrant from moving into the *intervene* quadrant due to increased threat conditions. Knowledge of which reefs fall under the monitoring strategy would help managers to decide where across the reef tract they might want to invest in more expensive, technical monitoring programs. Finally, the *limit* strategy may appear controversial as few reef managers would want to voluntarily accept limiting management actions for reefs that have become degraded or destroyed. And yet, where fiscal resources are inherently limited, reef management may become a system of triage where pragmatic decisions about the long-term prospects for reef recovery must be made despite the best of intentions of those responsible for protecting and restoring them. Given such a difficult scenario it would be beneficial for managers to know which reefs may be, or close to becoming, “ecologically extinct.”

This reef matrix approach to analyzing and classifying reef locations is made possible by the mapping of reef qualities and threats across a larger reef area, in this case, two island groups. If found to be useful by natural resource managers, there is no reason why this heuristic approach could not be scaled-up, for example, to include other reef systems in the Caribbean, or scaled-down to include small reef areas with a single reef complex.

Finally, the management matrix is derived solely on the basis of perceived conditions as noted by an expert group of SCUBA divers. When available, biophysical inventories of reef conditions should be overlaid with perceived condition data in the matrix to provide further guidance for management. Engagement in specific management activities would need to be informed by systematic physical inventories of the reefs.

5. Conclusion

The use of participatory mapping for coral reef assessment is still in early stages, but the method offers a number of strengths. First, the method provides managers with information about coral health and threats—in addition to other spatial data—that might not be captured using *in situ* or remote sensing methods. Moreover, managers will learn which are the most popular/familiar reefs and can use this information to decide whether to monitor reef quality, work to mitigate or reduce threats, initiate restoration activities, or simply divert management effort to other areas. Second, when this type of data collection is performed periodically over a long period of time, managers will be able to track the condition of the reefs. Managers will be in a better position to assess previous management actions (if taken) to determine whether these actions produced the desired effect, commonly referred to as *adaptive management*. Third, and perhaps most important, the participatory nature of this method engages local stakeholders in the reef management process. The range of potential management options is far greater when local communities and organizations are vested in the long-term health of the reefs and are willing to commit to action. The spatial information can be made available to stakeholders via a website to provide information about reef conditions as well as provide updates to reef conditions over time.

Of course, participatory mapping for reef assessment purposes is not without limitations. First, recruitment of divers is difficult. Locating and then obtaining participation from a large number of knowledgeable SCUBA divers is challenging, even under the best of circumstances. SCUBA divers are busy people and may not feel that it is worth their time to complete an internet-based mapping survey, especially in areas where internet connections may not be fast and reliable. A second limitation is that if the data collection is facilitated by a researcher (as an alternative to self-administration) the process is time-consuming for a researcher to assist divers through the mapping survey. Many of the divers in this study requested some level of assistance from the researchers and some divers spent several hours comprehensively mapping reef conditions. Third, people will map places for which they are most familiar. For this reason, to achieve broad spatial coverage of reefs, sampling effort needs to be large and geographically diverse. Additionally, knowing that most divers will map only a fraction of the reefs that they are familiar with, it would be advantageous to document as a part of future studies the complete spatial domain of respondent divers' reef familiarity. This would allow researchers to better understand areas of coverage and, more importantly, the gaps in coverage. Without an effective sampling design and data collection effort, the spatial information generated will have limited value.

Finally, it should be noted that the methodological design for collection of this type of data for purposes of long-term monitoring would likely require adjustments to ensure the comparability of data over time. These adjustments would be needed to better understand and address the potential challenge of “shifting baselines” due to differentials in the degree of diver temporal experience and specialization. The concept of shifting baselines relates to the starting point at which a resource or ecosystem, such as a coral reef, is compared for purposes of monitoring status [1]. Divers could hold very different perceptions on the health of a coral reef based on when their baseline was established, meaning when their experience with the reef began. Thus, as a part of developing a monitoring program using a participatory mapping approach, researchers should take care to understand if diver baseline significantly and systematically impacts their perceptions of reef quality. Moreover, researchers should account for possible differences that may be attributed to degree of diver specialization. [46] found that highly specialized divers in the Florida Keys, meaning those with high expertise and significant levels of involvement in recreational SCUBA diving, were “more likely to rate reef conditions as less acceptable, more degraded, and highly impacted.” There are a number of methodological approaches that could be employed to detect and potentially correct for bias related to differential baselines, such as the use of longitudinal panels or controlling for diver temporal experience and degree of specialization.

On balance, participatory mapping for reef assessment can be a valuable tool in a reef manager's tool box, especially in the absence of systematic collection of biophysical reef data. As demonstrated in this study, SCUBA divers can provide spatially explicit, useable information about threats to coral reefs, reef qualities, dominant activities, and the perceived potential for reef recovery. If biophysical reef data is available, participatory mapped data can serve to corroborate and triangulate observations collected from other sources.

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